Land use change and land degradation in the western Chaco

Tucumán Province, Northwest Argentina
Burruyacú Region

J.A. Zinck, Editor

Contributing authors: *E. Bergsma*
M.M. Collantes
E. Flores
L. Neder
L. Recatalá
J. Remeijn
J.M. Sayago
R. van Zuidam
J.A. Zinck

ITC

INGEMA

LAND USE CHANGE AND LAND DEGRADATION

IN THE WESTERN CHACO

Tucumán Province, Northwest Argentina

Burruyacú Region

J.A. Zinck, Editor

Contributing authors:
E. Bergsma
M.M. Collantes
E. Flores
L. Neder
L. Recatalá
J. Remeijn
J.M. Sayago
R. van Zuidam
J.A. Zinck

ISBN: 90-6164-248-5
ITC Publication number: 84
2006

International Institute for Geo-Information Science and Earth Observation (ITC),
Enschede, the Netherlands

Instituto de Geociencias y Medio Ambiente (INGEMA),
Universidad Nacional de Tucumán, San Miguel de Tucumán, Argentina

CONTRIBUTIONS

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

J.A. Zinck

This report describes the findings of the Burruyacú Project, a joint research venture sponsored by the Institute of Geosciences and Environment (Instituto de Geociencias y Medio-Ambiente, INGEMA), Tucumán University, San Miguel de Tucumán, Argentina, and the International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands. The project was carried out during the period 1995-1997 by an interdisciplinary team including experts in geomorphology, forestry and soil science from both institutes: Mirian Collantes, Emilio Flores, Liliana Neder and José Manuel Sayago from INGEMA, and Eelko Bergsma, Luis Recatalá, Jaap Remeijn, Robert Van Zuidam and Alfred Zinck from ITC.

The Burruyacú area lies at the eastern foot of the Andes, in the western part of the Chaco plain, Tucumán province, northwest Argentina. The terrain is gently eastward sloping, with a piedmont landscape in the west along the Andean foothills and a plain landscape in the east corresponding to the western Chaco plain. Soils are mainly Mollisols, developing from a generalized loess cover. Climate is seasonal subtropical semiarid, with rainfall ranging from 600 mm in the east to 800 mm in the west. The natural vegetation cover is Chaco forest, a dry forest that has been impoverished in species by timber extraction for railway sleepers and tannin in the 19th century, and is now mainly used for firewood and cattle browsing. In the recent past, agricultural land, restricted to the contact zone between piedmont and plain in the west, was mainly used for sugarcane and maize production. But, in the 1960s when the sugar industry entered in crisis and most of the sugarcane factories had to be closed, more market-oriented crops, especially soybean, were introduced in substitution of the traditional ones.

From the mid-1960s onwards, large areas of Chaco forest were cleared mechanically to expand the agricultural frontier in the western Chaco plain, in response to rising soybean prices on the international market. In the selected Burruyacú study area (106,000 ha), 57,000 ha of forest have been converted to cropland between 1971 and 1991 at an average deforestation rate of 2,850 ha per year. The expansion of the agricultural frontier has been favored by a notable annual rainfall increase at the beginning of the 1970s, allowing the extension of strongly market-driven but climatically risk-prone dry-farming into the drier east of the Chaco plain. Usually, this kind of speculative mining agriculture does not provide long-term care to the land and frequently leads to severe land degradation in the short term. Previous observations revealed that severe soil compaction and drainage impedance were taking place in the area after only two decades of soybean monoculture.

In view of the former, the main objective of this applied research project was to analyze and assess the effect of large-scale, heavily mechanized cash-crop agriculture on the deterioration of land quality, under the working title of “Assessment and monitoring of environmental changes after deforestation in the western Chaco plain, northwest Argentina”.

General objectives of the research project were set as follows:

- Evaluation of the influence of the common, non-protective land management on the soils of the area over a period of 20 years (1971-1991), by comparing forest sites with sites deforested at different dates for agricultural use;
- Identification of monitoring indices, which can help mitigate soil compaction and predict the influence of climatic variability on the sustainability of dry-farming in the region;
- Contribution to the improvement of the current land management practices to restore land quality and avoid degradation of newly incorporated soils into the fast expanding agricultural frontier in the east of the area.

To satisfy these objectives, research focused more specifically on the following aspects aimed at assessing the severity and speed of land degradation:

- Monitor land use changes over the period from 1971 to 1991;

- Assess physical soil degradation and fertility depletion in cultivated fields of various reclamation dates;
- Assess physical soil degradation in forest land submitted to extensive cattle grazing;
- Compare soil degradation between arable and forest land.

To guide the research process, secure its coherence in relation to the research objectives and allow integrating the various contributions from the research team, a comprehensive methodological framework and approach were used for data collection, processing and interpretation, and for risk prediction (Figure 1.1).

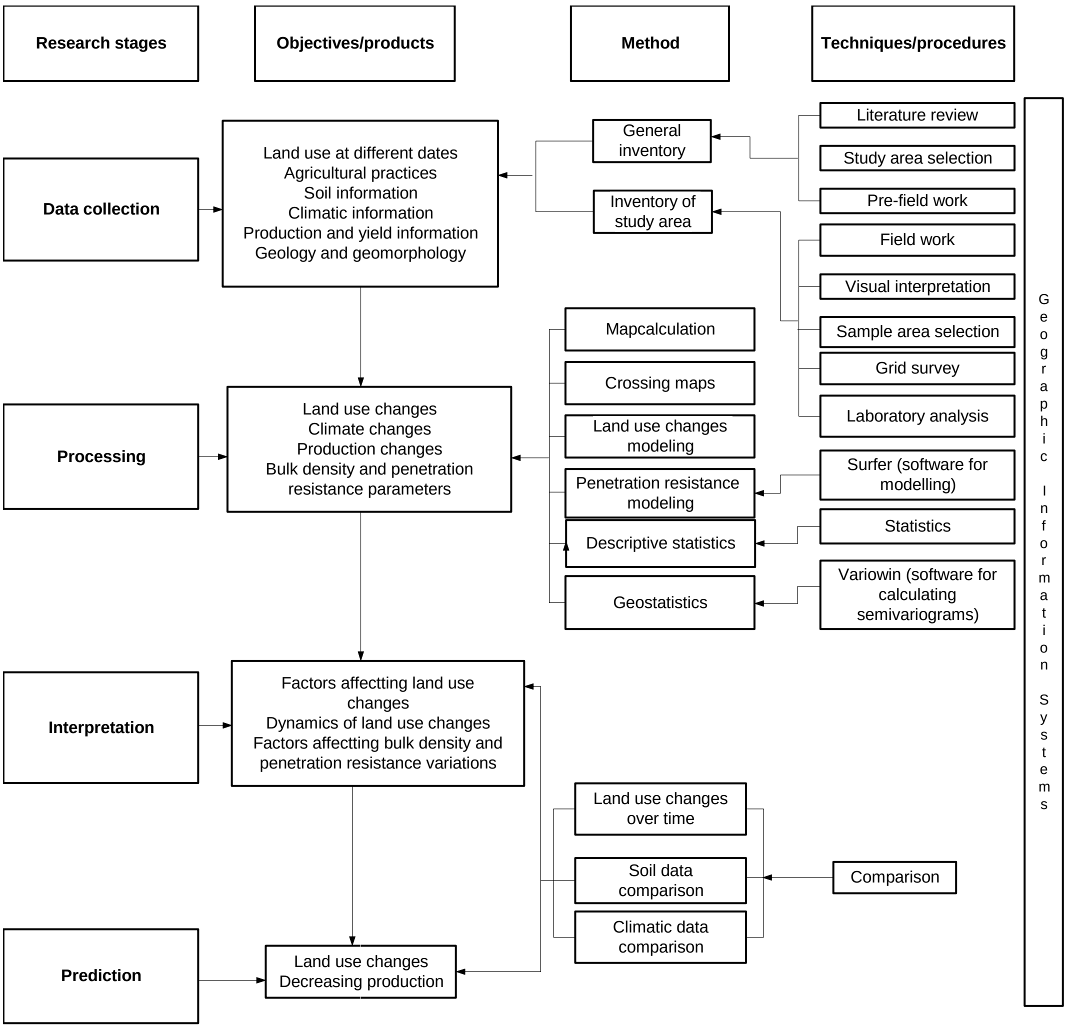


Figure 1.1. Methodological framework and approach.

Research results are presented in a set of chapters. Chapter 2 introduces main biophysical and socio-economic features of the study region. The paleoenvironmental history, with emphasis on the Pleistocene and Holocene landscape evolution, is covered in Chapter 3. The resulting geomorphic landscape structure and the current geomorphodynamics are analyzed in Chapter 4. The soil cover is described in Chapter 5, focusing on soil origin, classification, distribution and properties. Chapter 6 is devoted to the Chaco forest, with emphasis on its structure, floristic composition and productivity. Changes affecting the forest cover through clearing for agricultural purposes in the period 1971-1991 were identified using different methods, and results are discussed in Chapter 7. Chapter 8 describes the current land management and farming systems in view of their impact on land degradation and adresses the issue of improving soil management practices for sustainable land use. Soil surface features, especially those reflecting the effect of inadequate land management practices, are identified and evaluated in Chapter 9. Chapter 10 concentrates on the assessment of soil compaction and fertility depletion at regional, local and plot levels. In Chapter 11, land evaluation data are mobilized to formulate and discuss suitable land use options, with emphasis on solving land use conflicts and land use competition. Main conclusions of this applied research project are presented in Chapter 12. Soil data generated by field descriptions and laboratory determinations are recorded in Chapter 13.

Acknowledgements

The authors acknowledge the funds granted by ITC and INGEMA to carry out and publish this research work. We are grateful to Lic. Julieta Carrizo and Dr. Cristina Perea from the University of Tucumán for their contribution to identifying and labeling plant species (Chapter 6), to Marc Zinck for his contribution to editing several tables and figures and making the final layout of the text, and to the ITC facility services for scanning and reproduction.

Part of the information contained in Chapters 2, 7 and 10 was derived from the MSc thesis defended by E. Flores at ITC in 1997 under the following title:
Flores Ivaldi, E., 1997. Monitoring land use changes and comparing soil physical properties between arable and forest land in the western Chaco plain, NW Argentina. MSc Thesis, International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands, 151pp.

Photos are from E. Bergsma (EB) and A. Zinck (AZ).

CHAPTER 2

GENERAL FEATURES OF THE STUDY REGION

E. Flores, J.A. Zinck

2.1. LOCATION

The study region is located in Burruyacú district, in the northeast of Tucumán province, northwest Argentina (Figure 2.1). The Burruyacú district has an extent of 1329 km^2, bounded by longitudes 64°28'W and 65°00'W and latitudes 26°25'S and 26°48'S. The area borders on Candelaria and Rosario de la Frontera districts in the north, Cruz Alta district in the south, Tafi Viejo and Trancas districts in the west, and Pellegrini and Jiménez districts in the east. The town of Burruyacú is located about 60 km northeast of the provincial capital San Miguel de Tucumán. Burruyacú, Gobernador Garmendia, Gobernador Piedrabuena and La Ramada constitute the four corners of the study region (Figure 2.2).

The access from San Miguel de Tucumán to the study region is through the provincial asphalt road 304, connecting Tucumán with La Ramada, Benjamín Aráoz and Burruyacú. Other tarmac roads in the area connect the main settlements within the Burruyacú district. The road between Gobernador Garmendia and Gobernador Piedrabuena is not paved. Elevation ranges from 350 m in the east to 650 m in the west (IGM, 1988).

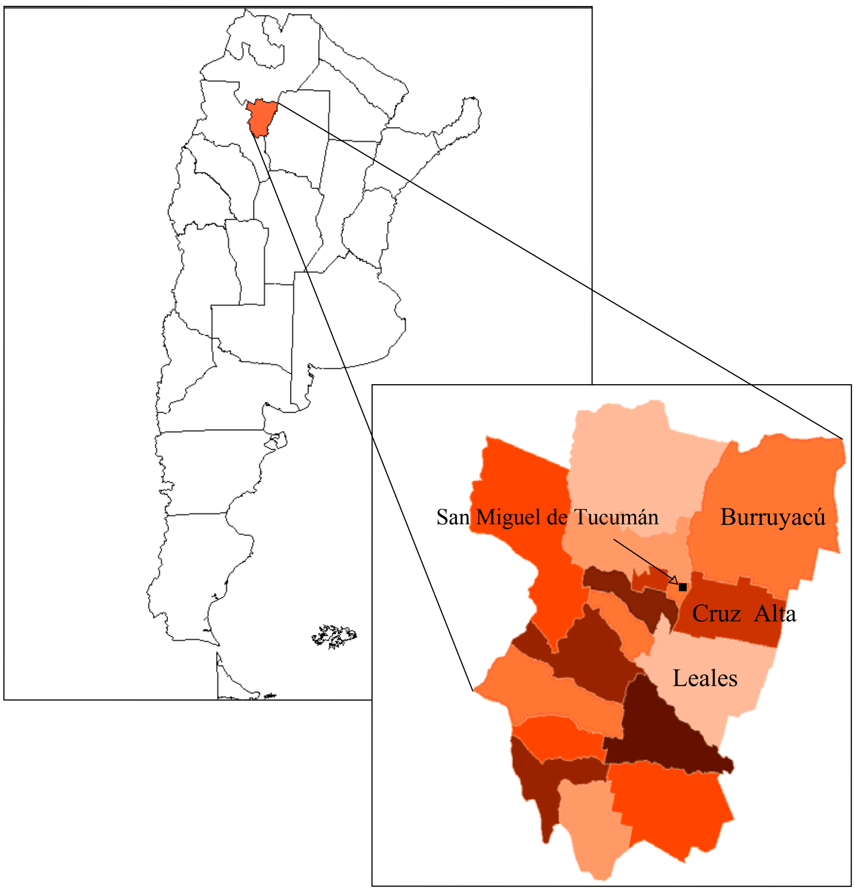


Figure 2.1. Location of Burruyacú district in Tucumán province, northwest Argentina.

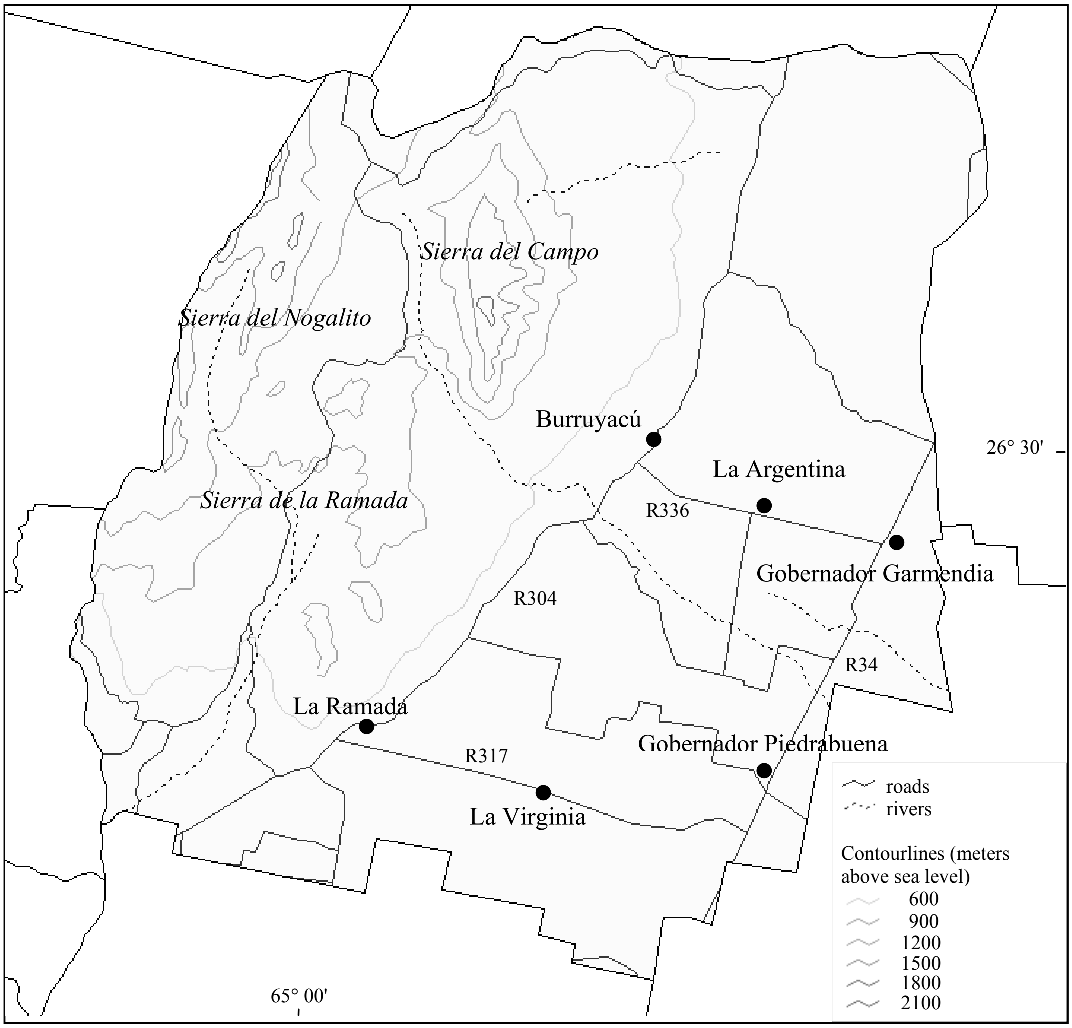


Figure 2.2. Elevation features and main localities in Burruyacú district.

2.2. PHYSIOGRAPHY AND GEOMORPHOLOGY

Two main physiographic units can be distinguished in Tucumán province: a mountain area and a plain area (Zuccardi & Fadda, 1972; Alderete, 1984; Sayago et al., 1984). The mountain area is composed of a set of SSW-NNE parallel ranges, called Sierras Pampeanas and Sierras Subandinas. The western boundary of the study region corresponds to the Sierras de Burruyacú, which belong to the Sierras Subandinas. Elevation ranges from about 650 m in the foothills to more than 2100 m at the mountain range summits.

The plain area in the eastern part of the province is called the "main plain" by Alderete (1984), while other authors split it into two subunits: the piedmont and the Chaco plain (Zuccardi & Fadda, 1972; Sayago et al., 1996). The piedmont has gentle to steep slopes facing southeast, with elevation of 500-650 m. The Chaco plain is an extensive flat terrain surface of 300-500 m elevation, incised by ephemeral streams.

Sayago et al. (1996) emphasized the importance of gully and sheet erosion in the Burruyacú area. Gully head walls collapse due to seepage flow, together with the dissolution of calcium carbonate (Bergsma et al., 1996). Gullies may be as deep as 2-3 m. Gully length varies from less than 50 m to more than 200 m (Sayago et al., 1996). Extreme gully incision is called cliff erosion (erosion en barrancos). Cliff gullies are 3-5 m deep and wide; length is very variable, sometimes hundreds of meters. Landslides occur at the heads of the cliff erosion forms.

Sheet erosion affects the area widely. Generally, laminar erosion starts with rain-splash, followed by overland flow when the soil is saturated or when soil compaction impedes water infiltration. The overland flow effect is compounded by high soil erodibility and long slopes.

2.3. GEOLOGY

The Burruyacú area is formed by a Precambrian crystalline basement and Tertiary sedimentary cover layers (Table 2.1). In the piedmont and in the Chaco plain there are alluvial, colluvial and eolian deposits. The latter are mainly loess sediments, which also contain volcanic glass materials.

Table 2.1. Pre-Quaternary geology of the Burruyacú area.

Age	Formation	Lithology	Definition	Distribution	Features
Tertiary	Río Sali	Limolites, lutites, marls and limestones	Bossi (1969)	Discontinuous around the Río Nío formation	Limolites stratified in layers 1-2 m thick, with intercalations of lutites and marls 5-6 m thick and oolite limestones.
	Río Loro and Río Nío	Limolites, marls and claystones of variable colours	Bossi (1969)	Exposed discontinuously around the Cadillal formation	Generally well stratified and concordant with the Cadillal formation at the bottom and with the Río Sali formation at the top.
Cretaceous	Cadillal	Conglomeratic sandstones and basalts	Turner (1969)	Around the metamorphic core	Angular discordance with the metamorphic core.
Upper Cambrian	Candelaria	Orthoquartzites and sandstones	Ricci and Villanueva (1969)	Isolated outcrops in the Sierra del Campo	Strongly folded and angular discordance with the Medina formation; covered concordantly by Ordovician lutites and limolites.
Cambrian-Precambrian	Medina	Slates, shales, metagreywackes and quartzites	Bossi (1969)	Between the Urueña river and the Tajamar river	Core of the anticlines forming the surrounding mountains; contains ichnites of Cambrian age (Aceñolaza, 1973).

2.3.1. Geologic history

The cratonization of a Precambrian marine basin in the northwest of Argentina played an important role in the paleogeographic evolution of the region (Bracaccini, 1960). To this central craton belong the older rocks of the Tucumán province, forming the pre-Andean mountain ranges (González, 1984). Metamorphism of deep-sea sediments alternating with turbidity current deposits originated the Medina formation. After a hiatus in the upper Cambrian, a shallow sea transgression moving from Bolivia created the La Candelaria formation. This transgression could not reach the western areas because of the obstruction of the central craton. There are no sedimentary records of Triassic and Jurassic ages. During these periods, the central craton was eroded and a peneplain developed. Erosion periods were interrupted by orogenic movements. During the Cretaceous, some areas were uplifted and exposed to erosion, providing the clastic sediments of the El Cadillal formation. Volcanic eruptions are recorded in the El Cadillal formation by the presence of basaltic layers. Marls and claystones present in the Río Salí and Río Nío formations might be related to the uplift of mountain ranges and the proximity of the sea. Large evaporating water bodies and aridic climate were the conditions that influenced the Río Salí formation genesis. The aridic climate of the Tertiary changed to more humid in the Quaternary. The main Quaternary deposits in the Tucumán area are alluvial and eolian. Volcanic eruptions in the Andes during the Quaternary explain the composition of the eolian deposits in large areas of Argentina. The presence of paleosols developed from loess material in the Chaco plain suggests environmental conditions alternating between dry and humid. Loess deposition occurred during the dry periods and soil formation took place during the humid periods. These alternating conditions might be related to the glacial-interglacial periods in the Andes and Patagonia (Imbelloni & Teruggi, 1993; Sayago et al., 2003, 2005).

2.3.2. Quaternary geology

Loess is the main cover material in the study area. During the Quaternary, loess was spread over large areas in the Pampa and Chaco plains of Argentina (Teruggi, 1957/1975; Clapperton, 1993; Imbellone & Teruggi, 1993; Sayago et al., 1996; Sayago et al., 2003). According to Teruggi (1957/1975), the loess deposits of Argentina have appearance and texture similar to those of North America and Europe. However, the mineralogical composition is different because of the presence of volcanic minerals. The main clay mineral in the Pampa loess is montmorillonite, with important amounts of volcanic glass.

According to Imbelloni and Teruggi (1993), the Pampa plain has paleosol sequences developed from several loess mantles. These sequences correspond to depositional pulses followed by periods during which soil formation took place. The paleosol sequences are successions of B and C horizons that are polygenic as a result of the encroachment of each soil formation event on the underlying loess mantle. Dominant cover soils are Mollisols, with hydromorphic and carbonatic features, while paleosols correspond mainly to buried Alfisols.

Loess in the Tucumán area is texturally homogeneous (Sayago et al., 1996). Volcanic glass and illite are the main minerals. The Quaternary stratigraphy of the Burruyacú area is shown in two profiles: one for the piedmont and another for the Chaco plain (Figures 2.3 and 2.4). The bottom and middle sections of the piedmont profile occur in different areas; the upper section outcrops in riverbed walls, mainly along the Tajamar river. The profile corresponding to the Chaco plain was described along the Paja Colorada river, near road 34.

Zuccardi & Fadda (1972) described the cover formations in the study area "as continental deposits of fine materials". These materials are mainly silty, with variable amounts of clay and very fine sand. The mineral composition of the upper layers is mostly volcanic glass (40-60%), with quartz (10-20%), feldspars (10-15%) and micas (3-10%). Volcanic glass decreases abruptly with depth to 10-20%, while the amount of quartz increases to 30-40%.

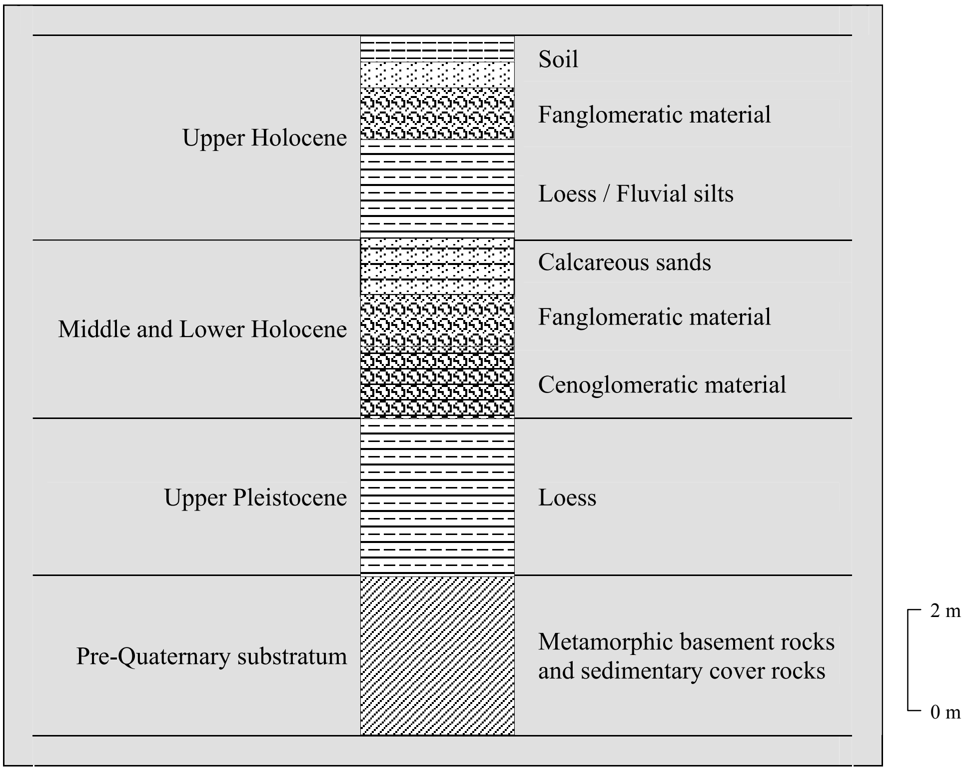


Figure 2.3. Stratigraphy of a piedmont profile (Sayago et al., 1996).

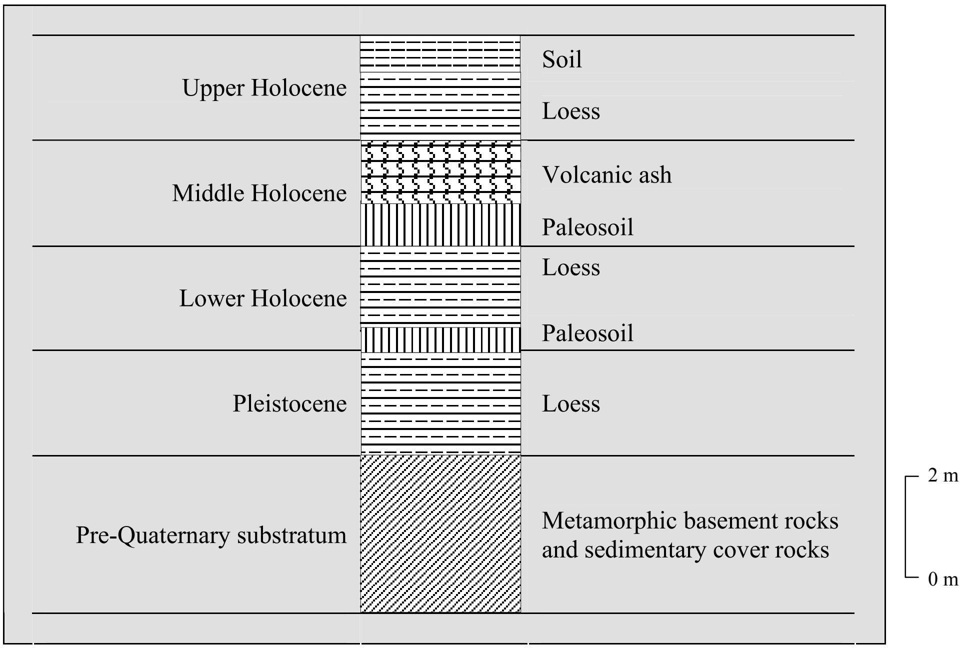


Figure 2.4. Stratigraphy of a Chaco plain profile (Sayago et al., 1996).

2.4. SOILS

The soils of Tucumán province have been studied by Zuccardi & Fadda (1972, 1985). In 1992, INTA produced the basic soil map of Burruyacú district (Gomez et al., 1992). All the soils in the Burruyacú area have developed from Quaternary sediments, mainly from loess deposits, and for this reason they are homogeneous over the whole area. Dominant texture is silt loam. In general, soil reaction is neutral but changes to slightly alkaline in the west because of higher calcium carbonate content in the sediments (Zuccardi & Fadda, 1985; García, 1990). Regional soil distribution, with soil classification according to USDA Soil Taxonomy (Soil Survey Staff, 1996) is shown in Figure 2.5.

Soils are mainly Mollisols (Zuccardi & Fadda, 1985). Fluventic and Cumulic Haplustolls are commonly associated in the dry subhumid piedmont. Soils of the humid and subhumid flat parts of Burruyacú district are Typic Argiudolls and Typic Argiustolls. In the soutwest of Burruyacú district, Cumulic and Fluventic Haplustolls are associated with calcareous Ustorthents. Typic Argiustolls together with Cumulic and Fluventic Haplustolls occur in the center of the area, while Typic and Entic Haplustolls dominate in the east. The contrast in soil water regime between west and east of the area has been described by Zuccardi et al. (1993).

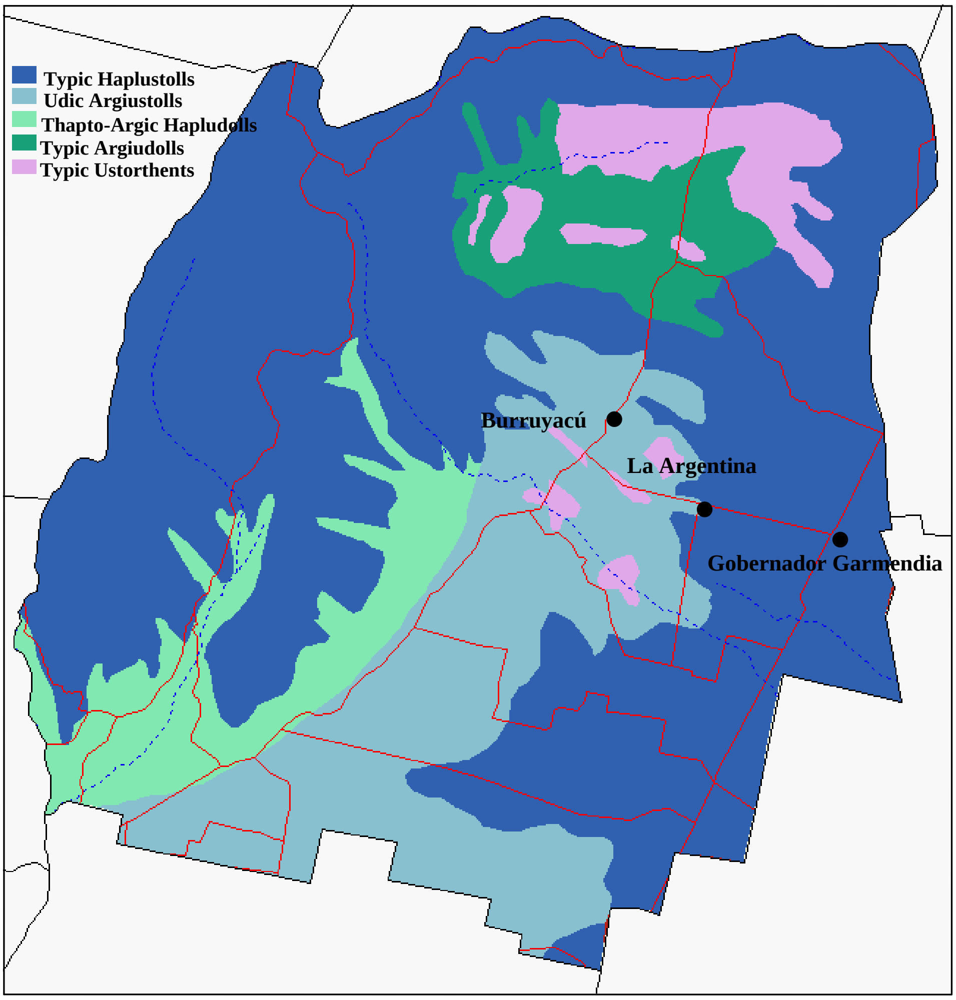


Figure 2.5. Soil map of Burruyacú district (INTA, 1996).

2.5. CLIMATE

The study region belongs to the bioclimatic province of the western Chaco, where summer rainfalls coincide with high temperatures (Figures 2.6 and 2.8) (Torres, 1972). The average annual rainfall increases from 600 mm in the east to 800 mm in the west due to the orographic rain effect caused by the north-south alignment of the pre-Andean mountain ranges. In the east, at Gobernador Garmendia site, the water balance is negative throughout the year because of high evapotranspiration, low cloud cover and high amount of sun hours (Figure 2.7). In the west, at Burruyacú site, there is water surplus from December till April (Figure 2.9). The climate is classified as tropical semiarid (Gomez et al., 1992).

According to Gomez et al. (1992) and Casanueva (1992), the main features of the regional temperature regime are as follows:

- Mean annual temperature around 20°C in Gobernador Garmendia and around 18°C in Burruyacú;
- Absolute maximum temperature from 40 to 45°C;
- Absolute minimum temperature from -5 to -10°C;
- Average annual frost days less than 5.

2.6. WATER RESOURCES

In the piedmont, streams are ephemeral because of the high permeability of the surface materials. The plain landscape has no defined, structured drainage network, a feature typical of the western Chaco plain. There are groundwater resources that some farmers use for irrigation to produce two crops per year with good yields. The government is promoting the use of groundwater through an irrigation project in the east of Tucumán province. In this area, with more than 300 frost-free days and good soil conditions, farmers could duplicate the production if they had sufficient water for irrigation (La Gaceta, 1996).

2.7. VEGETATION

The natural vegetation of the area has been drastically disturbed by human activities. The Chaco forest has been exploited for timber extraction and livestock browsing, before being cleared for cropping. Farmers have introduced allochthonous trees for alley cropping (Gomez et al., 1992).

The vegetation of the area has been extensively studied (Hueck, 1953; Morello & Toledo, 1959; Zuccardi & Fadda, 1972, 1985). Zuccardi and Fadda, following the description made by Morello and Hueck, divided the vegetation cover into plain vegetation and mountain vegetation.

In the plain landscape, vegetation characteristics change gradually from east to west according to rainfall increase, with a vegetation sequence including monte, Chaco forest and subtropical forest. In the study area, only the Chaco forest is represented, starting east of the 800 mm rainfall line. It has been subdivided into three types: the tala-mistol forest, the quebracho forest and the algarrobo forest.

- The tala-mistol forest occurs between the 600 mm and 800 mm rainfall lines. It is the wettest Chaco forest type, with mesophilous species like tala (*Celtis spinoza*, Spreng) and mistol (*Zizyphus mistol*, Gris). There are many herbs but no cacti.
- The quebracho forest is characterized by te presence of quebracho colorado (*Schinopsis quebracho colorado*, Engl) and quebracho blanco (*Aspidosderma quebracho blanco*, Schlecht). Cacti are present, herbs also but only during the rainy season.
- The algarrobo forest is the driest Chaco forest, occurring east of the 500 mm rainfall line. Characteristic species are algarrobo blanco (*Prosopis alba*, Gris) and algarrobo negro (*Prosopis nigra*, Gris).

Remeijn (1996) carried out a preliminary tree species inventory of the Burruyacú area (Table 2.2). Plant characteristics, floristic composition of the current vegetation cover and forest productivity are described in Chapter 6.

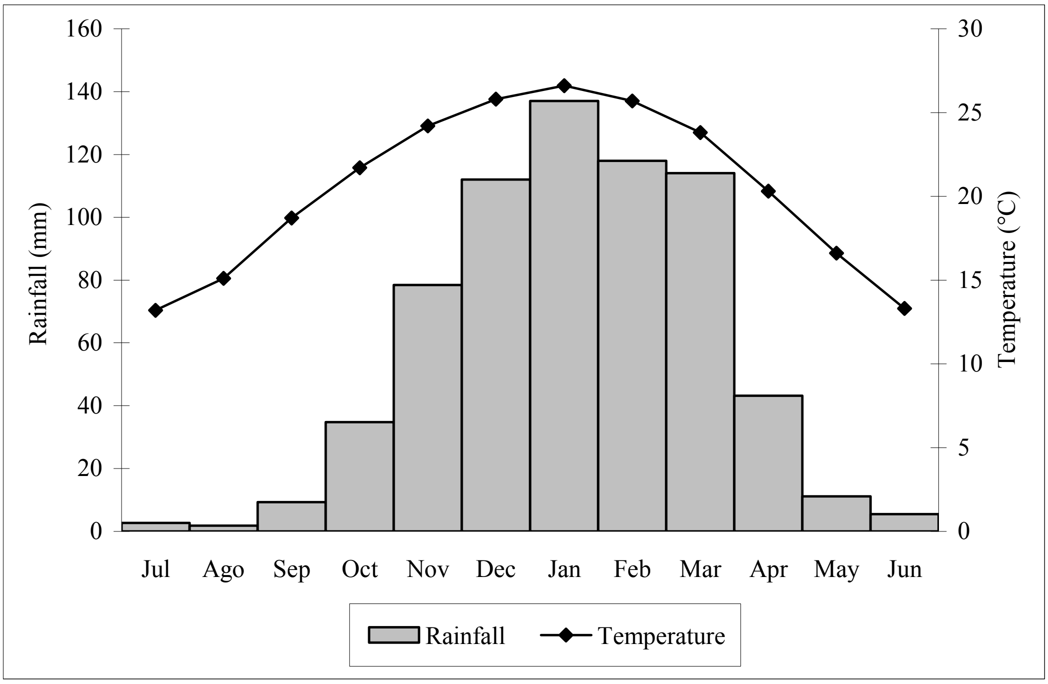


Figure 2.6. Average monthly rainfall and temperature at Gobernador Garmendia site for the period 1916-1989 (modified from Casanueva, 1992).

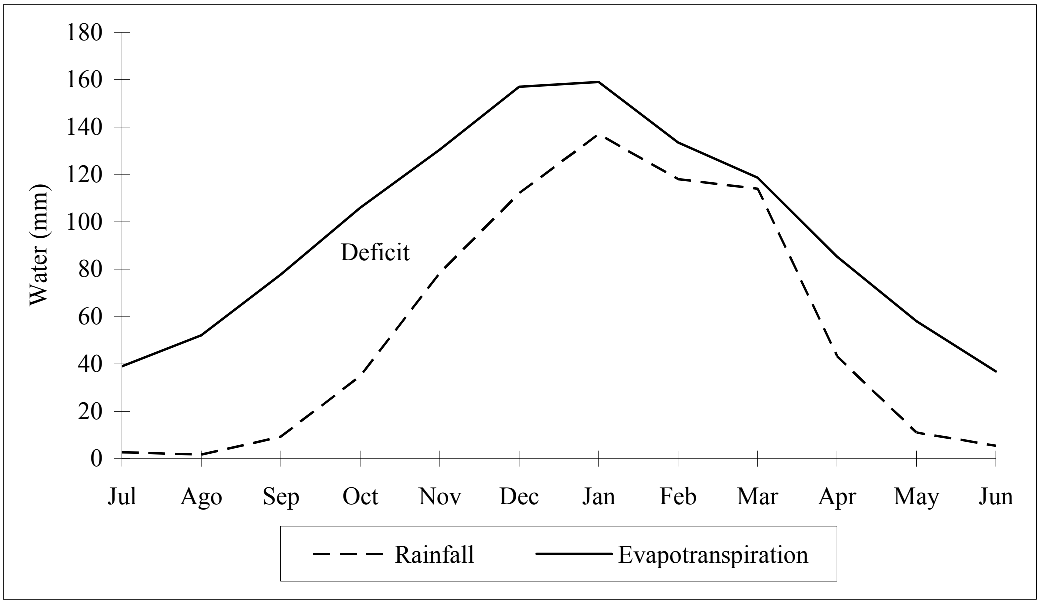


Figure 2.7. Water balance at Gobernador Garmendia site for the period 1916-1989 (modified from Casanueva, 1992).

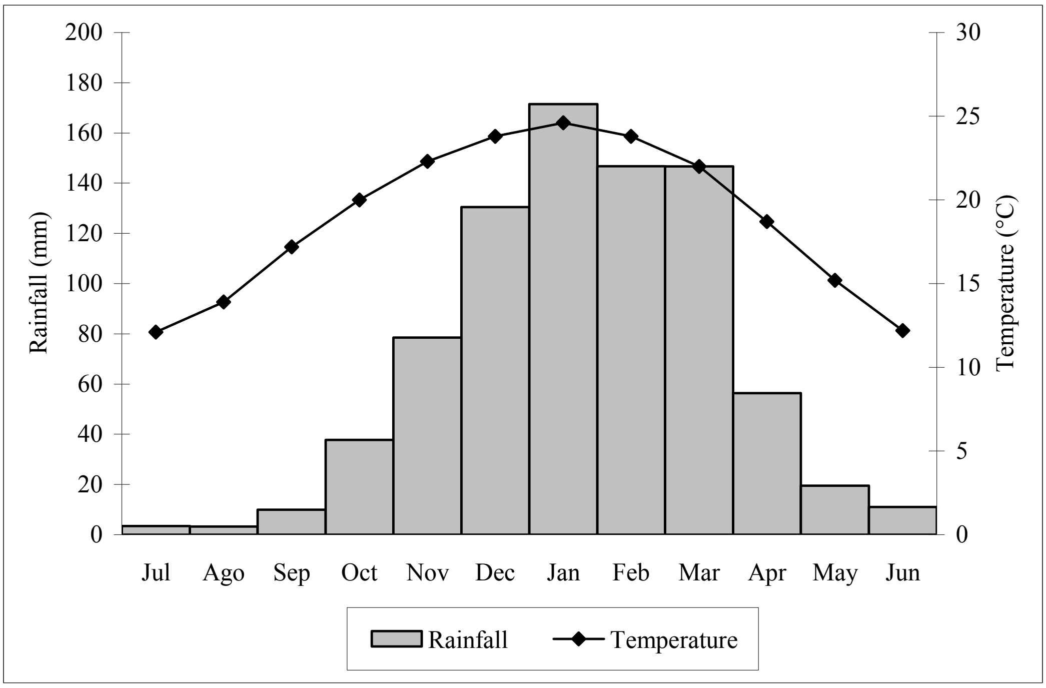


Figure 2.8. Average monthly rainfall and temperature at Burruyacú site for the period 1916-1989 (modified from Casanueva, 1992).

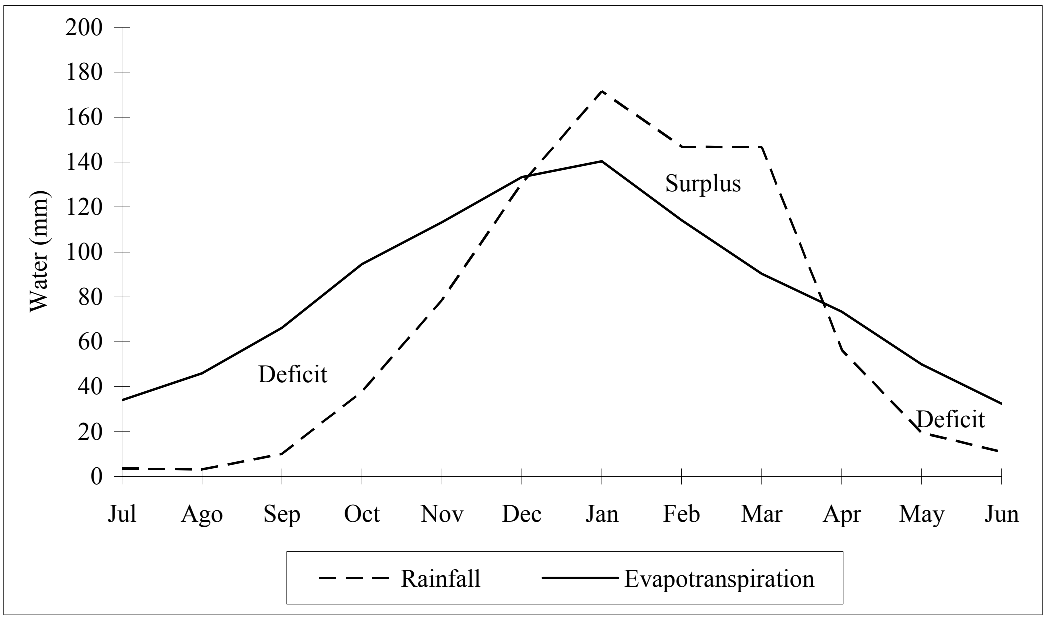


Figure 2.9. Water balance at Burruyacú site for the period 1916-1989 (modified from Casanueva, 1992).

Table 2.2. Tree species inventory of the Burruyacú area (Remeijn, 1996).

Sites: / Tree species:	Lobo	Argentina	Virginia	Elias 1	Elias 2	Elias 3	Piedrabuena
Algarrobo negro	x				x		
Ancoche	x					x	x
Arrayán	x		x	x			
Brunagaspe	x		xxx	x	x	x	xxx
Calahuchín		x					
Chalchal	x		xxx				
Churque	x	x					
Cucharero	x						
Guayacán		x					xxx
Guayaguilla blanco	x	x	x				
Guayaguilla negro		x					xxx
Ischiuil blanco /I. negro		x	xx				
Lata pobre	x						
Laurel	x						
Lecherón		x					
Mistol	x	x	xxx	x	x	x	xxx
Molle	x				x		xxx
Morera			x				
Ortiga		x					
Piquilllín grande	x		x	x			
Poleo montes							x
Quebracho blanco / Q.colorado		x	x	x			xxx
Sacha huacán / S.gochuchu /S. naranja	x	x	x				
Siempreverde		x					
Sombra de toro	x				x	x	
Sunchillo or suncho amargo	x	x					
Tala blanca /T. pispa / T. brava		x	xxx	x	x	x	xxx
Tuscal	x	x	xx	x	x	x	xxx
Viraru		x					

x: unfrequent; xx: moderately frequent; xxx: frequent.

2.8. LAND USE

In the 1970s, the principal crops in Tucumán province were sugarcane (70 % of the cultivated area), maize (14%), citrus (7%) and vegetables (7%) (Zuccardi & Fadda, 1972). By the mid 1990s, the province had become the main sugarcane and lemon producer countrywide (Table 2.3).

Statistics from the provincial government show that wheat covered 18,000 ha in the 1995-1996 cropping season, with an average yield of 2000 kg ha^{-1}. In 1995, soybean was cultivated in 70,000 ha, with an average yield of 1800 kg ha^{-1} (La Gaceta, 1996). Forecast made by that time did not foresee significant variations in the soybean area nor in the soybean production for the near future. In the study area, the main crops were soybean, maize and wheat, together with citrus and vegetables.

Vicini (1984) analyzed land use changes in Tucumán province between 1956 and 1980 (Table 2.4). Soybean, maize and wheat production data for the period 1965-1993 are shown in Figure 2.10. Although these data are for the whole province, it is known that soybean and maize were mainly cultivated in the east of the province, corresponding to Burruyacú, Cruz Alta and Leales districts. Wheat was cultivated in different areas, essentially in the east and south of the province, but also in Trancas district in the north of the province. The drop of production in 1988 might be related to an exceptionally dry year in the whole Tucumán province, although political and economic factors could also have played a role.

Table 2.3. Main crops in Tucumán province (1994-1995).

Crops	Production (tons)	Surface area (country %)
Sugarcane	8,620,000	67.0
Lemon	600,000	82.0
Soybean	156,800	1.3
Potato	120,000	6.0
Tobacco	7,542	9.6
Bean	6,220	2.0

(Consejo Federal de Inversiones, 1996)

Table 2.4. Area changes of the main crops in Tucumán province (thousands of ha).

Year	Sugarcane	Soybean	Maize	Sorghum	Bean
1956	230	-	31.5	-	0.88
1960	192	-	32.1	-	0.95
1966	169	2.2	47.5	-	0.96
1970	140	5.8	42.2	29.8	1.00
1976	250	24.9	14.0	7.5	10.60
1980	235	80.4	36.4	7.2	25.00

(Vicini, 1984)

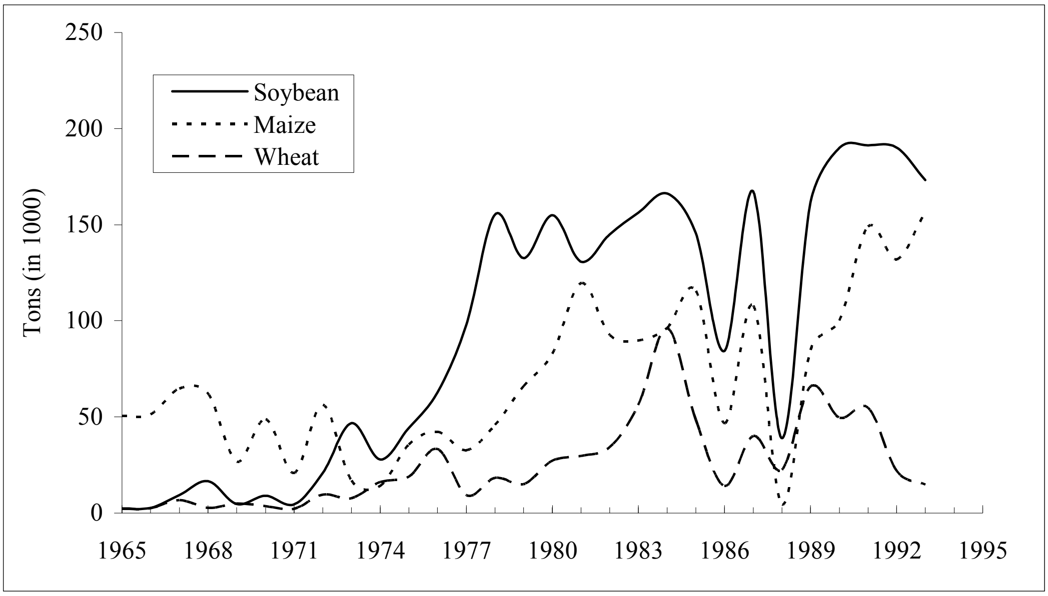


Figure 2.10. Soybean, maize and wheat production in Tucumán province during the period 1965-1993 (Agricultural Experimental Station of Tucumán).

2.9. REFERENCES

Aceñolaza, F.G., 1973. Sobre la presencia de trilobites en las cuarcitas del grupo Mesón en Potrerillos, Provincia de Salta. Rev. Asoc. Geol. Arg. 28(3): 309-311.

Alderete, M., 1984. Unidades fisiográficas. In: F.G. Aceñolaza, G.E. Bossi and A.J. Toselli (eds.), Geología de Tucumán. Colegio de Graduados en Ciencias Geológicas de Tucumán. S.M. de Tucumán, Argentina, pp.19-28.

Bersgma, E., Charman, P., Gibbons, F., Hurni, H., Moldenhauer, W.C., Panichapong, S., 1996. Terminology for soil erosion and conservation. Int. Soil Science Society. Wageningen, The Netherlands.

Bracaccini, I.O., 1960. Lineamientos principales de la evolución estructural de la Argentina. Petrotecnia, Revista del Instituto Argentino del Petróleo, 10 (6): 57-69.

Casanueva, P.R., 1992. Geología e hidrogeología del borde sur-oriental de la Sierra del Campo entre las localidades de La Gramilla y La Mesada. Tesis de Seminario. Universidad Nacional de Tucumán, San Miguel de Tucumán, Argentina.

Clapperton, C., 1993. Quaternary geology and geomorphology of South America. Elsevier. Amsterdam, The Netherlands.

Consejo Federal de Inversiones (CFI), 1996. Internet homepage.http://www.arw3.com/cfi/ingles/tuc.html.

García, J.R., 1990. Los suelos de la llanura chacopampeana. Genesis, clasificación y fertilidad. Avance Agroindustrial, Octubre de 1990. S.M. de Tucumán, Argentina.

Gomez, L.A., Ferrao, R.F., Casen, M.L., 1992. Carta básica de suelos del Departamento Burruyacú, Provincia de Tucumán. Instituto Nacional de Tecnología Agropecuaria, Centro de Investigaciones de Recursos Naturales, Instituto de Suelos. Castelar, Argentina.

González, C., 1984. Geología histórica. In: F.G. Aceñolaza, G.E. Bossi and A.J. Toselli (eds.), Geología de Tucumán. Colegio de Graduados en Ciencias Geológicas de Tucumán. S.M. de Tucumán, pp.171-177.

Hueck, K., 1953. Urlandschaft, Raublandschaft und Kulturlandschaft in der Provinz Tucumán in nordwestlichen Argentinien: ein Beispiel für die Bedeutung der ursprünglichen Pflanzendecke beim Werden einer subtropischen Landschaft. Bonner Geographische Abhandlungen Heft 10, 102p.

IGM, 1988. Mapa topográfico San Miguel de Tucumán, Hoja 2766-II. Instituto Geográfico Militar, República Argentina.

Imbellone, P.A., Teruggi, M.E., 1993. Paleosols in loess deposits of the Argentine Pampas. Quaternary International 17: 49-55.

INTA, 1996. Atlas de suelos de la República Argentina. Instituto Nacional de Tecnología Agropecuaria. Pergamino, Buenos Aires, Argentina.

La Gaceta, 1996. El riego como alternativa de desarrollo del Este. Artículo publicado 30-06-1996. S.M. de Tucumán, Argentina.

Morello, J.H., Toledo, C.S., 1959. El bosque chaqueño. Revista Agronomía del Noroeste de Argentina III (1): 5-79, III (2): 209-258.

Remeijn, J., 1996. Preliminary report on the vegetation of the Burruyacú area. ITC, Internal Report. Enschede, The Netherlands.

Sayago, J.M., Collantes, M., Neder, L., 1996. Hidrogeormofología de la cuenca paleofluvial del Río Tajamar, Dpto. Burruyacú, Tucumán. Reporte interno, INGEMA. Tucumán, Argentina.

Sayago, J.M., Ratto, L., Collantes, M. 1984. Geormofología. In: F.G. Aceñolaza, G.E. Bossi and A.J. Toselli (eds.), Geología de Tucumán. Colegio de Graduados en Ciencias Geológicas de Tucumán. S.M. de Tucumán, Argentina, pp.143-154.

Sayago, J.M., Zinck, A., Collantes, M.M., Toledo, M., 2003. Evolución ambiental de los valles preandinos y la llanura chaqueña occidental argentina durante el Pleistoceno tardío y el Holoceno. Actas II Congreso Argentino de Cuaternario y Geomorfología. Universidad Nacional de Tucumán, S.M. de Tucumán, Argentina, pp.185-200.

Sayago, J.M., Zinck, J.A., Collantes, M.M., Toledo, M., 2005. Environmental changes in the pre-Andean valleys and Chaco Plain (Northwest Argentina) during the Late Pleistocene and Holocene. Neues Jahrbuch für Geologie und Paläontologie Abh. (Stuttgart) 236 (1/2): 245-265.

Soil Survey Staff, 1996. Soil Taxonomy. Soil Conservation Service, US Department of Agriculture, Washington DC, USA.

Teruggi, M.E., 1975. The nature and origin of Argentine loess. In: I.J. Smalley (ed.), Loess: lithology and genesis. Benchmark Papers in Geology 26. Reprinted from J. Sed. Petrol. 27(3): 322-332 (1957).

Torres B., E.A., 1972. Mesoclimas de la Provincia de Tucumán. Revista Agronómica N.O. Argentina IX: 527-345.

Vicini, L., 1984. La cobertura boscosa de los Departamentos de Burruyacú, Cruz Alta y Leales, Provincia de Tucumán, Argentina. Informe interno INTA, Banda del Río Salí, Tucumán, Argentina.

Zuccardi, R.B., Fadda, G.S., 1972. Mapa de reconocimiento de suelos de la Provincia de Tucumán. Publicación Especial 3. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina. 99p.

Zuccardi, R.B., Fadda, G.S., 1985. Bosquejo agrológico de la Provincia de Tucumán. Publicación Miscelánea 86. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina.

Zuccardi, R.B, García, J.R., Sanzano, G.A., Giménez, R., 1993. Dinámica del agua edáfica en dos ecosistemas de la región semiárida tucumana. Actas XII Congreso Latinoamericano de la Ciencia del Suelo. Sevilla, España, pp.151-158.

CHAPTER 3

PALEOENVIRONMENTAL EVOLUTION

J.M. Sayago, J.A. Zinck, M.M. Collantes

3.1. INTRODUCTION

The study region is a transition area between the western Chaco plain and the pre-Andean mountain ranges of northwest Argentina. It includes an undulating piedmont at the eastern foot of the Sierras La Ramada and El Campo, in the west, and a nearly flat plain in the east. The geologic and geomorphic characteristics of the area reflect paleoenvironmental changes that took place in the subtropical mountain region of northwest Argentina during the Upper Pleistocene and Holocene. The aim of this chapter is twofold: (1) to discuss, at regional level, the origin of the loess cover in the western Chaco plain north of 30ºS latitude and (2) to describe, at local level, several loess-paleosol sequences occurring in the piedmont and plain of the Burruyacú area, northeast of S.M. de Tucumán. This information was used to reconstruct the paleoenvironmental evolution of the area during the Late Pleistocene and the Holocene at local and regional scales.

3.2. SUBTROPICAL LOESS

From mid-19th century onwards, many authors have described the wind-blown fine sand and silt materials that cover the Pampean plain north of Patagonia. In contrast, little was known, until recently, of similar sediments covering large parts of the subtropical region of Argentina north of 30ºS latitude. Loess deposits have been reported by Stappenbeck (1926) in several places of Santiago del Estero, by Cordini (1947) and Groeber (1958) in the Chaco-Formosa plain, by Ledesma et al. (1973) in the agricultural dorsal plain and the Chaco forest, by Bonaparte and Bobovnicov (1974) in the eastern Tucumán plain, by González-Bonorino (1978) in the valleys and piedmont of the Aconquija and Ambato mountain ranges, and by Sayago (1979) in the submeridional lowlands of the northern Santa Fe region. Over the last two decades, the inventory of loess materials in the pre-Andean valleys and in the Chaco plain between 20ºS and 30ºS latitude has substantially increased. Camino (1988), Esteban et al. (1988), Powell et al. (1992) and Collantes et al. (1993) contributed important litho- and biostratigraphic data describing surface loess sediments that were called "neotropical loess" due to their position between the South American tropical and temperate regions (Sayago, 1995). In spite of having been reworked by wind, water or ice, subtropical loess has many of the characteristics attributed by Teruggi (1957/1975) to the Pampean loess: "…a light yellowish-brown color, sometimes with reddish or grayish shades; it does not show stratifications and stays for a long time on vertical walls; it has tubes and calcareous concretions and contains traces of fossil vertebrates". In general, Pampean and subtropical loess are similar in mineralogy and chemical composition, but they are quite different in particle size distribution, the former being silty-sand and the latter silty-clay (Sayago, 1995). In Tucumán province, the western boundary of loess dispersion was observed to coincide with the pre-Andean ranges. There is no loess *stricto sensu* to the west of the Aconquija and Calchaquí ridges, in marked contrast with its wide distribution to the east (Figure 3.1).

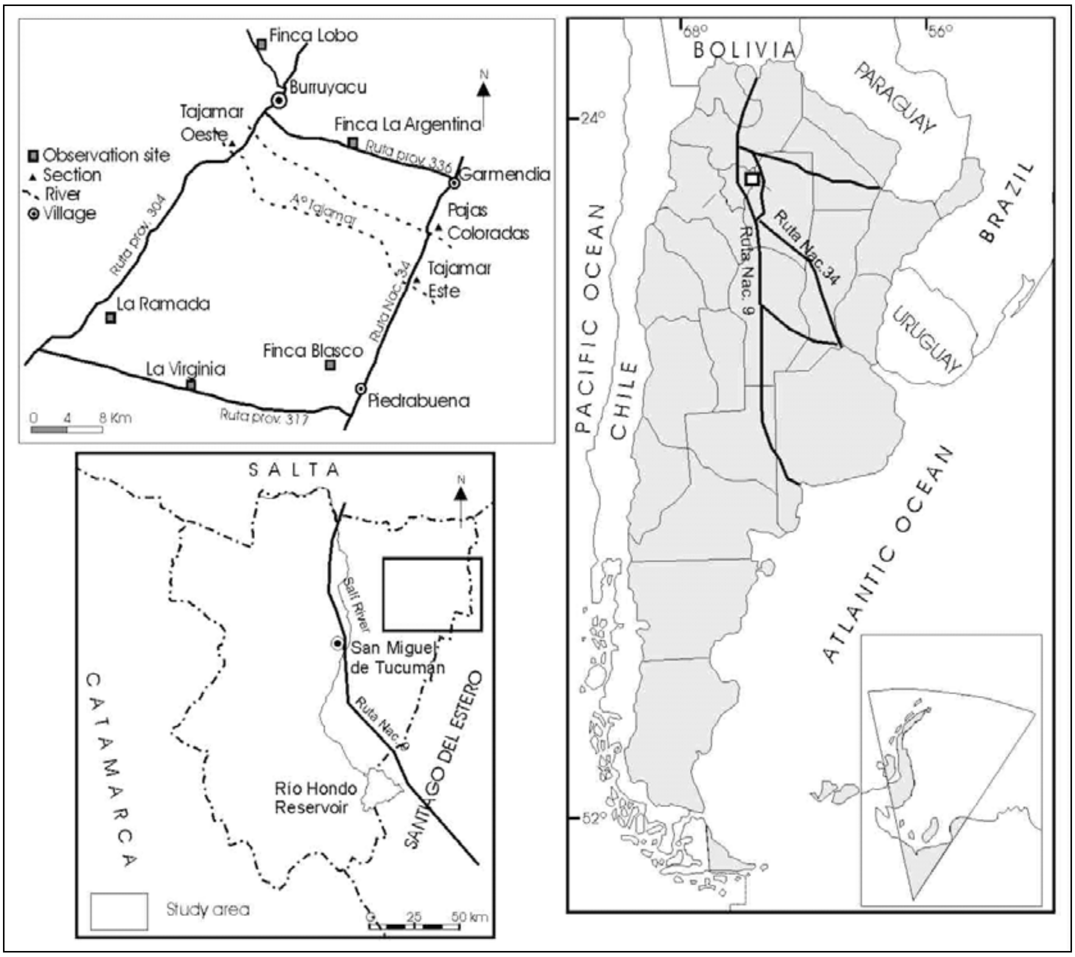


Figure 3.1. Location of stratigraphic profiles and observation sites.

3.2.1. Particle size distribution and mineralogy

Late Pleistocene and Holocene loess from the western Chaco plain and the pre-Andean valleys are mainly silty and silty clay (Figure 3.2). The subtropical loess is compared with the Pampean loess in Figure 3.3, which shows spatial variation in the particle size distribution of the loess cover between 26ºS and 39ºS latitude. The proportion of sand decreases from south to north, while those of silt and clay increase.

Similarly, there are significant differences in the mineral composition of the sand fraction between subtropical loess and Pampean loess due to transport mechanisms, local lithological influence and post-depositional processes controlled by the regional climate. In general, Pampean loess is characterized by a relative abundance of plagioclases (20-60%), lower content of quartz (15-30%) and constancy of volcanic glass fragments (15-30%) (Teruggi, 1957/1975; Scoppa, 1976). In contrast, in the Pleistocene subtropical loess of northwest Argentina, plagioclases (6-10%) and volcanic glass (3-6%) clearly decrease, while the quartz content remains at a comparable level (25-27%) (Ovejero, 1980). Holocene loess from the western Chaco plain shows nearly similar composition: 18-19% quartz, 3-8% feldspars and 3-12% volcanic glass (Zappino, 1992). Decrease in feldspars and volcanic glass is related to the effect of the subtropical climate on processes such as feldspar devitrification and alteration. However, in the semiarid Chaco, volcanic glass increases to 31% (Zappino, 1992), suggesting the influence of post-depositional volcanic additions. Similarly, in the loess of the eastern low-lying Chaco, Morras (1994a) found relatively low feldspar and volcanic glass contents (3-24%), except in cineritic layers. In contrast, quartz content was high, a fact that was interpreted by the author as the product of contributions coming from the Santa Fe forest wedge (cuña boscosa) on an old terrace of the Paraná river.

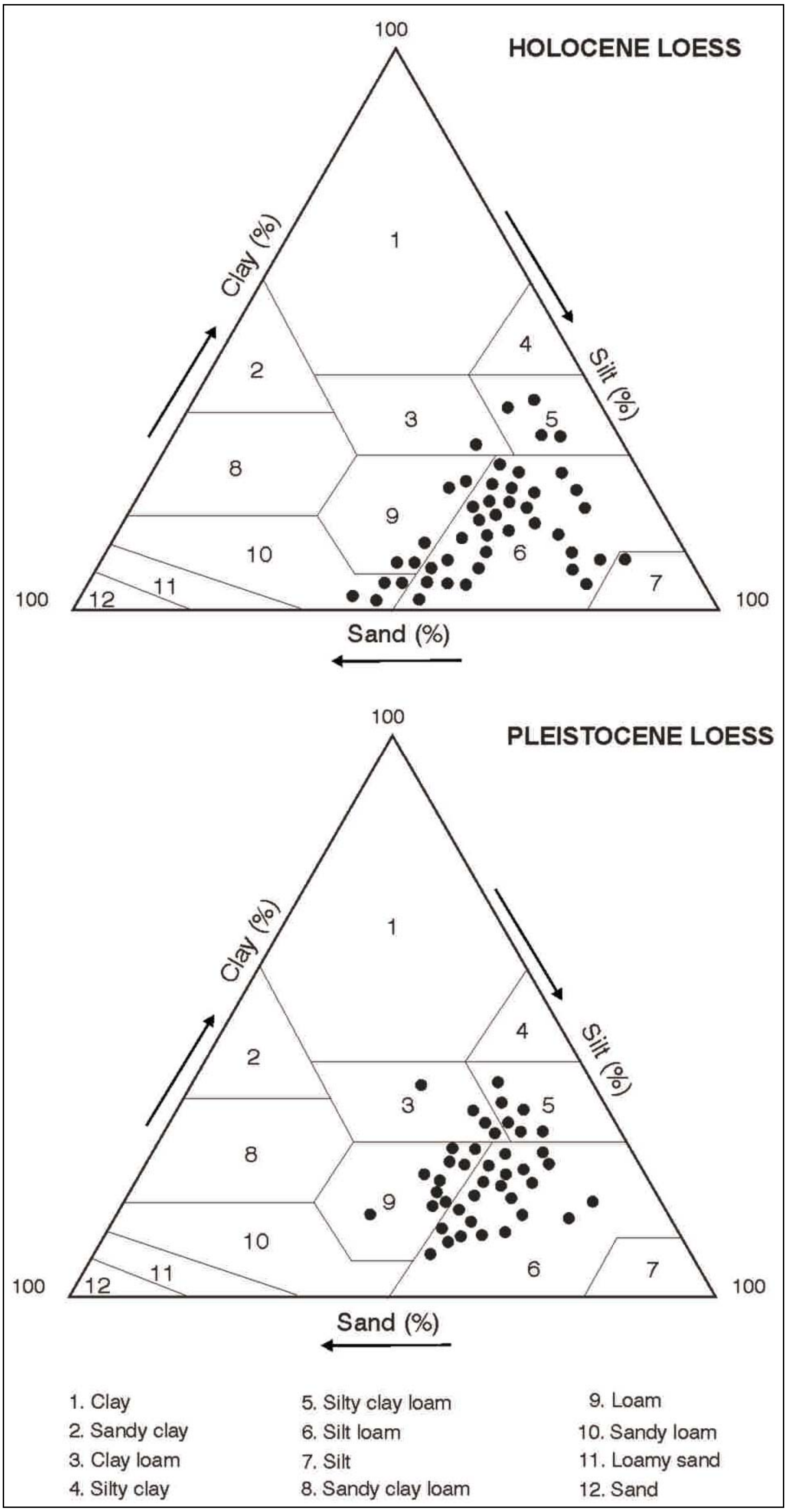


Figure 3.2. Textural grouping of Late Pleistocene and Holocene loess from western Chaco plain and northwestern pre-Andean valleys.

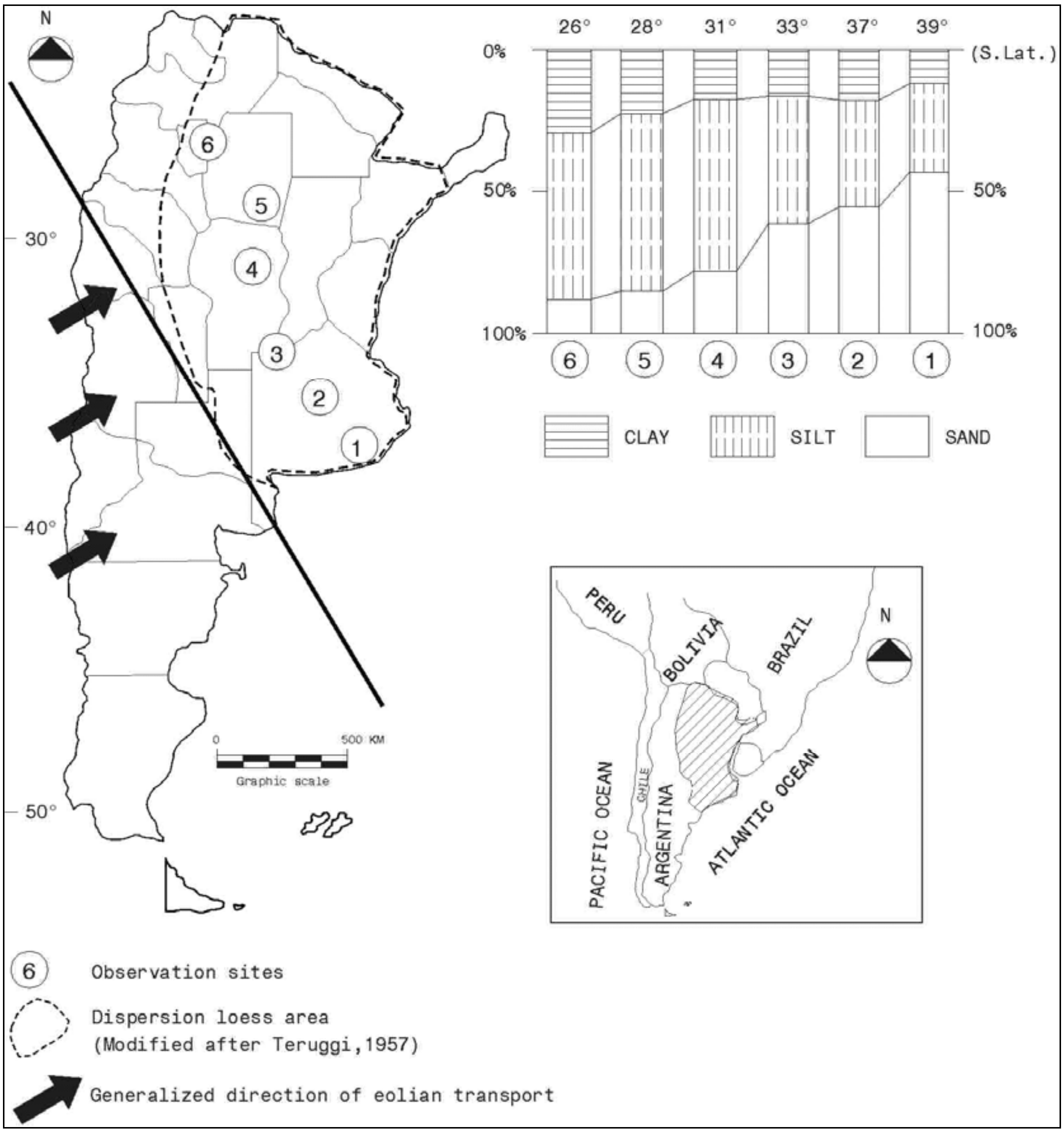


Figure 3.3. Particle size variation in the loess cover from the south of the Pampa to the western Chaco plain (Sayago et al., 2001).

In both the Pleistocene and the Holocene loess from the northwestern pre-Andean region, illite is the dominant clay mineral, while smectite and kaolinite occur in minor proportions (Camino, 1988; Collantes & Sayago, 1990). In the western Chaco plain, illite remains dominant, although there is a moderate increase in kaolinite and smectite with depth (see Chapter 5), and this coincides with the findings by Morras (1994b) in the western dorsal plain of the eastern Chaco. Thus, the mineralogy of the clay fraction is clearly similar in both the Pampean and the subtropical loess, in contrast to what happens with the sand fraction.

3.2.2. Origin and age of Pampean and subtropical loess

(1) Hypothesis of Patagonian origin

Although the idea of a relationship between Pampean loess and Patagonian glaciation through wind transport was suggested already in 1906 by Steinmann (quoted by Windhausen, 1931), it was only after several decades of field studies demonstrating a generalized desiccation of the South American subtropical regions during glacial periods that the concept of cold-dry glacial periods with loess transport and warm-moist interglacial periods began to be accepted. Working in the Buenos Aires coastal area of the Pampean plain, Tricart (1973) showed that deflation depressions developed on loess deposits during glacial sea retreat and that these were converted into hydro-eolian depressions with sea level rise during the interglacial periods. The former author hypothesized that the winds blowing from the southwest originated changes in the atmospheric circulation because of ice cap and glacier formation in the Patagonian Andes. This hypothesis was later supported by Rabassa (1990) and Zárate and Blasi (1991), among others. Zárate and Blasi (1991) also highlighted the significant role of fluvial transport in the reworking and dispersion of the Pampean loess. González-Bonorino (1965), in turn, confirmed the hypothesis already suggested by Teruggi (1957) that Patagonia constituted the loess generating area. He determined that the clastic minerals found in the Buenos Aires Upper Pampean Formation came from the abrasion of sandstones from the Río Negro Formation, Tertiary basalts and the northern Patagonian porphyritic series. Volcanic activity in the Patagonian Andes during Pleistocene and Holocene may have contributed significant amounts of cineritic material. There may be thus a common source of materials for both Pampean and subtropical loess. This is supported by the spatial variation in particle size distribution of the loess between 26ºS and 39ºS latitude, showing gradual decrease of the sand fraction together with increase in silt and clay from south to north (Figure 3.3). According to Mücher (1986), the percentage of clay and silt in the loess cover increases in proportion to the distance from the source area. Similarly to the hypothesis proposed of Pye and Zhou (1989) for the Chinese loess, it could be assumed that the Pleistocene loess came from the extra-Andean Patagonia, the central Andean piedmont and/or the Patagonian coastal regression plain. Southwestern winds, associated with adiabatic desiccation when crossing the Patagonian Andes, caused deflation of materials by means of two mechanisms derived from cyclonic conditions: first, strong low-altitude winds carried suspended sand particles over short distances and, subsequently, vertical advection blew fine particles to high elevation that were then carried to the north by high-altitude southern winds compounded by the influence of the jet stream (Sayago et al., 2001). Dating of reworked loess and paleosols from the western Chaco plain reveals ages ranging from Late Pleistocene to Late Holocene, especially the Neo-Holocene and Upper Holocene (Table 3.1).

(2) Hypothesis of Puna origin

It is generally admitted that thick loess deposits to the east of the northwestern pre-Andean mountain ranges have been brought in by winds blowing from the south and southeast (González-Bonorino, 1950; Frenguelli, 1955). However, some authors hypothesized that subtropical loess could have originated from the high-elevation plateaus of the Puna (Bloom, 1990, among others). This hypothesis faces a set of objections such as follows.

- The hypothesis is exclusively based on the dynamics of the current atmospheric circulation and seasonal wind regime of the Puna, without taking into account the regional and continental conditions during the Late Pleistocene, a period with maximal loess deposition.
- The western limit of loess deposits in northern Argentina has been reported to coincide with the mountain ridges of Aconquija and Cumbres Calchaquíes (Sayago, 1995; Sayago et al., 2001). To the west of this limit, only sand dunes and, exceptionally, pockets of eolian dusts are found.
- If the Puna high-plateau were the area generating the subtropical loess, sand deposits rather than silty clay loess would prevail in the western Chaco plain (Sayago et al., 2001).
- It is assumed that, during the Late Pleistocene when large loess covers formed in the lowlands, the Puna area was covered by lakes and many shallow water bodies (Clapperton, 1993; Igarzabal, 1999).
- Deflation depressions, spread across the Chaco plain and today turned into hydro-eolian depressions, show morphologic features that support the influence of southern and southwestern winds.
- Loess mineralogy of the pre-Andean valleys and Chaco plain is similar to that of the western Pampean region (Ovejero, 1980; Karlsson, 1987; Zappino, 1992; Collantes, 2001).
- There is a clear geochemical relationship between Pampean and subtropical loess (Arens, 1969; Camino, 1988; Morras, 1994a, 1994b).
- Because of frequent saline crust formation and surface pavements, hyper-arid areas such as the Puna high-elevation plateaus are much more resistant to deflation than semiarid regions (Goudie, 1983; Pye, 1995).

Table 3.1. Radiocarbon dates from the western Chaco plain.

Site	Coordinates	Elevation (masl)	Geomorphic environment	Dated material	Depth (m)	Soil horizon	Laboratory number	Age (years BP)	
Tajamar Este	26°36'45"S 64°36'35"W	365	Fluvio-eolian plain	Wood	2.50-2.80	C	GRn-23050(1)	225 ± 25	(a)
Tajamar Este	26°36'45"S 64°36'35"W	365	Fluvio-eolian plain	Loess	2.70-3.0	2wb1	GRn-23049(1)	655 ± 25	(a)
Finca Blasco	26°44'50" S 64°41'40" W	415	Fluvio-eolian plain	Loess	0.57-0.82	2Ab	GRn-23679(1)	2,660 ± 50	(a)
Finca Lobo	26°27'32"S 64°44'59"W	575	Dissected piedmont glacis	Loess	0.91-0.97	2Ab	Grn-22635(1)	2,840 ± 60	(b)
La Argentina	26°32'13" S 64°40'13" W	495	Fluvio-eolian plain	Loess	0.90-1.18	2Bwb1	GRn-23048(1)	3,040 ± 30	(a)
Finca Lobo	26°27'32" S 64°44'59" W	575	Dissected piedmont glacis	Loess	1.40-1.60	3Ab	GRn-22636(1)	3,780 ± 40	(b)
La Virginia	26°43'24" S 64°52'48" W	480	Fluvio-eolian plain	Loess	0.57-0.88	2Ab	GRn-23768(1)	4,670 ± 60	(a)
La Ramada	26°42'09" S 64°55'07" W	530	Fluvio-eolian plain	Loess	0.80-1.13	2Btb1	GRn-23770(1)	5,640 ± 40	(a)
Finca Elías	26°33'50"S 64°34'20"W	380	Fluvio-eolian plain	Loess	1.17-1.50	3Bwb2	GRn-22637(1)	6,290 ± 120	(b)
Tajamar Oeste	26°32'15"S 64°47'17"W	570	Dissected piedmont glacis	Loess	1.20-2.0	2Btb2	Beta-174840(2)	7,860 ± 60	(a)
Pajas Coloradas	26°32'14"S 64°35'40"W	370	Fluvio-eolian plain	Loess	1.90-2.58	3Btb1	GRn-23772(1)	11,020 ± 140	(a)
Pajas Coloradas	26°32'14"S 64°35'40"W	370	Fluvio-eolian plain	Loess	1.70-1.90	C	ILO1(3)	11,950 ± 2,070	(a)
Pajas Coloradas	26°32'14"S 64°35'40"W	370	Fluvio-eolian plain	Loess	2.58-3.13	C	ILO2(3)	17,390 ± 5,210	(a)

(1) Centre for Isotope Research, University of Groningen, The Netherlands (^{14}C)
(2) Beta Analytic Inc., Miami, Florida, USA. (AMS)
(3) Centre for Environmental Change & Quaternary Research, Cheltenham-Gloucester, UK. (TL)
(a) Unpublished
(b) Zinck and Sayago (1999)

3.3. LOESS-PALEOSOL SEQUENCES IN THE BURRUYACU AREA

The transition area between the sub-Andean Sierras and the western Chaco plain is occupied by two main landscape units, a piedmont and a fluvio-eolian plain. These units show spatial and temporal continuity in lithostratigraphic and soil features, which allowed reconstructing the paleoenvironmental evolution of the area during the Late Pleistocene and Holocene. The basic structure and the substratum of the area are of alluvial origin, and this is reflected by the presence of paleo-riverbeds, fluvial terraces and alluvial fans, the latter being largely confined to the piedmont of the Sierras de El Campo and La Ramada. The interfluves in the piedmont and plain are generally covered by loess-paleosols sequences, which suggest cycles of short dry periods with loess deposition and longer moist intervals with soil development. In the areas controlled by alluvial dynamics, fanglomeratic and cenoglomeratic deposits alternate with thinner layers of loess reworked by water or wind. Present soil development and loess-paleosol sequences were analyzed from soil profiles, lithostratigraphic cross-sections, laboratory determinations and radiocarbon dating.

3.3.1. Lower and Middle Pleistocene

One of the outstanding features of the Lower and Middle Pleistocene materials in the study area and in the province of Tucumán in general is the lack of representative fossils. This, together with only a few dated sites, explains why this period of the Quaternary is poorly documented. Strecker (1987) identified several pedimentation levels in the western intermountain valley of Santa María which, on the basis of three absolute dating figures, were assigned to the Lower, Middle and Upper Pleistocene, respectively. Within our study area, two glacis levels are traceable in the piedmont. The higher glacis truncates Tertiary sediments and could be tentatively matched with some of the Lower and Middle Pleistocene levels existing in the western valleys. The lower glacis, which occupies a large part of the piedmont of the Sierras de El Campo and La Ramada, has developed on loess sediments, partly covered by fanglomeratic deposits that give a character of covered glacis, particularly north of the Tajamar river. Flat-bottom valleys, with slightly concave profiles, have incised this glacis level when crossing the piedmont in west-east direction and extend into the eastern plain, slightly inclined to the east. Similarly to what happens in the western intermountain valleys and basins, there is no evidence of Lower and Middle Pleistocene deposits, a fact that suggests prevailing denudation under arid conditions during those periods.

3.3.2. Upper Pleistocene

In contrast to the western intermountain valleys that have thick loess-paleosol sequences with vertebrate fossils of Luján age, typified as Tafí-del-Valle Formation (Collantes et al., 1993), the Late Pleistocene loess cover in the eastern Tucumán plain is only moderately thick, with few well-developed paleosol sequences. The brown to reddish brown silty clay materials that outcrop in the piedmont of the Aconquija and Cumbres Calchaquíes ridges and in the western Chaco plain, have been named Tucumán Formation by Bonaparte and Bobovnikov (1974), mainly on the basis of paleontological features. A more detailed description of Quaternary lithostratigraphy and paleontology of the piedmont area was carried out by Esteban et al. (1988), who reported the presence of glyptodont fossils in loess strata alternating with thin detrital layers that extend eastward into the plain landscape. Late Pleistocene loess is widely distributed in the study area and constitutes a slightly folded substratum, underlying more recent loess and alluvial cover sediments. Two representative profiles are described hereafter.

(1) La Virginia profile

A stratigraphic profile encompassing the Late Pleistocene and a large part of the Holocene was described in an erosion ravine two kilometers south of La Virginia locality (YPF gas station), located in the distal piedmont of the Sierra La Ramada. The profile includes the following sequence of layers:

- Layer I (0-0.9 m): cover soil (A-Bw); very dark brown to brown clay loam; prismatic structure breaking into blocks; pH 6-6.5.
- Layer II (0.9-2.3 m): loess; dark brown clay loam; weak prismatic structure; pH 7.
- Layer III (2.3-2.8 m): cinerite; brown to pinkish loam; massive; few micro-concretions of $CaCO_3$; pH 7.5.
- Layer IV (2.8-4.1 m): paleosol (Btb); brown clay loam to sandy clay loam; prismatic structure; abundant micro-concretions of $CaCO_3$; pH 8-8.2.
- Layer V (4.1-4.8 m): loess; dark brown clay loam; prismatic structure; abundant micro-concretions of $CaCO_3$; pH 7.8.
- Layer VI (4.8-5.45 m): paleosol (Bwb); brown to dark brown clay to clay loam; prismatic structure; abundant micro-concretions of $CaCO_3$; pH 7.5.
- Layer VII (5.45-6.6 m): loess; dark brown sandy clay loam; blocky structure; abundant concretions of $CaCO_3$; pH 8.4; C*elidoteridium* rib dated 11480 ± 90 BP by ^{14}C method.
- Layer VIII (6.6-7.5 m): loess; dark brown clay loam; prismatic structure; abundant $CaCO_3$ in matrix and concretions; pH 8.2.

The sequence shows alternation of loess layers and paleosols, suggesting dry-moist cycles during the Late Pleistocene and Holocene. Strongly developed paleosols with clay illuviation are similar to the paleosols occurring in the Tafí-del-Valle Formation in the western intermountain valleys (Sayago et al., 2005).

(2) Pajas Coloradas profile

A second profile was described on the left bank of the Pajas Coloradas river, in the place where the river crosses road 34 that runs along the boundary between the provinces of Tucumán and Santiago del Estero. The sequence, including loess layers and paleosols, extends over large stretches along the river walls and can, therefore, be considered representative of loess deposition in the western Chaco plain during the Late Pleistocene. The profile includes the following sequence of layers:

- Layer I (0-1.9 m): loess; brown to dark brown silt loam; weak blocky structure to massive; abundant concretions of $CaCO_3$ in the lower part; pH 7-8.5; base of the layer dated 11950 ± 2007 BP by TL dating.
- Layer II (1.9-2.58 m): paleosol (Btb); dark brown silty clay to silt loam; prismatic structure; pH 8-8.5; 11020 ± 140 BP by ^{14}C dating.
- Layer III (2.58-3.13 m): cinerite-like loess; brown silt loam; weak blocky structure; abundant micro-concretions of $CaCO_3$; pH 8.5; 17390 ± 5210 BP by TL dating.
- Layer IV (3.13-3.48 m): paleosol (Btb); reddish brown silt loam to silty clay loam; prismatic structure; pH 8-8.5.

Stratigraphy of the sequence, paleosols and ages of the dated materials are similar to those of the upper part of the loess-paleosol sequence of La Mesada in the Tafí valley (Zinck & Sayago, 1999, 2001; Sayago et al., 2005), suggesting the alternation of dry periods with loess deposition and moist intervals with soil development. From the dating information, paleosols have developed during the Late Pleistocene and the upper paleosol is contemporaneous with the Younger Dryas.

3.3.3. Lower Holocene

A loess-paleosol profile was described in the wall of the Tajamar arroyo, in the piedmont area of the Sierra La Ramada. It can be considered representative of the paleoenvironmental evolution undergone by the interfluves between the Chaco plain to the east and the piedmont of the sub-Andean mountain ranges to the west. The profile comprises six main layers:

- Layer I (0-1.2 m): cover soil (A-Bw-C) developed from loess; very dark brown (10YR 2/2) to dark brown (7.5YR 3/2) loam to clay loam; prismatic structure breaking into blocks; common $CaCO_3$ nodules; medium to strongly alkaline reaction.
- Layer II (1.2-2.0 m): paleosol (Btb); very dark brown clay; prismatic structure; abundant organo-clay cutans; abundant $CaCO_3$ pseudomycelia; pH 8; 7860 ± 60 BP by AMS radiocarbon dating.
- Layer III (2.0-2.4 m): loess; dark brown silty clay loam; friable; blocky structure; abundant $CaCO_3$ pseudomycelia; pH 8-8.5.
- Layer IV (2.4-3.6 m): paleosol (two Btb horizons); very dark brown to dark brown clay loam; prismatic structure; abundant organo-clay cutans; pH 8.
- Layer V (3.6-5.1 m): loess; dark brown to brown sandy clay loam; friable; massive; abundant $CaCO_3$ nodules; pH 9.
- Layer VI (5.1-6.6 m): loess; dark brown to brown sandy clay loam; friable; massive; very abundant $CaCO_3$ nodules and common saline pseudomycelia; pH 8.5-9.

The upper paleosol is the oldest one found in the thin loess-paleosol sequences of the Holocene in the western Chaco plain. The presence of buried Bt horizons is a typical feature in the areas close to the Andean piedmont, moister than the areas to the east where buried horizons area usually of Bw type.

3.3.4. Middle and Upper Holocene

Several buried soil horizons, belonging to representative profiles spanning from moister west to drier east of the study area, were dated by radiocarbon method and provide the following ages (see full profile descriptions in Chapter 13):

- Northwest of the study area, Burruyacú, Finca Lobo, in the piedmont of Sierra de El Campo: a 2Ab horizon (91-97 cm) was dated 2840 ± 60 BP and a deeper 3Ab horizon (140+ cm) was dated 3780 ± 40 BP (Profile P2).
- Southwest of the study area, La Ramada, in the transition between piedmont and plain: a 2Btb horizon (80-113 cm) was dated 5640 ± 40 BP (Profile P17).

- North-central part of the study area, La Argentina, in the fluvio-eolian plain: a 2Bwb horizon (90-118 cm) was dated 3040 ± 40 BP (Profile P7B).
- South-central part of the study area, La Virginia, in the fluvio-eolian plain: a 2BAb horizon (57-88 cm) was dated 4670 ± 60 BP (Profile P10).

- Northeast of the study area, Gob. Garmendia, Campo Elías, in the fluvio-eolian plain: a 3Bwb horizon (117-150 cm) was dated 6290 ± 120 BP (Profile P4A).
- Southeast of the study area, Gob. Piedrabuena, Finca Blasco, in the fluvio-eolian plain: an 2Ab horizon (57-82 cm) was dated 2660 ± 50 BP (Profile P14).

The dated horizons spanning 6290-2660 BP indicate that soil formation took place during the Middle and Upper Holocene, generating soils from loess deposits anterior to the most recent and last loess mantle deposition bearing the current cover soils. In general, buried soils show stronger development (A-Bw-C and A-Bt-C profiles) than cover soils (A-C and A-Bw-C profiles) because of longer development time and/or moister climate. The last loess influx suggests a drier interval separating the current and former soil formation periods. A similar rainfall gradient from drier east to moister west equally influenced differential soil development during the consecutive soil formation periods. There is no strict correlation between radiocarbon age and depth of the dated buried horizons, indicating that loess accretion did not affect all areas at the same time and/or at the same rate of deposition. Considering the depth-age relationship of the buried horizons, it appears that loess influx increased over time from east to west along the northern transect (Garmendia-Argentina-Burruyacú), while the opposite seems to have happened along the southern transect (Piedrabuena-Virginia-Ramada).

3.3.5. Medieval Warm Period

In the pre-Andean region of northwest Argentina, a period of extreme aridity, presumably contemporaneous with the European Medieval Warm Period, caused migration and even extinction of indigenous cultures in the western intermountain valleys and basins (Sampietro et al., 2003; Sayago et al., 2003). In the study area, thick detrital deposits formed in the piedmont area during heavy-rain periods, while loess deposition took place during arid intervals.

3.3.6. Little Ice Age

The former arid period was followed by a lapse of higher rainfall that allowed paleosols to develop in the lower terrace of the main rivers of the region. On the right bank of the Tajamar river, at the boundary between the provinces of Tucumán and Santiago del Estero, the following profile was described:

- Layer I (0-1.67 m): interstratified fluvial and eolian sediments; dark brown to brown (7.5YR 3/4 - 4/3) loam to clay loam; alkaline reaction; common $CaCO_3$ nodules; a wood fragment buried at the base of this layer was dated 225 ± 25 BP by ^{14}C.
- Layer II (1.67-2.59 m): paleosol with two Bwb horizons; dark brown (7.5YR 3/2) loam to clay loam; prismatic structure breaking into blocks; 3% organic matter content; slightly to medium alkaline reaction; abundant CaCO3 nodules; the upper Bwb horizon was dated 655 ± 25 BP by ^{14}C.
- Layer III (2.59-3.29 m): loess; dark brown (7.5YR 3/4) clay loam; prismatic structure breaking into blocks; strongly alkaline reaction; abundant $CaCO_3$ nodules.
- Layer IV (3.29-3.66 m): cineritic material; pinkish gray (7.5YR 6/2) loam; blocky structure; strongly alkaline reaction.
- Layer V (3.66-4.51 m): paleosol (Ab-Btb-Cb); very dark brown to dark brown (7.5YR 2.5/3-4/4) sandy clay loam; prismatic structure breaking into blocks; strongly alkaline reaction; abundant $CaCO_3$ nodules.
- Layer VI (4.51-5.41 m): loess; dark brown to brown (7.5YR 4/4) sandy loam; prismatic structure breaking into blocks; strongly alkaline reaction; few $CaCO_3$ nodules.

Paleosol development suggests a moist and relatively cool period at 655-255 BP (1345-1775 AD), which approximately matches the Little Ice Age.

3.4. PALEOENVIRONMENTAL CHANGES

3.4.1. Climatic variations at local scale

The lithostratigraphic and paleosol sequences of the Tucumán fluvio-eolian plain and the piedmont of the Sierras de El Campo and La Ramada are recorded in Table 3.2 and spatially correlated in Figure 3.4.

- From Late Pleistocene to Upper Holocene, dry periods with loess deposition and moist periods with soil development alternated, suggesting that the climatic variability of the Pleistocene would have continued during the Holocene.
- The mineralogical relationship between the loess sequences of the Late Pleistocene and those of the Holocene suggests probable re-translocation of the Late Pleistocene loess during the arid periods of the Holocene. Additionally, loess material could also have originated from deflation of the extensive evaporite depressions (formerly continental lakes) that cover large parts of the western Chaco plain.
- There is good correlation between age and degree of development of the paleosols from Late Pleistocene to Upper Holocene. The oldest buried soils are more developed than the younger ones, which are similar to the present cover soils.
- Soil development in both the buried soils and the cover soils increases from drier east to moister west along the present rainfall gradient, suggesting that the adiabatic “rain shadow” effect caused by the proximity of the southern sub-Andean Sierras also occurred in the past.
- Spatial distribution of the loess-paleosol sequences shows correspondence of environmental conditions between the piedmont and the fluvio-eolian plain during both the arid periods and the moist intervals of the Late Pleistocene and the Holocene.

Table 3.2. Paleoenvironmental changes in the western Chaco plain.

Period	Age (years BP)	Lithostratigraphy	Geomorphology	Soil	Climate	Observations
Current	0-200	Fluvial sand Loess	Piedmont Fluvio-eolian plain	Ustolls Aridisols	Subtropical dry-moist	
Little Ice Age	200-600	Fluvial sand and silt Paleosols on loess	Erosion ravine Fluvial terrace	Entisols Ustolls	Moist and possibly colder than nowadays	
Medieval Warm Period	700-1200	Loess	Piedmont and fluvio-eolian plain	Aridisols	Very arid	Neotectonic activity
Upper Holocene	2190-2310	Fanglomerate Loess	Alluvial fans (piedmont) Fluvio-eolian plain	Regosols Entisols	Subhumid /semiarid	Expansion of agrarian cultures
	2660-3780	Paleosols on loess	Interfluvial plains (piedmont) Paleo-channels (fluvio-eolian plain)	Argiustolls	Wetter than nowadays	Formative Period
	3500-4500	Loess	Erosion glacis and fluvio-eolian plain	Entisols	Arid	
Middle Holocene	4670-6290	Paleosols on loess	Interfluvial plains (piedmont) and fluvio-eolian plain	Argiudolls?	Wetter than nowadays	
Lower Holocene	6500-7500	Loess	Erosion glacis and fluvio-eolian plain	Entisols	Arid and possibly cold	
	7860	Paleosols on loess	Low-lying interfluvial plains (piedmont)	Argiudolls?	Wetter than nowadays	
Upper Pleistocene	11020 11480 11950 17390	Tucumán formation (lower member)	Fluvio-eolian plain	Entisols y Argiudolls?	Short arid periods alternating with longer moist periods	

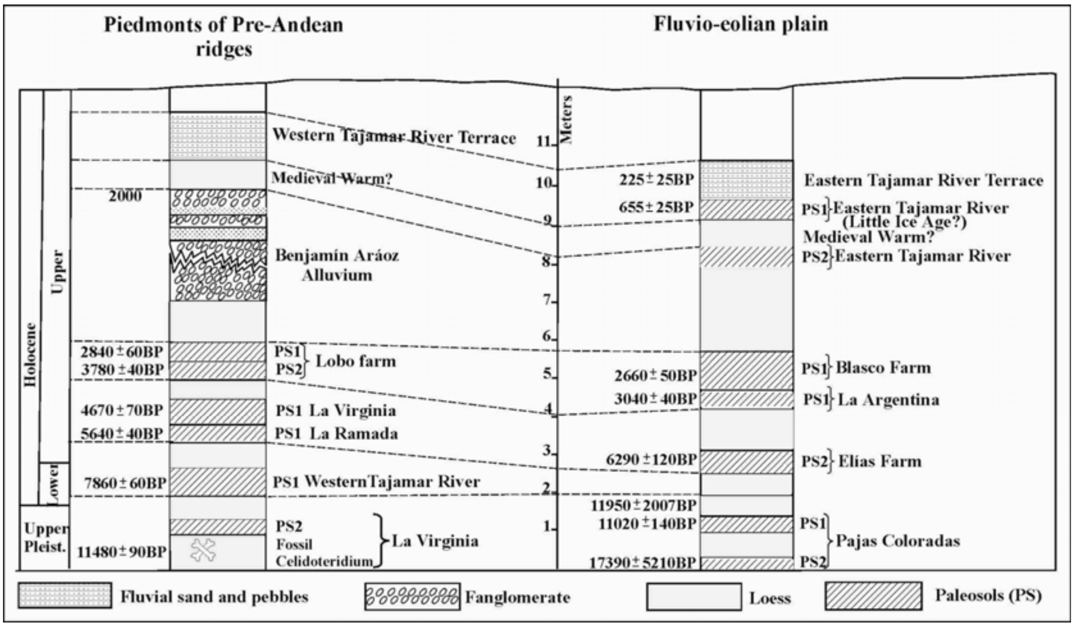


Figure 3.4. Comparison of lithostratigraphic and paleosol sequences between piedmont and fluvio-eolian plain.

3.4.2. Variation of air circulation at regional scale

Soil formation during moist periods of the Holocene in the western Chaco plain could be related to the strengthening of the anticyclone from mid-latitudes of the South Atlantic and/or the influence of the intertropical convergence zone (ITZ) (Bianchi & Yañez, 1992). However, considered from an inland perspective, the relationship between oceanic air circulation and regional climate conditions may be complex. There is a clear temporal correlation between the loess-paleosol sequences of the Late Pleistocene and Holocene in the western Chaco plain (+11020; +7870; 6290-4670; 3780-2660; 655-225 BP) and the glacio-chemical intervals detected in the GISP2 ice-core from Greenland (O'Brien et al., 1995). In addition to the Younger Dryas, O'Brien and collaborators identified four cold Holocene periods characterized by an increase in saline concentration: +11300; 8800-7800; 6100-5000; 3100-2400 and 610-0. They related these relatively colder intervals, resulting from the expansion of the boreal polar vortex and the strengthening of the northern circulation, with periods of glacial expansion at global level that have been proven by multiple proxy evidence (e.g. glacial advance, oxygen isotopes, pollen, dendrochronology, etc.). For instance, there is a striking coincidence between Greenland's glacio-chemical periods and Holocene glacial advances along the Patagonian mountain ranges. Geyh and Rothlisberger (1986) and Clapperton (1993) postulated glacial expansion in the Patagonian mountains during the following periods: 8400-7600; 6000-5000; 3200-3000; 2500-1300 and 900-200 BP. From analysis of carbon isotopes of benthonic foraminifers in the northeastern subpolar Atlantic, Oppo et al. (2003) found close correlation between Greenland's glacio-chemical periods and a decrease in the contribution of the North Atlantic Deep Water related, in turn, with a strengthening of the contribution of Southern Ocean Water. This temporal coincidence between Holocene cold periods detected in Greenland and a decrease of the North Atlantic Deep Water, together with a moisture increase at tropical latitudes as revealed by the development of paleosol sequences, on the one hand, and glacial expansion in Patagonia and the Antarctic Peninsula, on the other, would allow to speculate on the possible influence of North Atlantic atmosphere-ocean perturbations on climate fluctuations in South America during the Holocene. According to Rahmstorf (2002), the idea of a latitudinal shift of convection between Nordic Seas and the mid-latitude open Atlantic Ocean has found strong support, showing that such a mechanism can explain many observed features of the Dansgaard-Oerscher events. The same author suggests that the D/O-style temperature shifts in Greenland may be caused by shifts in the planetary atmospheric wave pattern, remotely controlled from the tropics. This is based on the strong control that tropical sea surface temperatures exert nowadays on the global atmospheric heat transport pattern. However, as Oppo et al. (2003) suggest, further well-dated deepwater proxy records are needed to test this hypothesis, although the climate-deepwater linkage may indicate an increasing sensitivity of deepwater to surface forcing from the Early to the Late Holocene.

3.5. CONCLUSION

During the Late Pleistocene and Holocene, the western Chaco plain was exposed to cyclic climate variations corresponding mainly to an alternation of dry and possibly colder periods with loess deposition, on the one hand, and moister periods with soil development, on the other, in a fashion similar to the recurrence of the Dansgaard-Oerscher periods detected in Greenland. Periods with soil development at tropical latitudes coinciding with intervals of glacial expansion in the Patagonian Andes and the Antarctica reveal temporal correspondence with the glacio-chemical periods detected by ice-core exploration in Greenland, together with a strengthening of the south oceanic contribution. This allows hypothesizing on a tele-connection in the atmospheric-oceanic dynamics between the North and the South Atlantic during the above-mentioned intervals.

3.6. REFERENCES

Arens, P., 1969. Algunos paisajes geoquímicos de la región pampeana. Actas V Reunión Argentina de la Ciencia del Suelo. Santa Fe, Argentina, pp.107-115.

Bianchi, A.R., Yánez, C.C., 1992. Las precipitaciones en el noroeste argentino. Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Agropecuaria Salta, Argentina. Segunda Edición, 383 p.

Bloom, A., 1990. Some questions about Pampean Loess. In: M. Zárate (ed.), Propiedades, cronología y significado paleoclimático del loess. Simposio Internacional sobre Loess, Mar del Plata, Argentina. Resúmenes Expandidos: 29-31.

Bonaparte, J.F., Bobovnikov, J., 1974. Algunos fósiles pleistocénicos de la provincia de Tucumán y su significado bioestratigráfico. Acta Geológica Lilloana 12: 171-183.

Camino, M., 1988. Estratigrafía y evolución paleoambiental durante el Cuaternario del valle de La Sala, provincia de Tucumán. Tesis de Grado inédita. Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, S. M. de Tucumán, Argentina, 120 p.

Clapperton, C., 1993. Quaternary of alluvial basins. Part III: Aeolian features: Paleoclimate. In: C. Clapperton (ed.), Quaternary Geology and Geomorphology of South America. Elsevier, Scotland, UK, pp.183-215.

Collantes, M.M., 2001. Paleogeomorfología y geología del Cuaternario de la cuenca del río Tafí, Departamento Tafí del Valle, Provincia de Tucumán, Argentina. Tesis Doctoral inédita. Facultad de Ciencias Naturales, Universidad Nacional de Salta, Salta, Argentina, 220 p.

Collantes, M.M., Sayago, J.M., 1990. Caracterización estratigráfica e interpretación paleoambiental del complejo loess-paleosuelos de Tafí del Valle, Tucumán, Argentina. In: M. Zárate (ed.), Propiedades, cronología y significado paleoclimático del loess. Simposio Internacional sobre Loess, Mar del Plata, Argentina. Resúmenes Expandidos: 143-148

Collantes, M.M., Powell, J., Sayago, J.M., 1993. Formación Tafí del Valle (Cuaternario Superior), Provincia de Tucumán (Argentina): litología, paleontología y paleoambientes. XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, Actas Tomo II: 200-206.

Cordini, R., 1947. Los rios Pilcomayo en la región del Patiño. Dirección de Minas y Geología, Anales-I, 84 p.

Esteban, G., Sayago, J.M., Powell, J., Collantes, M.M., 1988. Bioestratigrafía de los depósitos cuaternarios de Tafi Viejo, Tucumán, Argentina. Actas V Congreso Geológico Chileno, Tomo II: 12l-136.

Frenguelli, J., 1955. Loess y limos pampeanos. Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, La Plata, Argentina. Serie Técnica y Didáctica 7, 88 p.

Geyh, M., Rothlisberger, F., 1986. Gletscherschwankungen der letzten 10,000 Jahre. Ein Vergleich zwischen Nord- und Sudhemisphere (Alpen, Himalaya, Alaska, Sudamerika, Neusseland). Aarau, Switzerland.

Gonzalez Bonorino, F., 1950. Descripción geológica de la Hoja 13e, Villa Alberdi, Provincia de Tucumán. Dirección Nacional de Minería, Servicio Geológico Nacional, Buenos Aires, Argentina. Boletín 74, 78 p.

Gonzalez Bonorino, F., 1965. Mineralogía de las fracciones arcilla y limo del Pampeano en el área de la ciudad de Buenos Aires y su significado estratigráfico y sedimentológico. Revista Asociación Geológica Argentina 20 (1): 67-148.

Gonzalez Bonorino, F., 1978. Descripción geológica de la Hoja 14f. Dirección Nacional de Minería, Servicio Geológico Nacional, Buenos Aires, Argentina. Boletín 160, 50 p.

Goudie, A.S., 1983. Dust storm in space and time. Progress in Physical Geography 7: 502-530.

Groeber, P., l958. Bosquejo geológico y climatológico de Formosa. Academia Nacional de Ciencias, Córdoba, Argentina. Boletín XL: 265-284.

Igarzabal, A., 1999. El cuaternario de la Puna. In: R. Caminos (ed.), Geología Argentina. Servicio Geológico Minero Argentino. Anales 29, Capítulo 23: 683-687.

Karlsson, A., 1987. Estudios edafogénicos y mineralógicos comparados de perfiles de suelos desarrollados sobre diferentes rocas madres. Tesis Doctoral inédita. Universidad Nacional de Córdoba, Córdoba, Argentina, 250 p.

Ledesma, L., Barbona, S., Melgrattis, M.R., Sayago, J.M., Margosa, L.A., Rodriguez, F., 1973. Introducción al conocimiento de los suelos del Chaco. Publicación Especial, Instituto Nacional de Tecnología Agropecuaria, Estación Experimental Regional R.S. Peña, Chaco, Argentina, 158 p.

Morras, H., 1994a. Caracterización de la organización y composición química de las arcillas mediante técnicas microscópicas. Aplicación al estudio de arcillas del Chaco meridional. Actas V Reunión Argentina de Sedimentología: 271-276.

Morras, H., 1994b. Descripción y caracterización analítica de depósitos piroclásticos en dos perfiles de suelo de la región chaqueña. Actas V Reunión Argentina de Sedimentología: 165-170.

Mücher, H.J., 1986. Aspects of loess and loess-derived slope deposits: an experimental and micromorphological approach. Nederlandse Geografische Studies 23, 267 p.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., Whitlow, S.I., 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. Science 270: 1962-1964.

Oppo, W.D., McManus, J., Cullen, J.L., 2003. Deepwater variability in the Holocene epoch. Nature 422: 277-278.

Ovejero, R., 1980. Geología y geomorfología de la cuenca del río San Javier, Dpto. Tafí (Tucumán, Argentina). Tesis de Grado inédita. Facultad de Ciencias Naturales, Universidad Nacional de Tucumán, S. M. de Tucumán, Argentina, 123 p.

Powell, J.E., Duarte, R.G., Rufino, S.D., Mule, P.V., 1992. Mamíferos cuaternarios del Valle de Tafí, Provincia de Tucumán. IX Jornadas Científicas de la Sociedad de Biología de Tucumán, Argentina. Resúmenes Expandidos, p.44.

Pye, K., 1995. The nature, origin and accumulation of loess. In: E. Derbyshire (ed.), Aeolian sediments in the Quaternary record. Quaternary Sciences Reviews 14: 653-668.

Pye, K., Zhou, L.P., 1989. Late Pleistocene and Holocene eolian dust deposition in North China and Northwest Pacific Ocean. Paleogeography, Palaeoclimatology and Palaeoecology 73: 11-23.

Rabassa, J., 1990. Late Pleistocene and Holocene loess deposits in the upper río Sauce Grande basin, Sierra de la Ventana, Argentina. In: M. Zárate (ed.), Propiedades, cronología y significado paleoclimático del loess. Simposio Internacional sobre Loess, Mar del Plata, Argentina. Resúmenes Expandidos: 143-148.

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120.000 years. Nature 419: 207-214.

Sampietro, M.M., Sayago, J.M., Caria, M., Collantes, M.M., 2003. Cambio climático y dinámica poblacional en el noroeste argentino durante los periodos "Formativo" y "Desarrollos Regionales". In: M.M. Collantes, J.M. Sayago y L. Neder (eds.), Cuaternario y geomorfología. Actas II Congreso Argentino de Cuaternario y Geomorfología, S.M. de Tucumán, Argentina, pp.463-473.

Sayago, J.M., 1979. Geomorfología y suelos en el Establecimiento "Los Charabones", Fortín Chilcas, Dpto. Vera, Provincia de Santa Fe. Fundación J.M. Aragón. Publicación 13, 19 p.

Sayago, J.M., 1995. The Argentine neotropical loess: an overview. J. Quaternary Science Reviews 14: 755-766.

Sayago, J.M., Collantes, M.M., Karlsson, A., Sanabria, J., 2001. Genesis and distribution of the Late Pleistocene and Holocene loess of Argentina: a regional approximation. J. Quaternary International 76/77: 247-257.

Sayago, J.M., Sampietro, M.M., Caria, M., Collantes, M.M., 2003. Paleoclimatic changes and human crisis in Northwest Argentina during the European Medieval Warm Period. In: Quaternary Climatic Changes and Human Crisis in the Mediterranean Region. Alcalá de Henares, Spain, pp. 81-87.

Sayago, J.M., Zinck, J.A., Collantes, M.M., Toledo, M., 2005. Environmental changes in the pre-Andean valleys and Chaco Plain (Northwest Argentina) during the Late Pleistocene and Holocene. Neues Jahrbuch für Geologie und Paläontologie Abh. (Stuttgart) 236 (1/2): 245-265.

Scoppa, C., 1976. La mineralogía de los suelos de la llanura pampeana en la interpretación de su génesis y distribución. Relatorio Actas VII Reunión de la Asociación Argentina de la Ciencia del Suelo. IDIA, Supl. 33: 659-673.

Stappenbeck, R., 1926. Geologie und Grundwasserkunde der Pampa. E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart.

Strecker, M.R., 1987. Late Cenozoic landscape in Santa María valley, northwestern Argentina. Unpublished PhD Thesis. Cornell University, USA, 261 p.

Teruggi, M., 1975. The nature and origin of Argentine loess. In: Smaley (ed.), Loess: Lithology and Genesis, pp.195-205. (Reprinted from Jour. Sed. Petrol. (1957), 27(3): 322-332.

Tricart, J.L.F., 1973. Geomorfología de la pampa deprimida. Instituto Nacional de Tecnología Agropecuaria. Colección Científica, Boletín XII, 198 p.

Windhausen, A., 1931. Geología Argentina. 2da. Parte. Buenos Aires, Argentina.

Zappino, R., 1992. Caracterización físico-química y mineralógica de sedimentos loésicos de la provincia de Tucumán. Instituto de Geociencias y Medio Ambiente, Tucumán, Argentina. Reporte inédito, 20 p.

Zárate, M., Blasi, A., 1991. Late Pleistocene and Holocene loess deposits of the southeastern Buenos Aires province, Argentina. Geojournal 24 (2): 21l-220.

Zinck, A., Sayago, J.M., 1999. Loess-paleosol sequence of La Mesada in Tucumán province, northwest Argentina. Characterisation and paleoenvironmental interpretation. Journal South American Earth Sciences 12: 293-310.

Zinck, J.A., Sayago, J.M., 2001. Climatic periodicity during the late Pleistocene from a loess-paleosol sequence in northwest Argentina. Quaternary International 78: 11-16.

CHAPTER 4

GEOMORPHOLOGY

R. Van Zuidam, M.M. Collantes, J.M. Sayago

4.1. INTRODUCTION

The study of the geomorphology and morphodynamic processes in the Burruyacú area contributes to assessing the influence of global climate change and land use changes on environmental degradation. Global change of climate implies, among others, a slight but gradual rise in temperature and a change in the air pressure system and thus in wind direction, wind speed, air humidity and precipitation. In addition to natural causes of climate change, also land use changes do affect the general environmental conditions of the study area.

Most of the Chaco forest has been converted to arable land. This change in land use affects the local climate in a negative sense, i.e. the land is not covered by vegetation or crops during longer periods of the year. The atmosphere and the soils become drier in the dry season, heavy rains create severe overland flow during the rainy season, and wind blows faster for not being hindered by vegetation obstacles. It was observed that indeed more wind erosion takes place in the dry periods, while sheet, rill and gully erosion is (more) severe during the heavy torrential rains at the beginning of the rainy season when the (semi-natural) vegetation is sparse and crop cover is lacking.

The frequency and intensity with which these morphodynamic processes took place, particularly in the last decades, should be interpreted in the light of both the global climate and the local land-use changes. Therefore, a detailed geomorphic survey and subsequent soil and sediment analysis were carried out to help unravel the severity of the environmental changes that the study area is undergoing.

4.2 SURVEY AREA

4.2.1. Geographic setting

Based on the geographic situation, three main landscapes can be distinguished from west to east, including mountain, piedmont and plain landscapes.

(1) Mountain ranges

A set of parallel mountain ranges, running NNE-SSW, include: (a) in the NW, the Sierra del Campo with a maximum elevation of 2067 m a.s.l. (slightly outside the study area); and (b) in the SW, the Sierra de La Ramada with maximum elevation of 1105 m a.s.l. Both mountain ranges have steep, strongly dissected slopes covered by humid subtropical forest (bosque subtropical húmedo). The average yearly rainfall is estimated at 800-1000 mm. Because of the rugged topography, accessibility is very limited.

(2) Piedmont

Sub-Andean foothills, forming a piedmont zone, border the mountain ranges of Sierra del Campo and Sierra de La Ramada. Elevation ranges from 650 to 750 m a.s.l. The relief consists of (a) rounded and flat-topped hillocks, frequently covered by western Chaco forest (bosque Chaqueño occidental); (b) foot-slopes which are mainly under cultivation or used for pasture; and (c) wide and flat river channels.The average yearly rainfall is 600-800 mm. Accessibility is limited but not too difficult.

(3) Eastern plain

The eastern plain stretches from the foothill zone to the flats of Santiago del Estero. Elevation ranges from 650 m a.s.l. in the west to 350 m a.s.l in the east. Topography consists of (very) flat, slightly inclined to undulating terrain, dissected by rivers, paleo-channels, gullies and ravines. The regional physiographic outline is one of a fan-shaped relief, originated by the main river of the area, río Tajamar. Crop and pasture lands dominate, but some isolated patches or relicts of (degraded) western Chaco forest can be found. The average yearly rainfall is estimated at 550-700 mm. Accessibility is reasonably good, particularly in the dry season.

4.2.2. Geologic setting

The mountain ranges of Sierra del Campo and Sierra de La Ramada form part of the sub-Andean ranges, originated by the Andean uplift. Both ranges are N-S oriented anticlines and have cores of slightly metamorphosed, phyllitic basement rocks of Precambrian age belonging to the Medina formation (Figure 4.1). The Sierra del Campo is an asymmetric anticline, resulting from a fault on its western side with dip slopes of 10-15º E (Mon et al., 1971). The Sierra de La Ramada is a symmetric anticline with dips of approximately 15º.

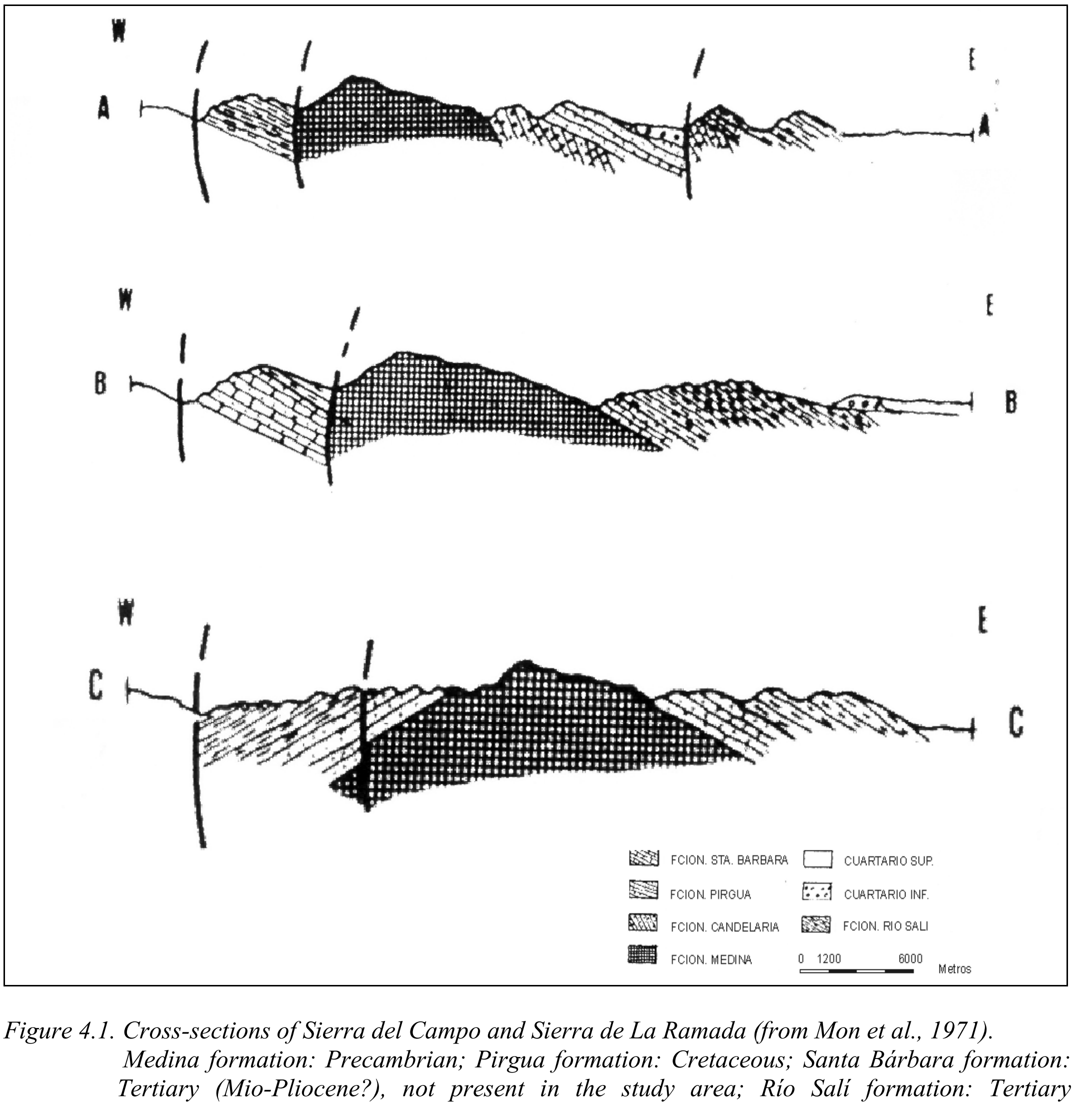


Figure 4.1. Cross-sections of Sierra del Campo and Sierra de La Ramada (from Mon et al., 1971). Medina formation: Precambrian; Pirgua formation: Cretaceous; Santa Bárbara formation: Tertiary (Mio-Pliocene?), not present in the study area; Río Salí formation: Tertiary (Pliocene?); Cuartario: Lower and Upper Quaternary formations.

The two anticlines are separated from each other by a NW-SE transcurrent fault, which coincides with the position of the riverbed of the río Tajamar, shifting the Sierra de La Ramada towards the NW with respect to the Sierra del Campo. This fault was and seems to be still active with vertical movements, particularly NE of the penetration of the río Tajamar into the piedmont area. Here, it can be observed that the Río Salí formation (Tertiary) overlies the Pirgua formation (Cretaceous), while normally the Pirgua formation first borders the anticlinal core of the Medina formation. Nowadays, the río Tajamar shifts towards the north, an indication of neotectonic activity with subsidence and /or tilt of the northern block.

Several smaller and less active faults can be detected in the mountain area, some of which extend into the piedmont and plain areas, influencing the orientation of rivers, gullies and barrancos. Mon (1971) found three main fault directions, including N-S, NNE-SSW and NW-SE, while Sayago et al. (1996) distinguished also an E-W direction.

The Precambrian phyllitic anticlinal cores belonging to the Medina formation are, in principle, bordered discordantly by the Cretaceous Pirgua formation, which consists dominantly of continental and/or lacustrine sedimentary rocks. This is the thickest formation (250 m) on the NE side of the Sierra del Campo, fainting out near the río Tajamar and appearing again in the Sierra de La Ramada (Mon et al., 1971).

On top of the Pirgua sedimentary rocks lies the Tertiary Río Salí formation, consisting of reddish and greyish sandstones (4-6 m thick), brown-red shales and claystones with gypsum intercalations (up to 60 cm thick), and calcareous oolite layers a few cm to 50 cm thick (Mon, 1971). Pirgua and Río Salí formations occur as sharp and round-crested hills and spurs in the upper piedmont and as steep to gentle glacis slopes beneath Quaternary gravel deposits in the lower piedmont.

Directly below or on top of the Pirgua and Río Salí formations there are lower Quaternary gravel deposits, which have been laid down in two phases forming extensive pedimentation surfaces that border the sierras (Mon, 1971). They have originated from the phyllites of the Medina formation and consist of a greyish breccia/conglomerate complex in the lower portion of the section and fine and poorly stratified clastic material in the upper portion. These deposits are followed by another series of fluvio-colluvial reddish gravels and sands, intercalated by volcanic ash. Additionally, there are poorly sorted slope breccias of phyllitic origin. These sediments are considered of upper Quaternary age (Mon, 1971).

The Quaternary formations of the Burruyacú area are comparable to the ones of Spain, Italy and other Mediterranean countries. In Spain, reddish fan-conglomerates, locally called "raña", have been dated Villafranchian, belonging thus to the Plio-Pleistocene transition (Van Zuidam-Cancelado, 1989). To explain their origin, it was hypothesized that, during the Plio-Pleistocene period, severe climate change led to the erosion of reddish tropical soils formed in the mountains during the Tertiary. These erosion products were removed by torrential, braiding streams and mud flows and subsequently deposited at the foot of the mountain ranges, forming huge cones and accumulation glacis (rañas). Later, during a second planation stage, cones and glacis were dissected and bevelled leading to the formation of erosion (or mixed) glacis, called rañizo, cut into the original raña or accumulation glacis. There is some similarity between this multiple-glacis formation in Spain and what has happened in the study area, where reddish fan-conglomerates were deposited on top of the irregular erosion surface of the Río Salí formation. Also erosion (or mixed) glacis surfaces have formed in the Burruyacú area, but they have been subsequently covered by greyish light-brown, fine fluvio-eolian sediments.

During the middle and upper Pleistocene, fluvial activity and slope retreat, controlled by climate changes, contributed to the formation of new erosion surfaces occurring as wide flats, glacis and valleys. This explains also the presence of eolian deposits (loess) in the eastern plains and the reworking by water of loess and older sediments, bearing some resemblance with European periglacial deposits called "Schwemmloess" (swimmed loess).

4.3. METHODOLOGY

4.3.1. Introduction

The aim of a geomorphic survey is to provide concise and systematic information about landforms, geomorphic processes and related natural phenomena in time and space. The maps produced are not only scientific documents in their own right but also valuable tools in natural resource studies and particularly for the assessment of natural hazards because of the relationships between the geomorphic characteristics of the land and other environmental factors. The information gathered is commonly presented in the form of a map, but it can also be stored in a database using a geographic information system.

Outlining major landform units and landform associations (by coloured area symbols) and plotting minor landforms (by line symbols) are frequently insufficient for the purpose and should be accompanied by thorough analysis leading to a reconstruction of the geomorphic landscape development under the influence of endogenous (geologic) and exogenous (climatic, etc.) factors of the past and present. Also, synthesis is required in the form of terrain analysis to relate the geomorphic "lay of the land" to the prevailing environmental conditions. Thus, morphometric and morphographic information must be complemented by morphodynamic, morphogenetic and morphochronologic data, on the one hand, and by environmental data (soils, hydrology, vegetation, etc.), on the other. Lithology and surface materials are of special importance because of their geomorphic significance and their possible economic importance as soil and construction materials.

Aerospace images greatly increase the efficiency of geomorphic surveying and are indispensable for obtaining adequate results in combination with field observations and laboratory determinations. Stereoscopic aerial photographs record landforms in great detail, while satellite images provide an overview of major landform complexes and structures. At the same time, aerospace images give an insight (through multispectral data) into the prevailing interrelationships between landforms and other environmental factors. They assist in a more rapid and precise geomorphic survey, because the geomorphic phenomena appear in their exact shapes and patterns. Moreover, morphometric information and many lithologic data can be obtained from them (Verstappen and Van Zuidam, 1991).

4.3.2. Survey procedures

The first step is to obtain an overview of the general geomorphology of the study area, including its relationships with adjacent areas, by means of a preliminary analysis of satellite images or through rapid scanning of aerial photos or photo mosaic. Simultaneously, all available sources of information, such as existing literature and thematic maps, among others, are consulted. Subsequently, geomorphic units and other relevant geomorphic features visible in the image are provisionally mapped.

The selection of the mapping scale and the time allocated to the survey depend on the purpose of the survey, the type of information required or available, and data visibility on the aerospace images. A provisional legend is drawn up and specific additional information is sought.

Detailed image interpretation ultimately results in the delineation of major geomorphic units, their subdivision into sub-units and the plotting of individual geomorphic features and processes using line symbols. Purely descriptive terms are allowed at this stage, if the genesis of geomorphic units and features cannot be revealed by image interpretation alone.

Field survey serves a double purpose: first, the provisional map has to be checked and, second, data that could not be obtained from aerospace images have to be added. The provisional map, as well as the images used for its preparation, is taken to the field and controlled wherever appropriate. Like image interpretation, field survey proceeds from general to specific: first, an overview is obtained using traverses and, thereafter, detailed observations and mapping are carried out. In reconnaissance mapping, field survey is limited to characteristic sites or key areas in every geomorphic unit or landform association. This applies particularly to small- and medium-scale mapping (e.g. 1:250,000). Semi-detailed maps are mostly field-checked, although some extrapolation and generalization are allowed. Detailed maps are fully checked in the field and generalizations are minor.

Final mapping and reporting constitute the last phase of the survey. Final analysis of aerospace images and laboratory analysis of samples gathered in the field are essential parts of it. Structure and hierarchy of the legend are finalized, colours for geomorphic units are selected and line symbols are chosen, as suggested by Verstappen and Van Zuidam (1991). In the Burruyacú study area, geomorphic survey was carried out at reconnaissance level, resulting in a geomorphic map at scale 1:100,000 (herewith annexed).

4.3.3. Information contained in the geomorphic map

Analytic geomorphic surveying has developed rapidly since the late 1940s, at the beginning especially for detailed mapping. Considerable consensus has been reached regarding the contents of such analytic maps (Verstappen, 1983). The following types of information are included in hierarchical order.

(1) Morphogenesis

The landforms mapped in their spatial arrangement are specified and classified from a geomorphic point of view, using morphologic terms (e.g. river terrace, planation surface, etc.) instead of descriptive, topographic ones. Since identification of landforms is normally based on their mode of formation, morphography and morphogenesis are hardly separable. The forms, in fact, should be represented in such a way that their origin and development are clearly recognizable. Geomorphic processes and geologic structures have a profound effect on landforms and thus deserve full attention.

Morphogenetic information is represented in the form of geomorphic units, if the phenomena concerned can be mapped at the selected scale, and by line symbols if the features are too small or considered less relevant. Because of their position at the highest level in the mapping system and the legend, morphogenetic units are represented by means of coloured area symbols. In the present study, landforms are grouped in four major classes according to their specific origin (with recommended colours), comprising: structural (purple), denudational (brown), fluvial (green) and eolian (yellow) geomorphic units.

Transitional groupings, such as forms of structural-denudational, fluvio-denudational and fluvio-eolian origin, are introduced in the legend as appropriate. Here, main genetic groups result from combination of different types of actions, including: (1) endogenic-tectonic action exposing various rock types, while the different denudational resistances express the structure and thus the landforms of those rocks; (2) fluvial action in combination with denudational processes such as colluviation and erosion, thus resulting in specific slope development; and (3) fluvial action in combination with eolian deflation and/or accumulation or with the reworking of loess deposits by rivers.

(2) Morphostructure and lithology

The nature of the bedrock strongly effects landforms and geomorphic processes. Lithology is thus of prime importance and deserves the second-highest hierarchic place in the legend. It also plays an important role in soil development as parent material, while in lowland areas the texture of unconsolidated materials is of interest. Usually, lithology is indicated by patterns, screens or hachures in a subdued colour (grey or light brown) to render it visible without undue emphasis. The Burruyacú area is lithologically so homogeneous that the lithological units were not given special representation, except the lithomorphologic units of structural-denudational origin.

(3) Morphometry

The third hierarchic level in the legend consists of quantitative information about relief. Its simplest form of representation is through height spots and/or contour lines with additional line symbols for slope breaks, valley depth/dissection, height of terrace edges, etc. The topographic map covering the Burruyacú area at scale 1:250,000 contains too few morphometric details to be included in the geomorphic map at scale 1:100,000.

(4) Morphochronology

Since every form is characterized by the period of its formation and further development, it is essential to make a distinction between forms of different ages, in particular between recent forms and those forms inherited from earlier periods when different (climatic) conditions prevailed. Since the chronology and, in particular, the absolute dating of most of the units could not be resolved at this research stage, age information is not included in the geomorphic map of the area.

4.3.4. Survey of the study area

The study of geomorphology and morphodynamic processes was based on a set of activities and documents, including:
- aerial photo-interpretation, using 27 air photos taken in 1985 at scale 1:85,000;
- topographic map interpretation, using a topographic map of 1985 at scale 1:250,000;
- literature review, particularly papers on regional geology;
- fieldwork executed with INGEMA staff.

Photo-geomorphic units and features were identified and described in the field, while soil and sediment samples were taken and analyzed. This has led to (1) the preparation of the geomorphic map at scale 1:100,000; and (2) the detailed description of the stratigraphy of selected profiles, particularly in the fluvial, fluvio-eolian and eolian map units.

The results of the aforementioned activities, together with a hydro-geomorphic survey, have permitted to draw conclusions on the vulnerability of the area to environmental changes, erosion and desertification, and recommend conservation measures to mitigate these environmental threats.

4.4. GEOMORPHOLOGY AND GEODYNAMIC ASPECTS

4.4.1. Geomorphic landscape and map units

Three main geomorphic landscapes, subdivided into several map units, were identified and visualized in the geomorphic map covering the study area at scale 1:100,000.

(1) Structural mountain ranges

Sierra del Campo and Sierra de La Ramada are steeply sloping, strongly dissected anticlines. The cores consist of slightly metamorphosed phyllites belonging to the Medina formation (map unit E1), while the borders are formed by soft, continental and/or lacustrine sedimentary rocks of the Pirgua formation (map unit E2) and Río Salí formation (map unit E3). The Pirgua formation is common in the steep, lower portion of the mountain ranges, while the Río Salí formation occurs mainly in the piedmont area (Figure 4.1).

At various places in the lower portions of the mountain ranges, hill-spurs with flat tops at distinct levels can be observed. The highest ones are structural platforms supported by resistant rock layers (map unit E6). The lower ones are more of denudational origin and classified as initial glacis (map units D1 and D2). These flat-topped spurs may reflect stages of relief planation, most probably of late Pliocene when the climate in this region was hot and humid, following a sedimentation phase which might have been hot and dry in view of desert sedimentary rock types in the Río Salí formation (i.e. playa sediments with desiccation cracks and gypsum fillings).

Another important aspect of relief development in the mountain ranges is the presence of active faults. The drainage network is controlled by faults, in particular by the NW-SE oriented Río Tajamar transcurrent fault. Many drainage ways run in the same direction as the Río Tajamar, with some displacement of rivulets and interfluves. Also the N-S and NNE-SSW faults seem to be (sometimes) active, because of the presence of (dissected) fault facets (map unit E5) in the lower portions of the mountain ranges, coinciding frequently with the proximal sectors of the piedmont glacis.

Aerial photo interpretation and field observations have shown that the densely vegetated mountain zone is rather stable concerning water erosion. Barren patches resulting from erosion and/or mass movements are limited. The riverbeds are dry most of the year, conveying little sediments to feed the piedmont fans. Hence, it seems that, at present, the mountain zone does not contribute substantial volume of sediments to the low-lying eastern plains.

(2) Piedmont area

The piedmont area, east of the Sierra del Campo and Sierra de La Ramada, consists of (a) rounded or flat-topped hillocks (denudational hills) and spurs (structural edges), included in map unit E4; (b) elongated gently sloping surfaces (glacis) or flat-topped (and sometimes rounded) elevated plains (raña and rañizo types of glacis); (c) wide and flat riverbeds; and (d) fluvio-colluvial plain depressions. The glacis surfaces are the most characteristic features in the piedmont area. They developed on top of and/or in the soft sedimentary rocks of the Río Salí formation and, locally, the Pirgua formation. Three main stages of glacis development can be distinguished.

(a) Cone-glacis

Reddish soils and clastic materials of the mountain ranges in the Sierra del Campo and Sierra de La Ramada were eroded, transported and deposited as fan conglomerates at the foot of the mountains, forming raña-type cone-glacis (map unit D3). In general, the contact of these deposits with the underlying Pirgua and Río Salí formations is a very clear, irregular erosion surface with depressions in which most coarse fluvial and mudflow deposits accumulated, followed by a series of sediments with variable grain size, frequently without or with faint sorting and stratification.

In general, the coarsest sediments without sorting and stratification are found in the fan apexes, near the contact with the mountain ranges, as mudflows and fluvio-torrential accumulations. Downstream, fluvio-torrential accumulations dominate, with finer textures, slightly rounded coarse fragments and weak stratification. At several places, calcrete or tosca horizons have formed, particularly in the top portion of the eastern distal areas of the accumulation cone-glacis. This reflects that cone-glacis have formed during the dry glacial periods of the middle and upper Pleistocene and that calcium carbonate has accumulated in the subsoil through pedogenetic and/or geogenetic processes.

Northwest of Burruyacú, three glacis levels were identified, while such levels are limited to initial (erosion) glacis or are absent in other parts of the study area. Nowadays, most of these three original surfaces are only observable as flat- or round-topped, elongated spurs and hillocks.

Steep denudational hillocks, located near the mountain ranges and topped by some fan-conglomerate deposits, are usually covered by (degraded) western Chaco forest or commercial pine plantation (map unit D5). In contrast, low hillocks with smooth surfaces, such as those occurring in the east along the provincial road 304 (map unit D6), are used for agriculture and therefore prone to erosion, with removal of fine sediments further deposited in the eastern plain.

(b) Erosion glacis and mixed glacis

During a second period of footslope development, glacis erosion took place or mixed glacis (of rañizo type) formed (map unit D4). Erosion glacis were incised in the original accumulation glacis, appearing either as narrow zones between the remnants of the higher cone-glacis (map unit D3) and the lower younger glacis (map units D7 and P1) and alluvial plains, or as bevelled cone-glacis surfaces, such as for instance north of Burruyacú. In general, erosion and mixed glacis are east-sloping, thus in the same direction as the original cone-glacis. This means that the regional erosion base at the time of the glacis development was also situated in the east, while a third-generation glacis was formed from a local erosion base level controlled by local rivers.

In addition of being located at lower elevation, the rañizo-type glacis differs from the raña-type glacis by its surface materials. The latter consist of greyish-brown fine sediments with angular pebble fragments. However, sediment sections vary from place to place, sometimes showing braided fluvial features and/or colluvial slope features. Sometimes, they simulate "Schwemmloess", a type of loess redeposited by surface runoff.

Likewise the raña-type glacis, the rañizo-type glacis is frequently covered by degraded western Chaco vegetation in the west and has been converted to arable land in the east. The latter is exposed to water erosion and removed materials may support sedimentation in the valleys and on the eastern plain.

(c) Front-slope, embayment and valley glacis

A third generation of footslopes is found in the depressions and valleys developed between the remnants of raña-type and rañizo-type glacis and the current riverbeds as front-slope, embayment and valley glacis. During the upper Pleistocene and Holocene, vertical erosion took place dissecting the D3 and D4 surfaces and the outcropping Pirgua and Río Salí formations. Pedimentation, resulting in erosion glacis formation through slope retreat, must have taken place during the cold and dry periods of the upper Pleistocene. Erosion glacis were formed particularly in the soft sedimentary rocks of the Pirgua and Río Salí formations. According to their position, front-slope (near a scarp), embayment (valley head) and valley glacis are distinguished. Their slightly concave, gentle slopes are oriented towards local erosion base levels corresponding to the present riverbeds. These glacis types are nearly always used for agriculture or pasture thanks to gentle slopes and fairly good soils. This landscape is susceptible to sheet, rill and gully erosion, which might provide sediments to the piedmont valleys and depressions but also to the eastern plain.

(d) Riverbeds, alluvial plains and depressions

Finally, the piedmont zone is crossed by wide and flat riverbeds, alluvial plains and depressions (map units P2, P3, F1 and F3). Nearly all rivers and rivulets originating in the mountain ranges are intermittent, bearing water only in the rainy season. The drainage pattern and the presence of relatively fresh sediments indicate the torrential character of the streams. The smaller rivers spread out at short distance (1-5 km), forming fluvio-colluvial fans. The larger ones have distinct riverbeds, which may extend into the eastern plain. They frequently have one or two narrow erosion-accumulation terraces (map unit F2), with local crevasse splays on the outer meander banks. There are also abandoned river channels that indicate riverbed shifts resulting from local plugging of the channels by torrential sedimentation, with or without tectonic tilting of the substratum, as seems to happen along the fault of the río Tajamar.

During the upper Pleistocene and Holocene periods, valley widening must have taken place since all valleys in the study area are misfit. They are filled in by dominantly fine sediments, originated (a) from the waste products coming from the structural mountain ranges, the residual hillocks and the glacis; and (b) from the eolian deposits of loess and volcanic ash, which have been reported to happen during the upper Pleistocene and Holocene (Sayago, 1995).

Although slopes in the alluvial plains and depressions are very gentle and smooth, they are nevertheless susceptible to sheet, rill and gully erosion because of rainfall erosivity, soil erodibility, and agricultural uses without conservation measures. Hence, both river and overland flows, occurring in these wide valleys and depressions, have caused most of the deposition of fine and medium-coarse sediments in the eastern plain, except the loess influx.

(3) Eastern plain

The eastern plain occupies the main portion of the study area, comprising isolated remnants of planation surfaces (map units D3, D4, D7 and P1); depressions (map units P2 and P3); plains with riverbeds (map units P4, P5, P6 and P7) and narrow valleys (map unit F1); fluvial terraces (map unit F2); glacis-terraces, alluvial fans and large barrancos with steep valley sides and flat bottoms (map unit F3).

The boundary between piedmont and eastern plain cannot be sharply drawn. There is a transition zone in which the old planation surfaces (i.e. the raña-type, rañizo-type and other glacis surfaces) are much bevelled and dominantly covered by loess materials, likewise other areas of the eastern plain. Most of the wide and flat valleys start in the piedmont and continue into the eastern plain where they faint out through a number of paleo-channels. Such channels could be traced only at some places, particularly in map unit P6, as elongated meandering depressions with somewhat more moisture and more luxuriant vegetation or crops. Paleo-channels are frequently buried through silting up by loess and Schwemmloess, or blurred by repeated farming practices.

The eastern part of the study area is dominantly flat, with slope less than 1º east. At some places, portions of undulating terrain (map unit P4) occur, reflecting probably underlying topography of raña- and rañizo-type of planation surfaces and/or denudational hills on the Río Salí formation, covered by a thick mantle of loess, Schwemmloess and volcanic ash. The "heights" (<2.5 m) are N-S aligned, with interruption at the passage of the wide and flat transversal valleys. This may be an indication of (neo-) tectonics, more or less parallel to the main N-S or NNE-SSW faults of the sub-Andean ranges. Further research would be needed to check this hypothesis.

The presence of old non-loess sediments or sedimentary rocks near the terrain surface and/or (neo-) tectonic activity, in combination with up-welling groundwater, may have led to the development of barrancos in several places, including the area northeast of Benjamín Aráoz, in Gobernador Garmendia, in San Juan south of Gobernador Garmendia, in Tajamar north of Gobernador Piedrabuena, and south of La Virginia. In Benjamín Aráoz and Tajamar, marly materials presumably of Plio-Pleistocene age are exposed at the bottom of the barrancos, covered by loess, Schwemmloess and volcanic ash containing one or two paleosoils.

In the profile of the Tajamar barranco, a blackish swamp horizon, 60 cm thick and hundreds of meters wide, was identified. It lies approximately 4 m above the marl substratum and about 12 m below the terrain surface of the eastern plain. Hence, this horizon may be a good chronostratigraphic indicator for dating the loess, Schwemmloess and volcanic ash deposits and paleosol sequences in the study area.

4.4.2. Geomorphic map legend

The following legend was designed for the geomorphic map of the Burruyacú area.

E: Structural-denudational units
Unidades estructural-denudativas

(In general: in mountain areas)
(En general: en la zona montañosa)

E1 Spur, strong structural slope (Medina formation)
Espinazo, pendiente fuerte estructural (formación Medina)
E2 Spur, strong structural slope (Pirgua formation)
Espinazo, pendiente fuerte estructural (formación Pirgua)
E3 Strong structural slope (Río Salí formation)
Pendiente fuerte estructural (formación Río Salí)
E4 Complex of small spurs
Complejo de espinazos pequeños
E5 Facet
Faceta
E6 Structural-denudational platform, residual, high
Plataforma estructural-denudativa, remanente, alta

D: Denudational units
Unidades denudativas

(In general: in piedmont areas)
(En general: en la zona de piedemonte)

D1 Initial glacis, structural-denudational platform, medium-high
Glacis inicial, plataforma estructural-denudativa, media-alta
D2 Initial glacis, structural-denudational platform, medium-low
Glacis inicial, plataforma estructural-denudativa, media-baja
D3 Cone-glacis (raña-type)
Glacis-cono (tipo raña)
D4 Degraded mixed glacis (rañizo-type)
Glacis mixto degradado (tipo rañizo)
D5 Residual hill, strong slope, high
Colina residual, pendiente fuerte, alta
D6 Residual hill, gentle slope, low
Colina residual, pendiente suave, baja
D7 Piedmont glacis, front-slope glacis, undulating, high, inactive
Glacis de piedemonte, glacis de frente, ondulado, alto, durmiente

P: Fluvio-denudational/eolian units
Unidades fluvio-denudativas/eólicas

(In general: in the eastern plain)
(En general: en la planicie oriental)

P1	Valley glacis, embayment glacis, semi-active Glacis de valle, glacis de golfo, semi-activo
P2	Fluvio-denudational depression, inactive Depresión fluvio-denudativa, durmiente
P3	Fluvio-denudational depression, low flat area, semi-active Depresión fluvio-denudativa, zona plana baja, semi-activa
P4	Denudational plain, fluvio-eolian, undulating, inactive Plano denudativo, fluvio-eólico, ondulado, durmiente
P5	Fluvio-eolian plain, undulating, inactive Plano fluvio-eólico, ondulado, durmiente
P6	Fluvio-eolian plain, flat, inactive to semi-active, level I Plano fluvio-eólico, plano, durmiente a semi-activo, nivel I
P7	Fluvio-eolian plain, flat, semi-active, level II Plano fluvio-eólico, plano, semi-activo, nivel II

F: Fluvial units
Unidades fluviales

(In general: in D and P areas)
(En general: en las zonas D y P)

F1	River channel, narrow valley Lecho del río, valle angosto
F2	Fluvial terrace Terraza fluvial
F3	Glacis-terrace, fluvial fan, flat barranco bottom Glacis-terraza, abanico fluvial, fondo plano de barranco

O: Other units and symbols
Otras unidades y símbolos

Road / Carretera, camino principal
Settlement / Poblado
Glacis / Glacis
Fault / Falla
Alluvial fan / Abanico fluvial
Lithologic boundary / Límite litológico

4.5. HYDROGEOMORPHOLOGY AND PALEOHYDROLOGY

4.5.1. Introduction

The analysis of the hydrogeomorphic features of the study area, using photointerpretation and field observations, allowed mapping and classifying the geoforms created by the present and past river dynamics, with emphasis on the channels of the Tajamar and Pajas Coloradas rivers. These features are represented in the hydrogeomorphic map of the lower Tajamar river basin (Figure 4.2). Paleochannels with structural control, migrating paleochannels and paleochannels turned into ravines by human-induced erosion were characterized according to their morphology and/or genesis (Sayago et al., 1996, 1999).

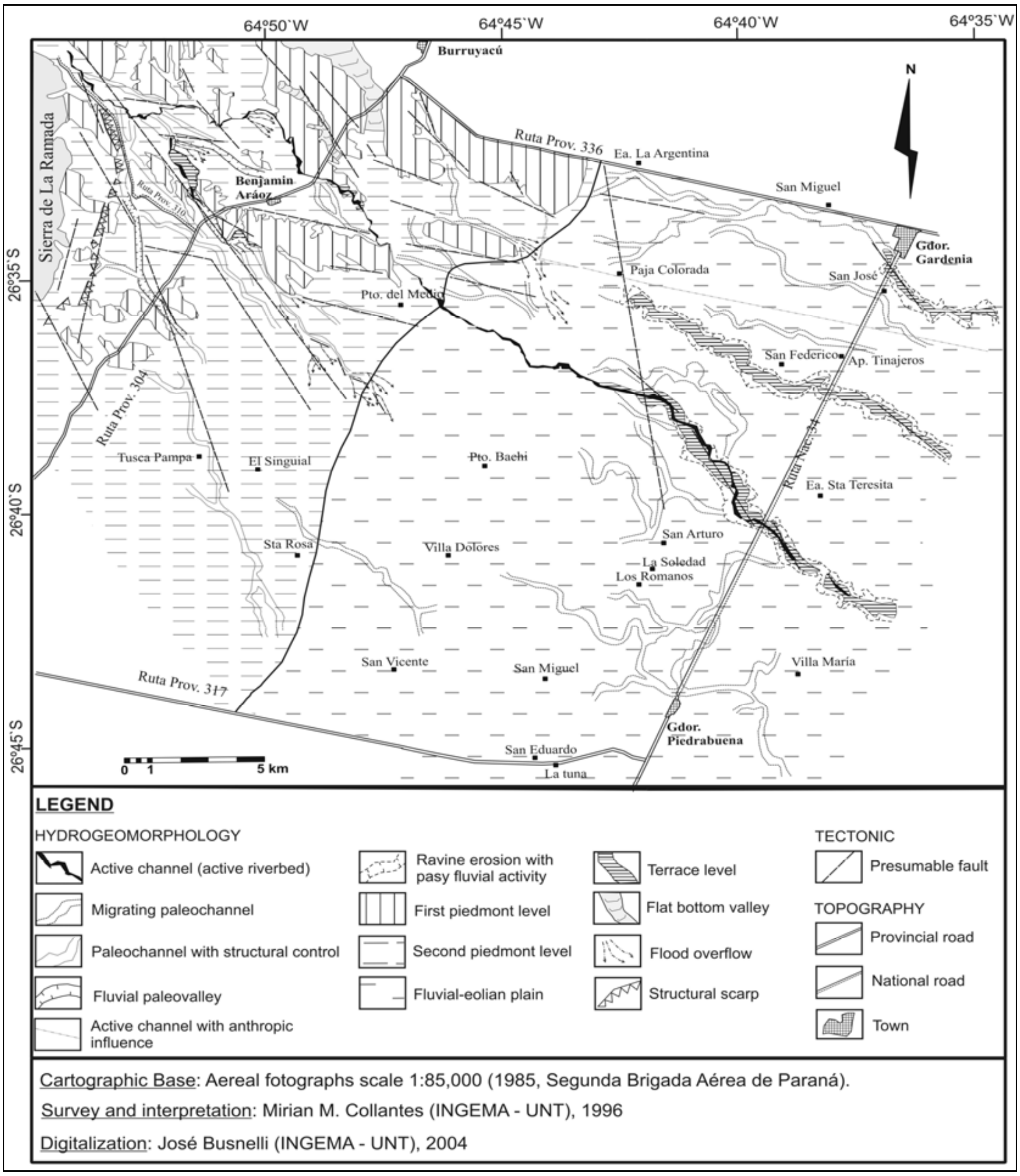


Figure 4.2. Hydrogeomorphic map of the lower Tajamar river basin.

4.5.2. Channel of the Tajamar river

The Tajamar river rises in the structural valley that separates the Sierra de La Ramada from the Sierra del Campo within the morphostructural system of the sub-Andean ranges. After crossing the piedmont, the river stretches eastward into the undulating plain where it shifts from its earlier NW-SE direction to the present W-E orientation. Channel changes are controlled by structural (neotectonics), climatic (paleoclimatic variations) and anthropic factors which influenced the shape of the present riverbed, particularly over the last decades. After flowing northward along the piedmont in response to neotectonics, the river moved to its present valley and developed a terrace level in the piedmont area, observable from the bridge on road 304. The presence of paleomeanders on the terrace could indicate recent neotectonic activity. At its penetration into the plain, the river developed an alluvial fan, clearly visible in the 1968 aerial photograph, now stabilized and mostly covered by Chaco forest.

Intensive clearing of the Chaco forest from the 1970s onwards, together with a rainfall increase of about 25% above average, caused substantial change in the infiltration-runoff relationship. After removal of the forest cover, infiltration rate of the soils directly exposed to rainfall decreased and runoff increased, generating higher river discharge and allowing eastward extension of the channel incision. As a consequence, the primitive alluvial fan was reactivated, with increasing flood hazard to agricultural areas. Artificial channeling in the piedmont and the plain to prevent overflow and flooding turned the river into a semi-permanent stream. In the place where road 34 crosses the Tajamar river, the latter developed a recent smaller channel incised in the sediments that filled the bottom of the San Juan paleofluvial valley.

4.5.3. Channel of the Pajas Coloradas river

The Pajas Coloradas river originates in a flat-bottom valley, located in the transition between the piedmont and the fluvio-eolian plain, in an area locally known as Finca Griet. Pajas Coloradas and Tajamar rivers are the only water courses with some kind of permanent runoff in the study area. Pajas Coloradas river has a rectilinear course about 5 m deep and 15-20 m wide, thus exhibiting characteristics of an anthropogenic channel. After crossing road 34, the channel widens over a short stretch. From its source in the piedmont, the river first flows eastward, then southward over a short distance, and finally again eastward when crossing the plain towards the neighbouring province of Santiago del Estero. It works as the local collector of the water infiltrated in the proximal area of the piedmont and the eastern slope of the Sierra del Campo. Although water supply is not really significant, it can be used for irrigation because of its permanent runoff.

4.5.4. Paleochannels with structural control

From the piedmont of the Sierra del Campo and Sierra de La Ramada, several elongated flat-bottom valleys run down into the plain as shallow, sometimes buried, paleoriverbeds with clear structural control. On its southward migration, the Tajamar river occupied a sequence of valleys generated by neotectonics. The morphology of the paleoforms suggests that they were developed by NW-SE running streams with moderate energy and high competence. Although they are presently inactive, subsurface or even surface runoff during heavy rain periods might occur. River behaviour seems to be related to paleofluvial conditions, together with fault and fracture control.

4.5.5. Braided paleochannels

Braided paleochannels are frequent throughout the fluvio-eolian plain, occurring as shallow channeled depressions generally masked by crops or artificially drained. Such channels can be attributed to relatively recent overflows from the Tajamar river. They served as local collectors of excess water during heavy rain periods, when the region was still covered by Chaco forest. Nowadays, they behave as local areas of runoff storage on soils having high capacity for moisture retention that plays an important role during drought periods.

4.5.6. Fluvial paleovalleys

In the western sector of the study area, large elongated depressions, similar to real fluvial valleys, start in the fluvio-eolian plain about 15 km west of road 34 and extend southward over several tens of kilometers. Three of them are important: (1) the Barranco de San Juan, which corresponds to the distal stretch of the Tajamar river; (2) the San Federico paleovalley that lies in a similar position 5 km northward; and (3) the paleovalley near Gobernador Garmendia developing in the distal portion of a braided paleochannel that rises on the limit between piedmont and fluvio-eolian plain.

Up to 10 m deep and 500-800 m wide, they extend eastward through the fluvio-eolian plain and disappear in the saline depressions of Santiago del Estero. They seem to be related to intensive head-retreat erosion during the moist Holocene periods, with runoff increase from the west, and/or to changes in the eastern base level by neotectonic reactivation. In all cases, ravine heads are located in the plain, not in the piedmont. This could be related to the existence of an area depressed by tectonics that would have diminished river incision, and/or it could be caused by decrease in water supply from the west due to climatic change. All these channels coincide, in some stretch of their courses, with structural features causing slightly asymmetric margins. Additionally, mass movements might have contributed not only to channel widening but also to channel stabilization through creeps and flows from the hillsides.

4.6. STRATIGRAPHY OF SELECTED SEDIMENT AND SOIL PROFILES

4.6.1. Introduction

Several sediment and soil profiles were described at selected road and river exposure sites. Their stratigraphy and paleoenvironmental significance are representative of the materials deposited in the area and the evolution of the fluvio-eolian landscape during the upper Quaternary.

4.6.2. Tajamar-Aráoz profile

The Tajamar-Aráoz profile (Figure 4.3) is a sequence of materials associated with the first piedmont level of the Sierra de La Ramada, corresponding to a cone-glacis (unit D3 in the geomorphic map). The section was described along a 14.65 m thick road cut on the east side of road 304, close to the bridge over the Tajamar river. It is mainly made of alluvial materials showing variations in the transport dynamics of the channels that originated the Tajamar river migrating fan and the alluvial cones developed on the eastern piedmont of the Sierra de La Ramada during the moist periods of the Holocene. It also reflects climatic variations that took place in the upper catchment areas.

The profile sequence has high sand content and consists of an alternation of fanglomeratic layers, with blocks in a sandy matrix, and layers with gravel and sand. At the profile base, there is a sandy layer with high content of silt and clay, together with calcareous micro-concretions. The lower section, including layers I, II and III, is composed of finely stratified sand layers showing conditions of low transport energy. From layer IV upwards, fanglomerates of block- to gravel-size clasts within a loamy sand matrix alternate with loamy sand layers showing intercrossed laminar stratifications. In the upper section of the profile, this cyclic interlayering is altered by the presence of a petrocalcic clay loam horizon (layer X), rich in calcareous macro-concretions.

4.6.3. Western Tajamar profile

A 6.6 m thick profile (Figure 4.4) was described on the left bank of the Tajamar river about 0.5 km west of road 34. It constitutes a section of retransported loess deposits on the first piedmont level of the Sierra de La Ramada. Two paleosols in the middle and upper sections, respectively, consist of Bt horizons separated by a retransported loess layer. The upper paleosol (layer V) has an AMS radiocarbon age of 7860 ± 60 BP.

4.6.4. Eastern Tajamar profile

A 5.41 m thick profile (Figure 4.5) was described on the right bank of the Tajamar river, near the bridge on road 34. It exhibits the characteristics of the materials typical of the fluvio-eolian plain in two contrasted sections. The lower section, from the profile base to about 4 m upward (layers I to V), includes an alternation between retransported loess layers and two paleosols, the upper one having a radiocarbon age of 655 ± 25 BP; a tephra layer (layer IV) overlies the lower paleosol. The upper section (layers VIa to VIg) is made of a succession of 20-30 cm thick loamy sand and clay loam layers with laminar sedimentary structure, that seem to have been deposited in a marshy environment about 1.7 m thick. At the base of this section, a fragment of buried tree stem, a rather frequent type of material in this section, gave a radiocarbon age of 225 ± 25 BP. The material reflects sedimentation in a water-filled depression, which could have resulted from an overflow of the Tajamar river or could evidence the presence of swamps generated by the primitive Tajamar river when flowing into the plain, before the recent incision of the riverbed.

4.6.5. La Virginia profile

A 7.5 m thick profile (Figure 4.6) was described on the right border of an erosion ravine developed near the locality of La Virginia, in the fluvio-eolian plain. The exposed section constitutes a sequence mainly composed of loess with two paleosols (layers III and V). The sequence includes also a volcanic ash layer (layer VI) on top of the upper paleosol. In layer II made of sandy clay loam loess, a *Celidoterium* rib was found with radiocarbon age of 11480 ± 90 BP. This loess-paleosol profile is better developed than the western Tajamar profile, but lacks the marshy deposits at the top of the sequence probably because it occupies a higher position within the undulating plain, far from the influence of any riverbed.

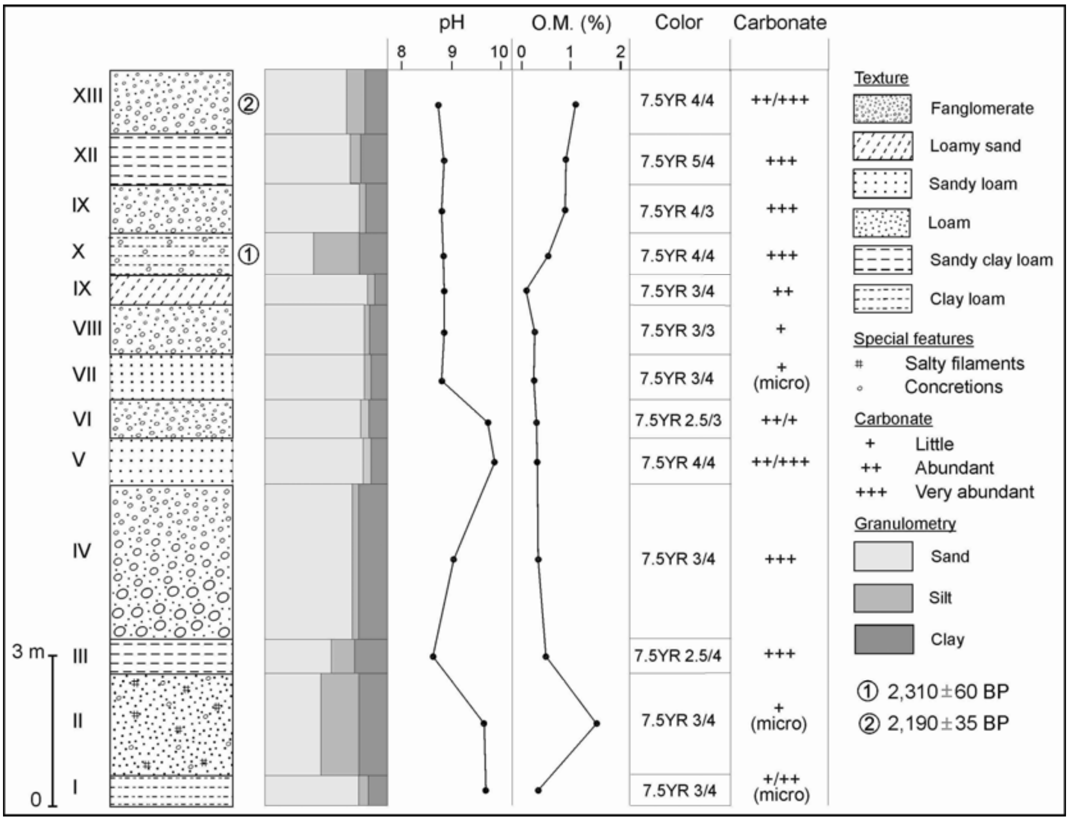


Figure 4.3. Sequence of alluvial deposits in the Tajamar river fan (Tajamar-Aráoz).

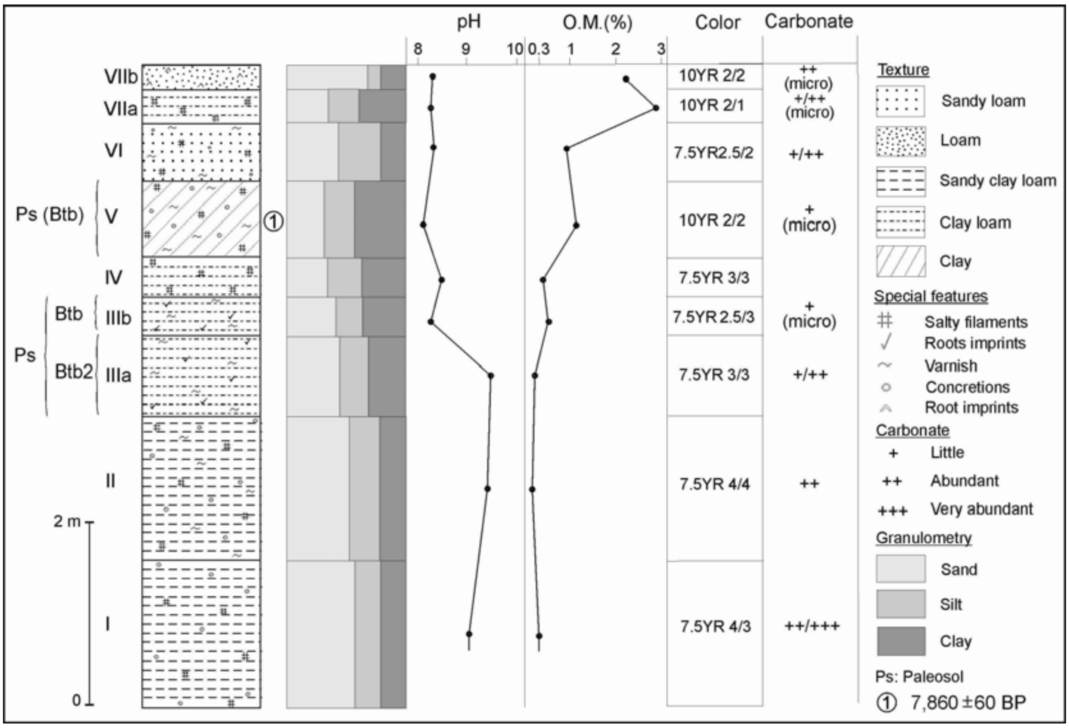


Figure 4.4. Loess-paleosol sequence in the piedmont area (Western Tajamar).

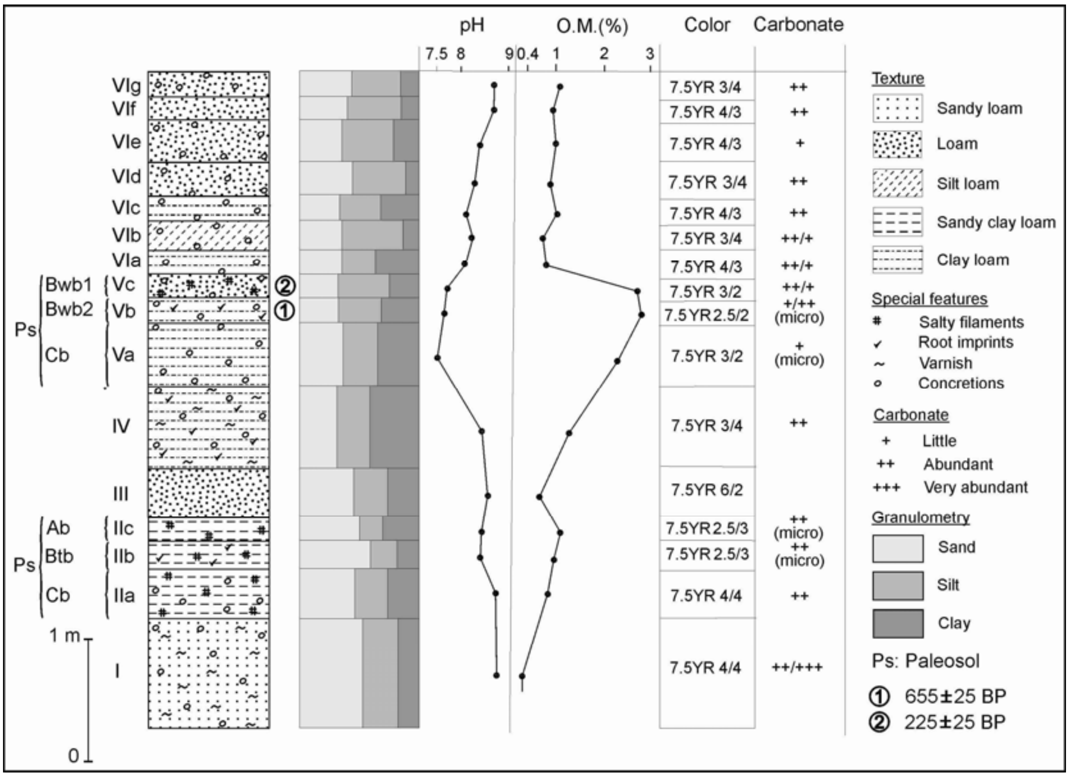


Figure 4.5. Loess-paleosol sequence in the fluvio-eolian plain (Eastern Tajamar).

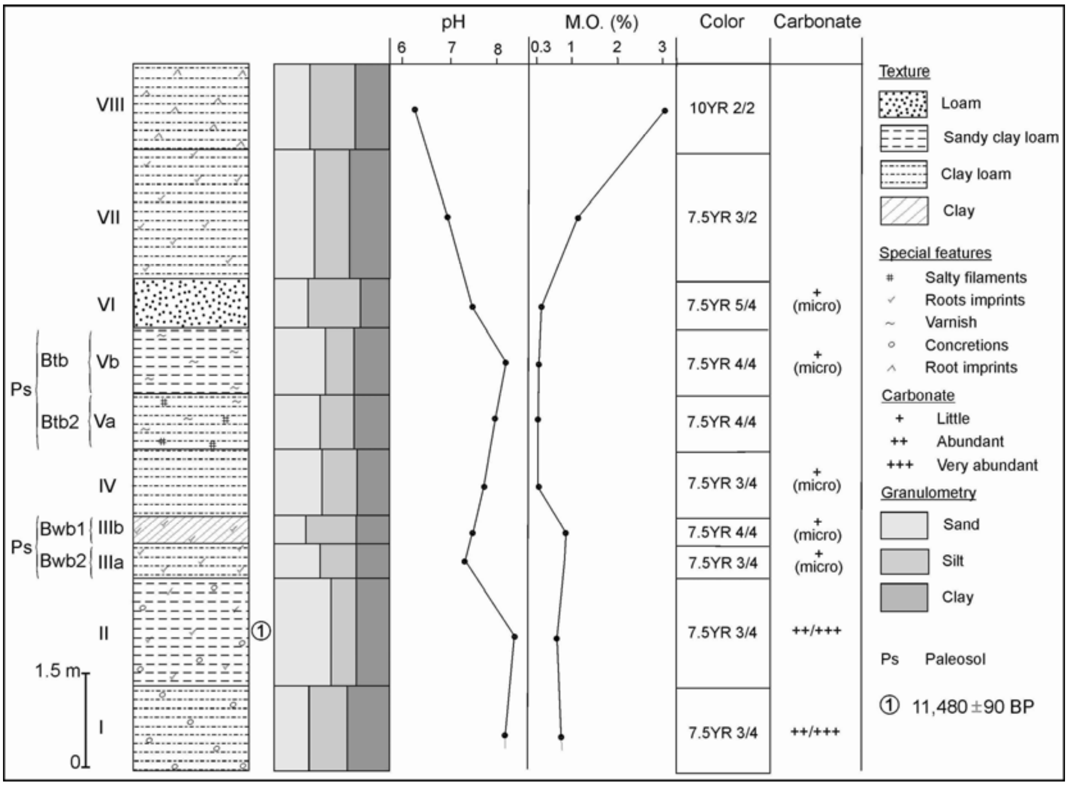


Figure 4.6. Loess-paleosol sequence in the fluvio-eolian plain (La Virginia).

4.7. GEOMORPHOLOGY AND ENVIRONMENTAL CHANGES

4.7.1. Introduction

Although the geomorphic survey of the Burruyacú area is at reconnaissance level, it provides sufficient knowledge for more detailed investigations in the fields of:
(a) Quaternary geology and geomorphic landscape evolution;
(b) Soil formation, degradation and conservation;
(c) Vegetation cover and land use changes in relation to (a) and (b);
(d) Detection of possible regional changes in natural environment, leading to desertification.

The main geomorphic landscape units in the mountain ranges and in the piedmont zone are exposed to sheet and gully erosion, fluvial erosion and mass movements, generating sediments which are deposited onto the eastern plain. This plain, in its turn, is susceptible to eolian erosion and barranco development, particularly as a consequence of land cover and land use changes and the fragility of the loess-derived soils.

More humid conditions in the past favoured strong river activity. Abandoned riverbeds, with elongated depressions and meanders, can still be observed in the field. Nowadays, fluvial action is limited to short-distance riverbeds, alluvial fan deposits, and gully and barranco development. This may reflect a trend towards desertification in the area. Since desertification is the product of both physically- and man-induced processes, an analysis of the past and present processes and environmental changes is most important to understand the fate of agriculture in this area

4.7.2. Indications of former environmental changes: paleochannels

Paleofluvial features resulting from riverbed migrations are significant geomorphic indicators of paleoenvironmental changes in the western Chaco plain, in particular climate changes that affected the region throughout the Middle and Upper Holocene. In the case of the Salado-Juramento catchment, however, the pattern of the paleofluvial system resulting from river shifting reflects also regional neotectonic influence (Ríos et al., 1999). The paleoclimatic variability of the region consisted of cycles including dry periods with loess deposition and moist periods with soil development. During the moist periods, probably intense river activity took place, as shown by the paleofluvial pattern in the study area as well as in a large portion of the western Chaco plain.

Together with higher moisture conditions, neotectonics has played an important role in the development of the regional paleofluvial network. The Tajamar river, for instance, has migrated northward until reaching its current location. Similarly, the Salí river moved from an approximately NW-SE direction to its present N-S position and further developed southeastward in the province of Santiago del Estero. This shows the regional extent of the climatic and tectonic controls on river behavior. Collantes (1983) mapped a significant paleofluvial network on both banks of the Dulce river between Termas de Río Hondo and Los Quiroga, in the province of Santiago del Estero. Nowadays, the paleochannels lie about 5 m above the Dulce river base level. This situation confirms the influence of climatic conditions different from today's ones on earlier riverbed development and the influence of neotectonics on riverbed incision causing the formation of paleochannels hanging above the current river base level.

4.7.3. Current morphodynamic features

The occurrence of erosion and sedimentation in the various geomorphic landscape units depends on (a) the climatic conditions, particularly rainfall erosivity, (b) slope steepness and length, (c) rock and soil erodibility, (d) vegetation cover, (e) morphodynamic processes, and (f) the duration these processes act on the terrain surface.

From a geomorphic point of view, mass movements, sheet, rill and gully erosion, fluvial dynamics, and eolian activity are most relevant for the characterization of environmental changes in the study area. In the uplands, the geomorphic processes diminish the soil and vegetation layers through eroding the topsoil, leaving coarse materials at the surface, or even exposing the underlying rocks or parent materials. In contrast, in the lowlands and particularly in the eastern plain, dominates the accumulation of medium- to fine-grained sediments burying soils and vegetation. Also locally, water may stagnate, creating swampy areas with salinization features.

Academic debate concerning the origin of the sediments and soils in the eastern plain, must focus on whether soil degradation is a consequence of clearing the western Chaco forest or whether more environment-oriented changes actually cause the gradual destruction of the land. Soil degradation seems to result from a combination of several factors, including (a) the destruction of the (semi-) natural Chaco vegetation, (b) the low technical level of the agricultural activity, (c) the soil properties, and (d) the aridity that avances from the east. Soil degradation is a form of desertification and the question is whether or not this hazard will result in permanent environmental change. From a geomorphic perspective, this will probably not be the case (a) as long as orographic rainfall continues in the mountain ranges and the piedmont zone, and (b) as long as the transport and accumulation of fresh sediments onto the eastern plain and the eolian erosion can be controlled. However, if farmers do not control the runoff of rain, riverine and drainage water nor take wind protection measures, gullies and barrancos will develop freely. Then, the study area may be partially converted into badlands and environmental change will really occur.

4.7.4. Potential environmental changes

Sheet, rill and gully erosion, as well as eolian erosion, are not effectively controlled by farmers. If precipitations decrease and rainfall events become more torrential, in combination with sparser vegetation cover, this can lead to more severe soil and geologic erosion in the future. In the mountain ranges, the soft phyllites of the Medina formation will be exposed to more gully and valley erosion and to more mass movements, including solifluction and landslides. Also severe sheet, rill and gully erosion and solifluction will happen in the piedmont zone, on the denudational hillocks developed in the soft, little resistant materials of the Pirgua and Río Salí formations, and on the various glacis surfaces. The eastern plain is already suffering from inadequate drainage and irrigation practices used by the farmers, generating gullies and barrancos. Piping, soil collapse and gully-head extension take place along the existing barrancos.

Deflation is a serious threat to the environment. Scarce vegetation and open crop cover, in combination with low rainfall, low soil moisture, low organic matter content in the topsoil and strong winds, will result in blowing out the soils developed on loess and volcanic ash. If no proper conservation measures are adopted to counteract wind and water erosion, the environment may change drastically and desertification may take place. As a consequence, badlands may form, vegetation may disappear, and rainfall may decrease and become more irregular. Agricultural production may then diminish and the quality of live be seriously threatened. Furthermore, desertification may expand to neighbouring areas.

It is recommended to apply conservation measures in the agricultural areas, including strip cropping, bunding and crop rotation in the sloping areas and wind fencing in the flat areas, while preserving as much as possible the humid subtropical forest in the mountain ranges and the western Chaco forest in the piedmont and eastern plain.

4.8. CONCLUSIONS AND RECOMMENDATIONS

4.8.1. Conclusions

- The whole study area is vulnerable to denudation, with dominant processes being creep, solifluction and landsliding in the mountains, water erosion in the mountain and piedmont zones, and eolian erosion in the eastern plain.

- The low-lying areas are exposed to flooding and deposition of fluvio-eolian materials, including fluvio-colluvial sediments in the piedmont and fluvio-eolian sediments both in the piedmont and eastern plain, with overbank flows near rivers and irrigation channels.

- The destruction of the western Chaco forest, together with the absence of soil conservation measures and the lack of improvement of soil fertility, will result in the acceleration of water and wind erosion, change in the environment and alteration of the local climate, together with disruption of wind and moisture regimes and intensification of desertification.

4.8.2. Recommendations

- Conservation of the western Chaco forest by preserving the current vegetation cover in the mountains and steep slopes of the piedmont.

- Conservation and recuperation of the western Chaco forest in the eastern plain using wind fences to reduce eolian erosion and increase soil moisture.

- Conservation of agricultural and pasture land through soil conservation by bunding and terracing and through prevention of soil salinization by improving the drainage in low-lying areas and depressions.

4.9. REFERENCES

Collantes, M.M., 1983. Geología de la cuenca del Río Dulce entre Termas de Río Hondo y Los Quiroga, con énfasis en geomorfología, provincia de Santiago del Estero. Tesis de Grado. Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, S. M. de Tucumán, 120 p.

Mon, R., 1971. Estructura geológica del extremo austral de las sierras subandinas, Prov. de Salta y Tucumán, República Argentina. Revista de la Asociación Geológica Argentina, Tomo XXVI (2) (abril - junio, 1971): 209-220.

Mon, R., Urdaneta, A., Suayter, L., 1971. Estudio geológico de las sierras del Campo y La Ramada (Provincia de Tucumán). Acta Geológica Lilloana XI (15): 293-306.

Ríos, R., Neder, L., Sayago, J.M., 1999. Influencias neotectónicas en la evolución paleohidrológica de la llanura tucumana. Resúmenes IV Reunión de Comunicaciones. Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, S. M. de Tucumán, 102 p.

Sayago, J.M., 1995. The Argentine neotropical loess: an overview. Quaternary Science Review 14: 755-766.

Sayago, J.M., Collantes, M.M., Neder, L., 1996. Hidrogeomorfología de la cuenca paleofluvial del río Tajamar, Dpto. Burruyacú, Tucumán. Serie Científica INGEMA, Avances de Investigación N° 5, S. M. de Tucumán, 23 p.

Sayago, J.M., Collantes, M.M., Toledo, M.A., 1999. Geomorfología. En: Geología de Tucumán. Colegio de Graduados en Ciencias Geológicas de Tucumán. Segunda Edición, Capítulo 11: 241-257.

Van Zuidam-Cancelado, F.I., 1989. Desarrollo geomorfológico de la cuenca del Río Aljucén y sus alrededores inmediatos, Extremadura, España: una hipótesis del desarrollo de planaciones. Tésis doctoral. Universidad de Utrecht, Países Bajos, 243 pp.

Verstappen, H.Th., 1983. Applied geomorphology; geomorphological surveys for environmental development. Elsevier, Amsterdam, The Netherlands.

Verstappen, H.Th., Van Zuidam, R.A., 1991. The ITC system of geomorphological survey. ITC Publication Number 10. Enschede, The Netherlands.

CHAPTER 5

THE SOIL COVER

J.A. Zinck

5.1. INTRODUCTION: ANTECEDENT SOIL INFORMATION

In 1992, INTA produced the basic soil map of the Burruyacú district at scale 1:77,000 (Gomez et al., 1992). Twenty-three map units were established and delineated on the basis of soil-landscape relationships. Each map unit is composed of two or three soil phases, except for a few units characterized as undifferentiated soil groups representing riverbeds, streams and infrastructures. The map was digitized using the ILWIS software (ITC, 1997) and is represented in Figure 5.1.

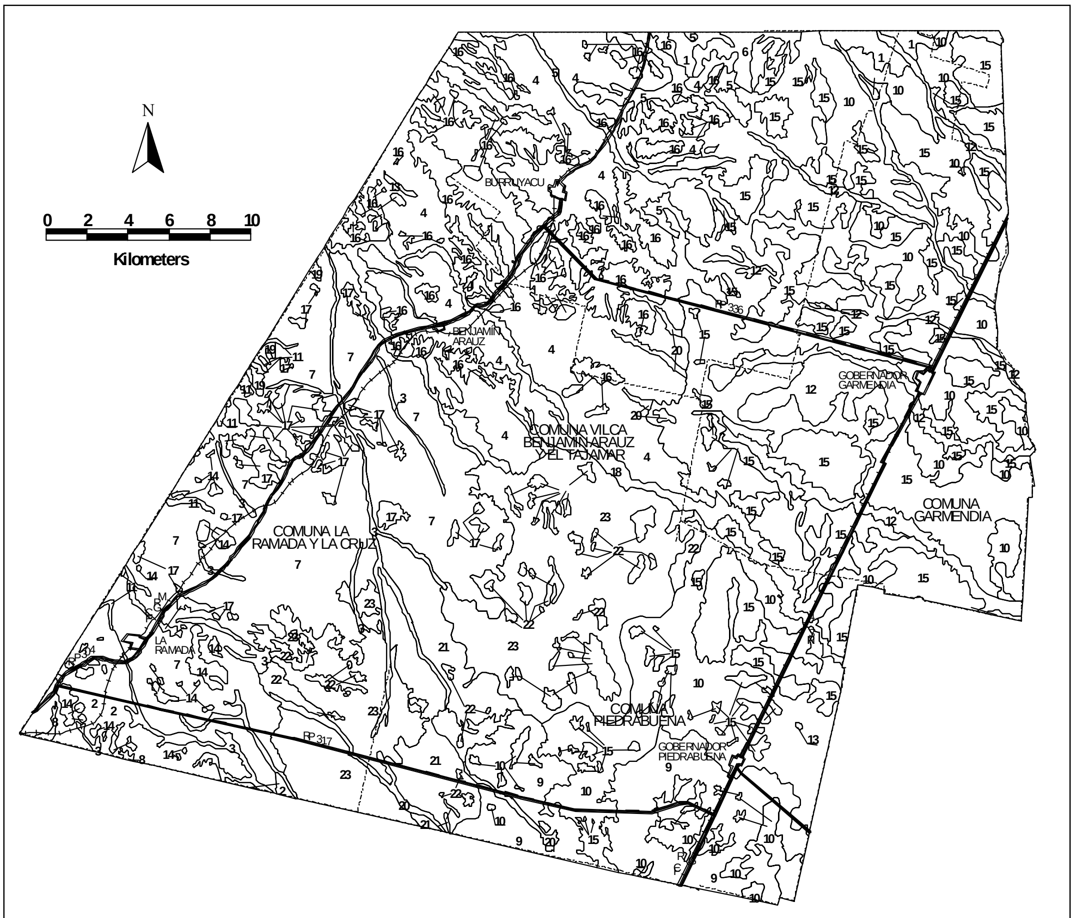


Figure 5.1. Soil map of the Burruyacú district (INTA, 1992).
Numbers refer to soil map units and letters to local names given to soil units by INTA. 1-Ab (7-de-Abril), 2-Ald (Alderete), 3-BA (Benjamín Aráoz), 4-BU (Burruyacú), 5-Chi (Chilcas), 6-EA (El Atacal), 7-EC (El Chañar), 8-ETi (El Timbo), 9-Ga (Garmendia), 10-GPi (Gobernador Piedrabuena), 11-HV (Huerta Vieja), 12-Jul (Juliana), 13-L (Lagunas), 14-LC (La Cruz), 15-LEz (La Esperanza), 16-LMo (Los Morros), 17-LR (La Ramada), 18-NT (Ríos Nio-Tajamar), 19-PMo (Padre Monti), 20-SGe (San Gerónimo), 21-Taj (El Tajamar), 22-TP (Tala Pozo), 23-Vir (Virginia).

All the soils in the Burruyacú area have developed from Quaternary sediments, mainly from loess deposits, and for this reason they are homogeneous over the whole area (Zuccardi & Fadda, 1972, 1985). Dominant texture is silt loam. In general, soil reaction is neutral but changes to slightly alkaline in the west because of higher calcium carbonate content in the sediments (Zuccardi & Fadda, 1985; García, 1990). Regional soil distribution, with soil classification according to USDA Soil Taxonomy (Soil Survey Staff, 1996) is shown in Figure 5.2.

Soils are mainly Mollisols, followed by Entisols (Zuccardi & Fadda, 1985; Gomez et al., 1992). Fluventic and Cumulic Haplustolls are commonly associated in the dry sub-humid piedmont. Soils of the humid and sub-humid flat parts of Burruyacú district are Typic Argiudolls and Typic Argiustolls. In the southwest of the district, Cumulic and Fluventic Haplustolls are associated with calcareous Ustorthents. Typic Argiustolls together with Cumulic and Fluventic Haplustolls occur in the central part of the area, while Typic and Entic Haplustolls dominate in the east. The soil moisture regime varies from ustic bordering aridic, in the east, to udic in the west (Gomez et al., 1992; Zuccardi et al., 1993).

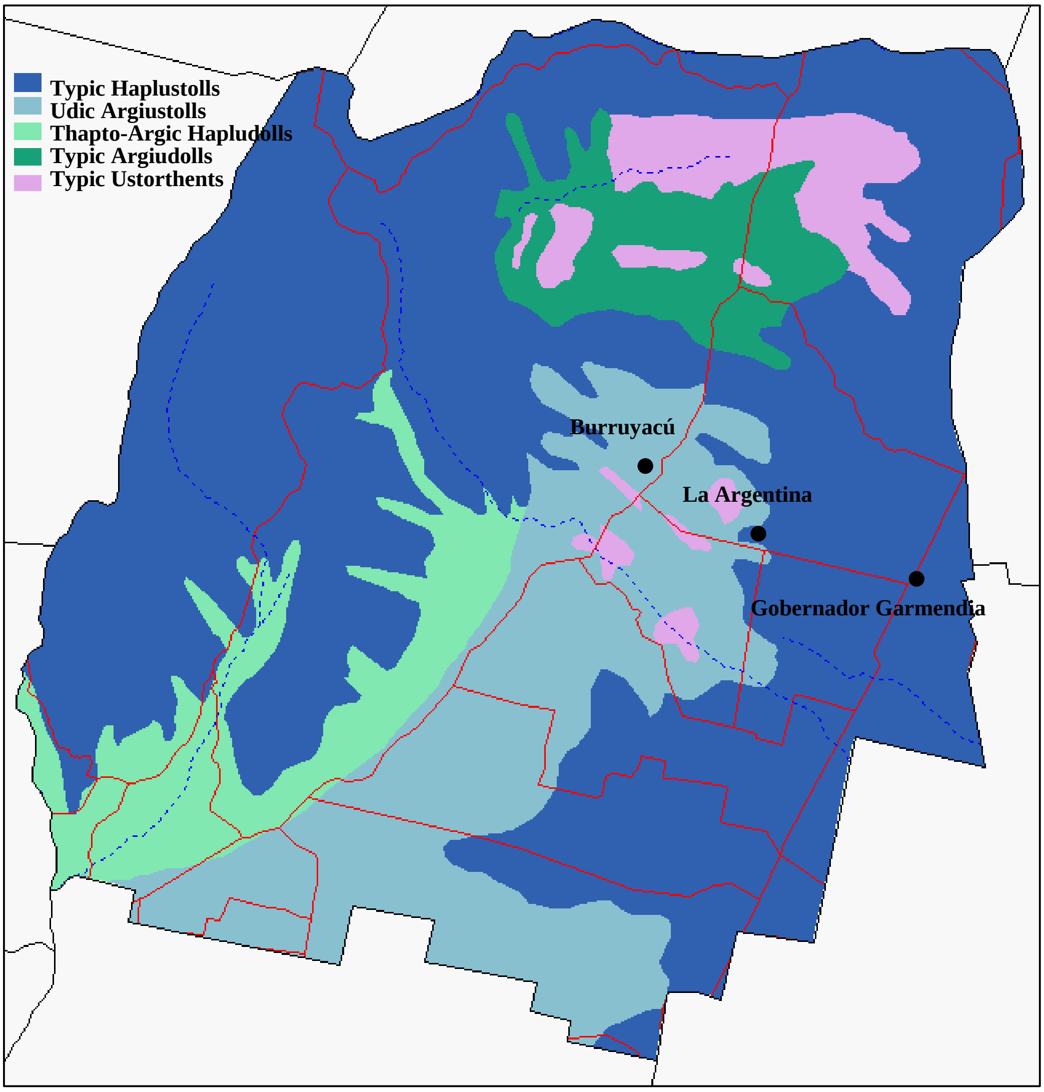


Figure 5.2. Soil map of the Burruyacú district (INTA, 1996).

5.2. SOIL FORMATION AND CLASSIFICATION

The study area comprises two landscape types: (1) in the west, a small strip of distal piedmont, including slightly undulating glacis with 1-3% slope, at the foot of a series of sub-Andean mountain ranges that reach 1000-2000 m elevation; and (2) in the center and east, a plain landscape, mainly flat with 0-1% eastward slope but incised by small river vales and rivulet swales, that occupies about 80% of the study area. Both landscapes are covered by a Quaternary loess mantle.

With exception of rainfall, the soil formation conditions do not vary substantially throughout the study area, which is essentially flat, slightly eastward sloping, uniformly covered by a loess blanket and originally covered by Chaco forest. Annual rainfall, in contrast, varies from more than 800 mm in the west to less than 600 mm in the east. This is the main factor controlling soil development and differentiation. To analyze spatial trends in soil formation, representative pedons were described in six sample areas distributed along two west-east transects at the northern (Burruyacú-Argentina- Garmendia) and southern (Ramada-Virginia-Piedrabuena) edges of the study area (Figure 5.3). They include 17 deep profiles (2 m deep) and 29 shorter profiles (<1 m deep).

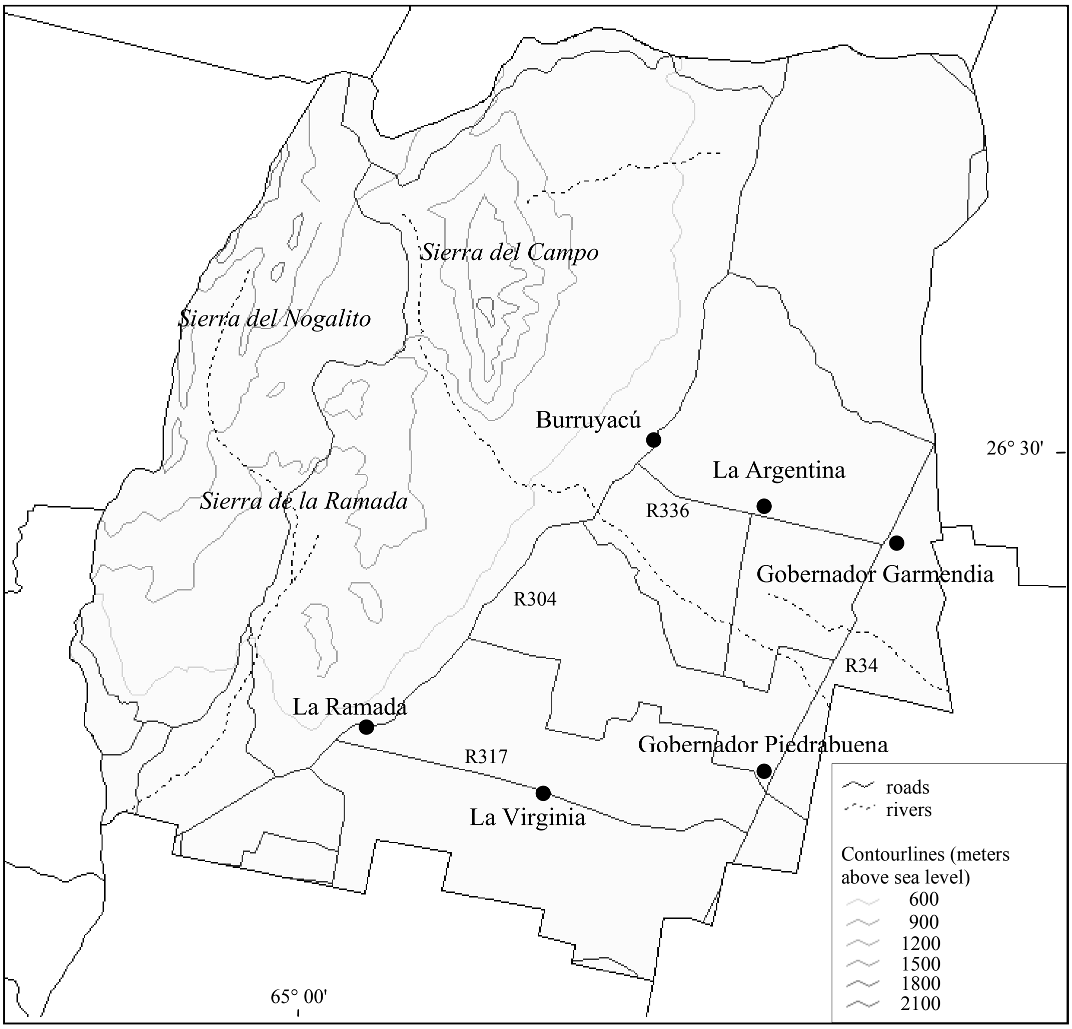


Figure 5.3. Location of the two transects at the northern (Burruyacú-Argentina-Garmendia) and southern (Ramada-Virginia-Piedrabuena) edges of the study area.

5.2.1. Loess as parent material

All soils in the study area have formed from loess parent material. Loess deposition took place several times during the Quaternary. An overview of the paleoenvironmental evolution of the area is given in Chapter 3. Here reference is made only to the upper two-meter-thick loess blanket from which the current soil cover and the underlying buried soil mantle have formed. Cumulative particle-size curves were established for loess materials from C and 2Cb horizons. All curves are S-shaped, reflecting strong grain selection by wind with dominant particle concentration in the silt fraction peaking in coarse silt (0.05-0.02 mm) and medium silt (0.02-0.005 mm).

The loess in the C horizons, which occurs mainly at 40-60 cm depth and constitutes the parent material of the cover soils, shows a spatial deposition trend from east to west (Figure 5.4). In the eastern strip, summation curves have a clear sigmoid pattern with a strong slope corresponding to the silt fraction, which constitutes the largest part of the sediment (60-70%). In the western strip, the slope of the silt fraction is less steep and the curves are more flattened, with a tendency towards logarithmic mode. In the central strip, summation curves are transitional between the eastern and western patterns. From east to west, the dominant wind lost strength and constancy during deposition time in the Upper Holocene, causing particle-size selection and dominance of the silt fraction in the sediment to decrease westward. Deposition and deflation were likely to alternate in the west.

The loess in the 2Cb horizons, which occurs at 120-160 cm depth and constitutes the parent material of the buried soils, does not show the same east-west differentiation as the younger loess strata of the C horizons do (Figure 5.5). All summation curves are clearly S-shaped, with strong slopes corresponding to the silt fraction. Thus, the dominant wind pattern was similar in the east and the west during the Middle Holocene, promoting throughout the area strong particle selection with silt dominance (70-80%).

Figure 5.6 highlights strong affinity between summation curves of the loess materials deposited at comparable depths (40-60 cm) in the C horizons of the cover soils and distributed over a large sector in the southeast of the study area. All curves show remarkable pattern similarity, with pronounced S-shape and concentration of particles in the silt fraction as a result of selection by dominant constant winds blowing from east. The abundance of silt in the six C layers compared in Figure 5.6 varies over a very narrow range (63-66%), reflecting the spatial homogeneity of the loess mantle.

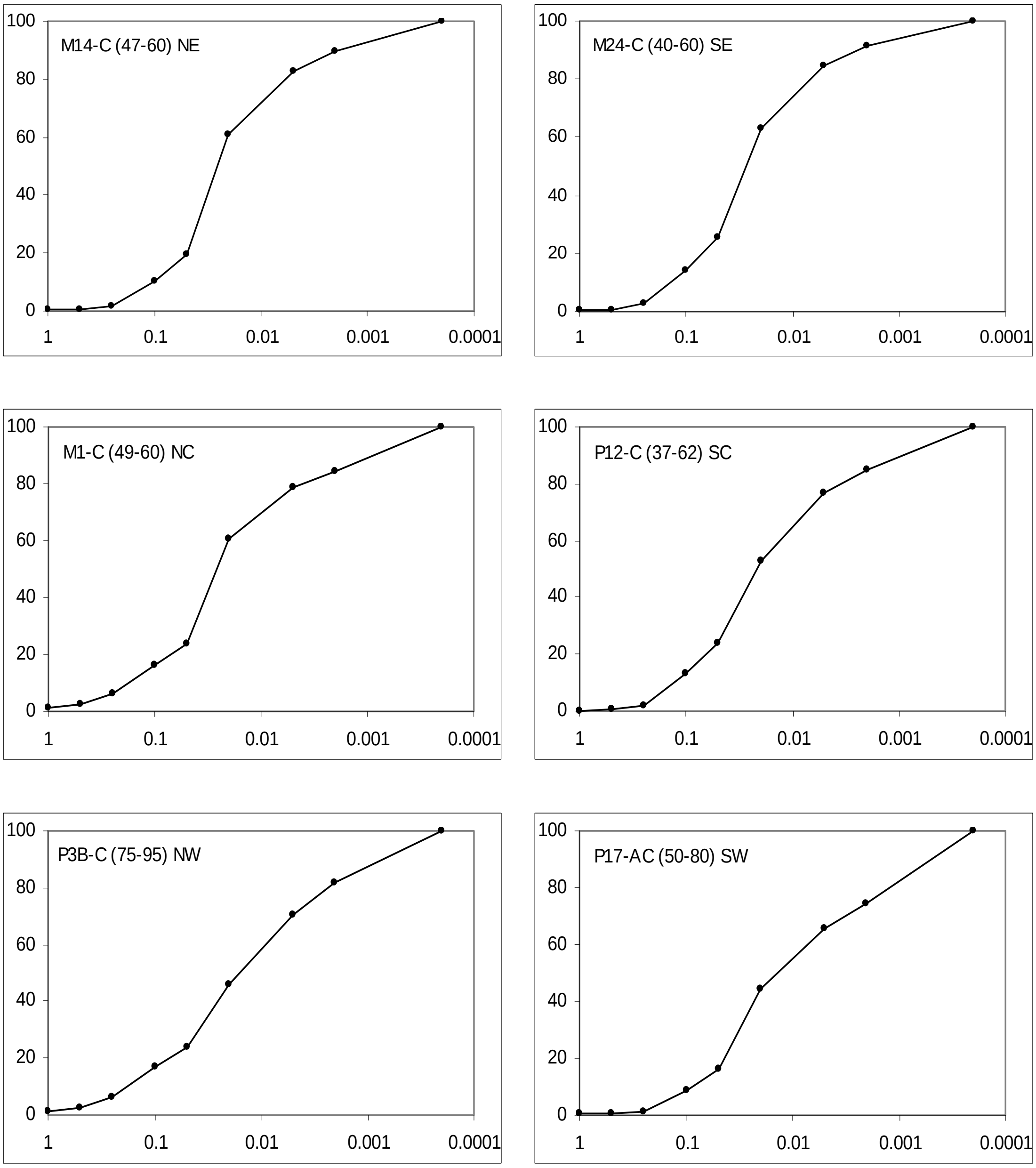


Figure 5.4. Cumulative particle-size curves of loess materials in C horizons (cm depth) in the east (NE and SE), center (NC and SC) and west (NW and SW) of the study area. Cumulative particle weights (%) on the Y-axis and particle-size classes (mm) on the X-axis.

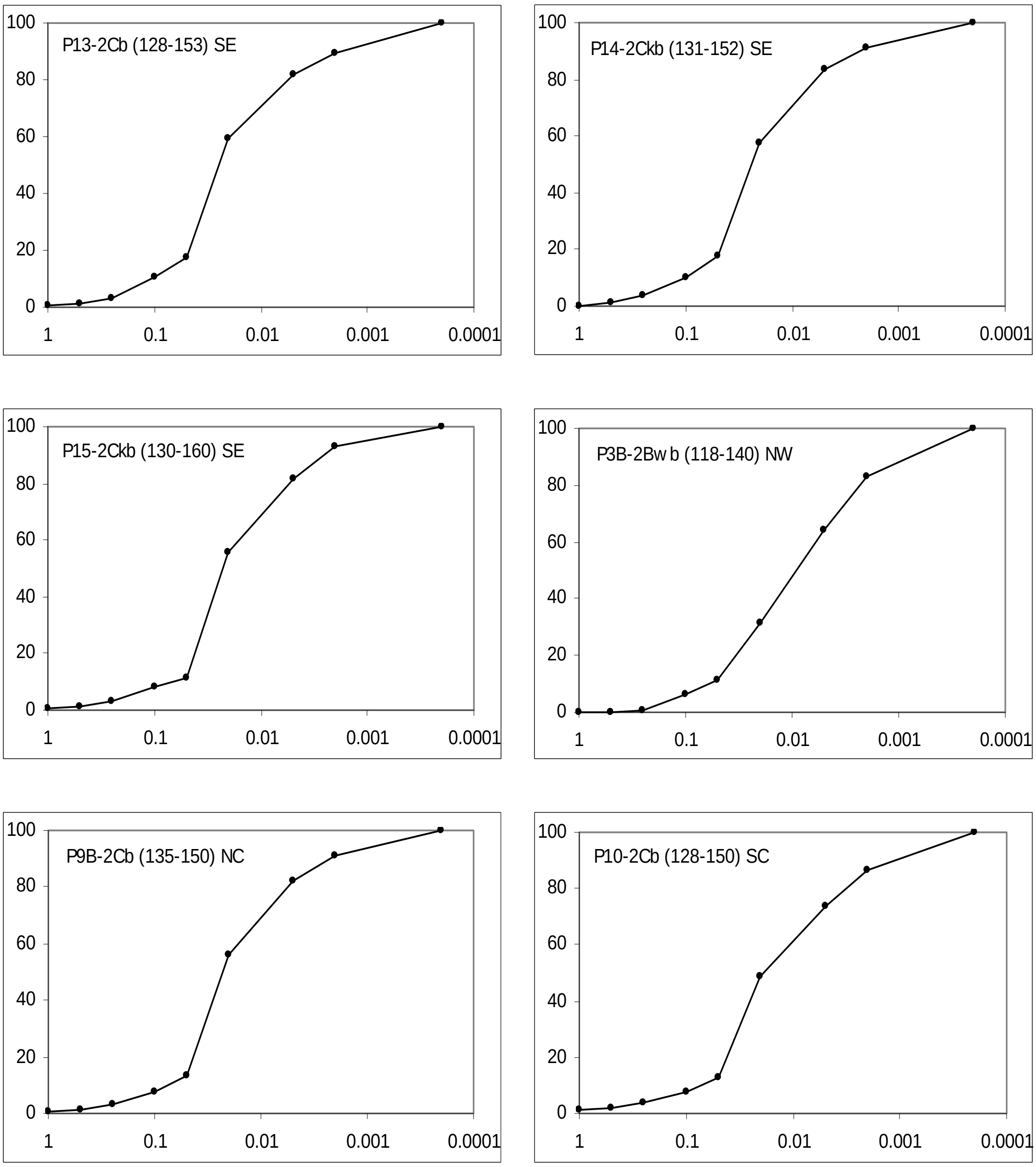


Figure 5.5. Cumulative particle-size curves of loess materials in 2Cb horizons (cm depth) in the east (SE), center (NC and SC) and west (NW) of the study area. Cumulative particle weights (%) on the Y-axis and particle-size classes (mm) on the X-axis.

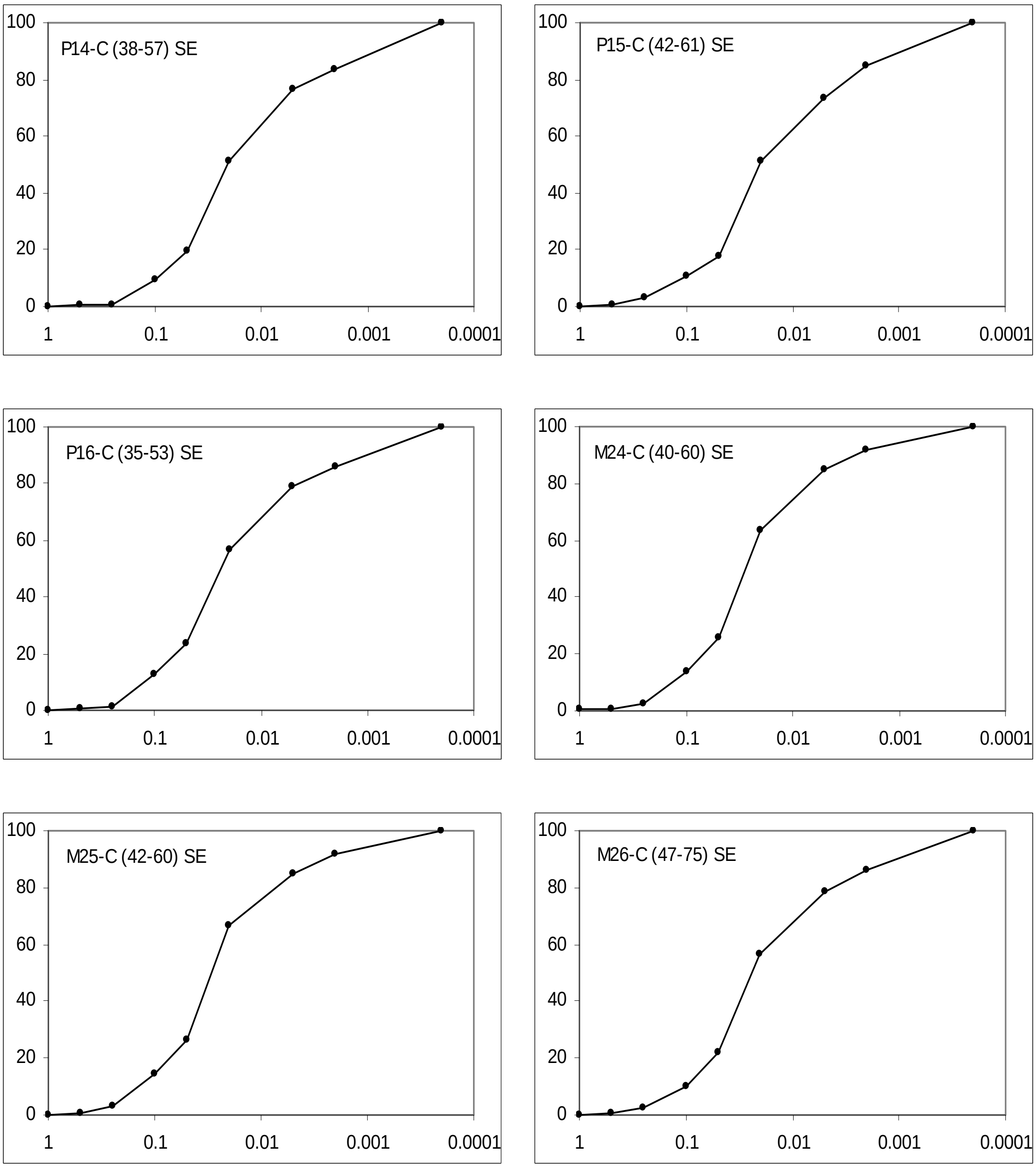


Figure 5.6. Cumulative particle-size curves of loess materials in C horizons (cm depth) in the southeast of the study area. Cumulative particle weights (%) on the Y-axis and particle-size classes (mm) on the X-axis.

5.2.2. Cover soils

In the western strip of the study area (530-650 m.a.s.l.), under sub-humid to humid climate with more than 800 mm rainfall per year, moderately thick to thick mollic epipedons have formed under dense Chaco forest. The moisture regime is ustic bordering udic. This has promoted clay illuviation and the formation of Bt horizons, which in general just meet the diagnostic requirements for argillic horizon. As a reflection of the former, dominant soils are Argiustolls (57%) with Pachic and/or Udic subgroups. Subordinated soils are Haplustolls exhibiting frequently Bt horizons. Fine silty is the most frequent particle-size family (79%). According to the WRB classification, dominant soils are Phaeozems (71%), followed by Luvisols (29%) (Table 5.1).

In the central strip (470-560 m.a.s.l.), under sub-humid to semiarid climate with 600-800 mm rainfall per year, clay illuviation is restricted and incorporation of organic matter in the A horizon is less abundant. Soil profiles are dominantly of ABwC or AC types. Soils are mainly Typic Haplustolls with Bw horizons (40%) and Entic Haplustolls without Bw horizons (27%). Fine silty is the most common particle-size family (67%). Siltic Phaeozems represent 93% of the soils (Table 5.2).

In the eastern strip (405-450 m.a.s.l), under semiarid climate with less than 600 mm rainfall per year, low moisture limits soil development to the formation of AC and ABwC profiles. Clay illuviation is no longer taking place and mollic horizon formation is at its limit. Dominant soils are Haplustolls (88%), mainly Torriorthentic Haplustolls without Bw horizons (41%) and Aridic Haplustolls with Bw horizons (35%). Coarse silty is the most frequent particle-size family (76%). Siltic Phaeozems are still dominant (59%), while the presence of Silti-Eutric Cambisols (41%) indicates the effect of decreasing rainfall (Table 5.3).

In conclusion, there is a clear rainfall-controlled soil development trend from drier east to moister west (Figure 5.7). Typically, the dry end-members of the climosequence in the east are Aridic and Torriorthentic Haplustolls, followed by Typic and Entic Haplustolls in the sub-humid central part, while the moist end-members in the west are Udic and Pachic Argiustolls. Paralleling this climatic soil sequence, there is also a particle-size trend from coarse silty in the east to fine silty in the west, which reflects decreasing wind competence from east to west and subsequent spatial gradation of the westward loess influx. However, the total silt content remains approximately constant throughout the area, while the sand fraction decreases and the clay fraction increases from east to west (Figure 5.7).

Table 5.1. Representative pedons (14) in the western strip (sub-humid to humid).

Site	Area (1)	USDA (2)	WRB (3)	Cover soil (4)	Buried soil (4)	Elevation (5)
P1A	B	T Argiustoll fs	S-C Luvisol Thluv	Bt (13-35)	2Btb (90-165)	640
P2	B	P Argiustoll fs	S-L Phaeozem Thluv	Bt (28-52)	2Btb (97-117)	650
P3B	B	P Argiustoll fs	S-C Luvisol Thcam	Bt (9-50)	2Bwb (118-140)	650
M2	B	U Haplustoll fs	S-L Phaeozem	Bt (48-73)		650
M3	B	T Argiustoll fs	S-L Phaeozem	Bt (35-60)		640
M4	B	T Argiustoll fs	S-C Luvisol Thluv	Bt (15-42)	2Btb (50-60)	650
M9	B	T (P) Haplustoll cl	S Phaeozem	Bw (28-52)		595
M15	B	U (P) Argiustoll fs	S-C Luvisol	Bt (11-50)		595
M28	B	U Haplustoll fs	S Phaeozem	Bt (55-70)		585
P17	R	P (Uo) Haplustoll fs	S-P Phaeozem Thluv	A (0-50)	2Btb (80-125)	530
M17	R	U Argiustoll c	S-L Phaeozem	2Bt (53-80)		550
M18	R	U Argiustoll fs	S-P-L Phaeozem	Bt (57-80)		540
M19	R	P (U) Haplustoll c	S-P Phaeozem	2Bt (54-70)		600
M20	R	P (U) Haplustoll fs	S-P Phaeozem	Bt (75-85)		530

(1) Area B = Burruyacú area (north): pedons are located on alluvial glacis covered by loess in a plain adjacent to a piedmont landscape, with gently undulating topography and 0-2% slope;
Area R = La Ramada area (south): pedons are located on alluvial glacis covered by loess in the distal sector of a piedmont landscape, with flat topography and 0-1% slope.
(2) USDA = USDA Soil Taxonomy (2003); T = Typic, P = Pachic, U = Udic, Uo = Udorthentic; (-) = bordering subgroup; cl = coarse loamy, fs = fine silty, c = clayey; all soils have thermic temperature regime and mixed mineralogy.
(3) WRB = World Reference Base for Soil Resources (1998); S = Siltic, C = Cutanic, L = Luvic, P = Pachic; Thluv = Thaptoluvic, Thcam = Thaptocambic.
(4) Main genetic horizons (depth in cm).
(5) Elevation in m.a.s.l.

Table 5.2. Representative pedons (15) in the central strip (sub-humid to semiarid).

Site	Area (1)	USDA (2)	WRB (3)	Cover soil (4)	Buried soil (4)	Elevation (5)
P6B	A	T Haplustoll cl	S Phaeozem Thcam	Bw (28-51)	2Bwb (70-138)	500
P7B	A	E Haplustoll cl	S Phaeozem Thcam	A (0-68)	2Bwb (90-140)	495
P9B	A	T Haplustoll fs	S Phaeozem	Bw (29-72)	2Bwb (110-135)	560
M1	A	T Haplustoll cl	S Phaeozem	Bw (32-49)		500
M5	A	C Haplustoll fs	S Phaeozem	2Bt (30-60)		500
M6	A	P Haplustoll fs	S Phaeozem	2Bw (40-65)		500
M7	A	P Haplustoll fs	S Phaeozem	Bt (32-50)		500
M8	A	T Haplustoll fs	S Phaeozem	Bw (37-60)		495
M16	A	T Haplustoll fs	S Phaeozem	Bt (32-42)		495
P10	V	E Haplustoll fl	S Phaeozem Thluv	A (0-38)	2Btb (88-128)	480
P11	V	E Haplustoll fs	S Phaeozem Thluv	A (0-34)	2Btb (100-130)	480
P12	V	E Haplustoll fs	S Phaeozem Thluv	A (0-37)	2Btb (90-137)	480
M21	V	T Haplustoll fs	S Phaeozem	Bw (42-60)		470
M22	V	T Haplustalf c	S-C Luvisol	2Bt (33-60)		480
M23	V	P Argiustoll fs	S-L Phaeozem	Bt (34-63)		475

(1) Area A = La Argentina area (north): pedons are located on alluvial flats covered by loess in a plain landscape, with flat to slightly undulating topography and 0-1% slope;
Area V = La Virginia area (south): pedons are located on alluvial glacis and flats covered by loess in a plain landscape, with flat topography and 0-1% slope.
(2) USDA = USDA Soil Taxonomy (2003); T = Typic, C = Cumulic, E = Entic, P = Pachic; cl = coarse loamy, fl = fine loamy, fs = fine silty, c = clayey; all soils have thermic temperature regime and mixed mineralogy.
(3) WRB = World Reference Base for Soil Resources (1998); S = Siltic, C = Cutanic, L = Luvic, P = Pachic; Thluv = Thaptoluvic, Thcam = Thaptocambic.
(4) Main genetic horizons (depth in cm).
(5) Elevation in m.a.s.l.

Table 5.3. Representative pedons (17) in the eastern strip (semiarid).

Site	Area (1)	USDA (2)	WRB (3)	Cover soil (4)	Buried soil (4)	Elevation (5)
P4A	G	Tf Haplustept cs	S-E Cambisol Thcam	A (0-41)	3Bwb (90-150)	440
P5A	G	P (To) Haplustoll cl	S-P Phaeozem	A (0-31)	3Bwkb (110-160)	435
P8B	G	A Haplustoll cs	S Phaeozem Thcam	Bw (11-40)	2Bwb (52-120)	440
M10	G	A Haplustoll cs	S-E Cambisol	Bw (18-59)		440
M11	G	A Haplustoll cs	S-E Cambisol	Bw (22-64)		440
M12	G	A Haplustoll cs	S-E Cambisol	Bw (17-42)		435
M13	G	Tf Haplustoll fs	S Phaeozem	Bt (24-54)		450
M14	G	A Haplustoll cs	S Phaeozem	Bw (25-47)		450
M27	G	A Haplustoll cs	S Phaeozem	Bw (30-56)		450
M29	G	To Haplustoll cs	S-E Cambisol	A (0-30)		445
P13	P	P (A) Haplustoll cs	S-P Phaeozem Thcam	A (0-60)	2Bwb (80-128)	410
P14	P	To Haplustoll fs	S Phaeozem Thcam	A (0-38)	2Bwb (82-131)	415
P15	P	To Haplustoll cs	S Phaeozem Thcam	A (0-25)	2Bwb (61-130)	405
P16	P	To Haplustoll fs	S Phaeozem Thcam	A (0-35)	2Bwb (52-138)	415
M24	P	To Haplustoll cs	S Phaeozem	A (0-23)		415
M25	P	A Haplustept cs	S-E Cambisol	Bw (10-25)		415
M26	P	To Haplustoll cs	S-E Cambisol	A (0-23)		415

(1) Area G = Garmendia area (north): pedons are located on alluvial flats covered by loess in a plain landscape, with flat topography and 0-1% slope;
Area P = Piedrabuena area (south): pedons are located on alluvial flats covered by loess in a plain landscape, with flat topography and 0-1% slope.
(2) USDA = USDA Soil Taxonomy (2003); A = Aridic, P = Pachic, Tf = Torrifluventic, To = Torriorthentic; (-) = bordering subgroup; cl = coarse loamy, cs = coarse silty, fs = fine silty; all soils have thermic temperature regime and mixed mineralogy.
(3) WRB = World Reference Base for Soil Resources (1998); S = Siltic, E = Eutric, P = Pachic; Thcam = Thaptocambic.
(4) Main genetic horizons (depth in cm).
(5) Elevation in m.a.s.l.

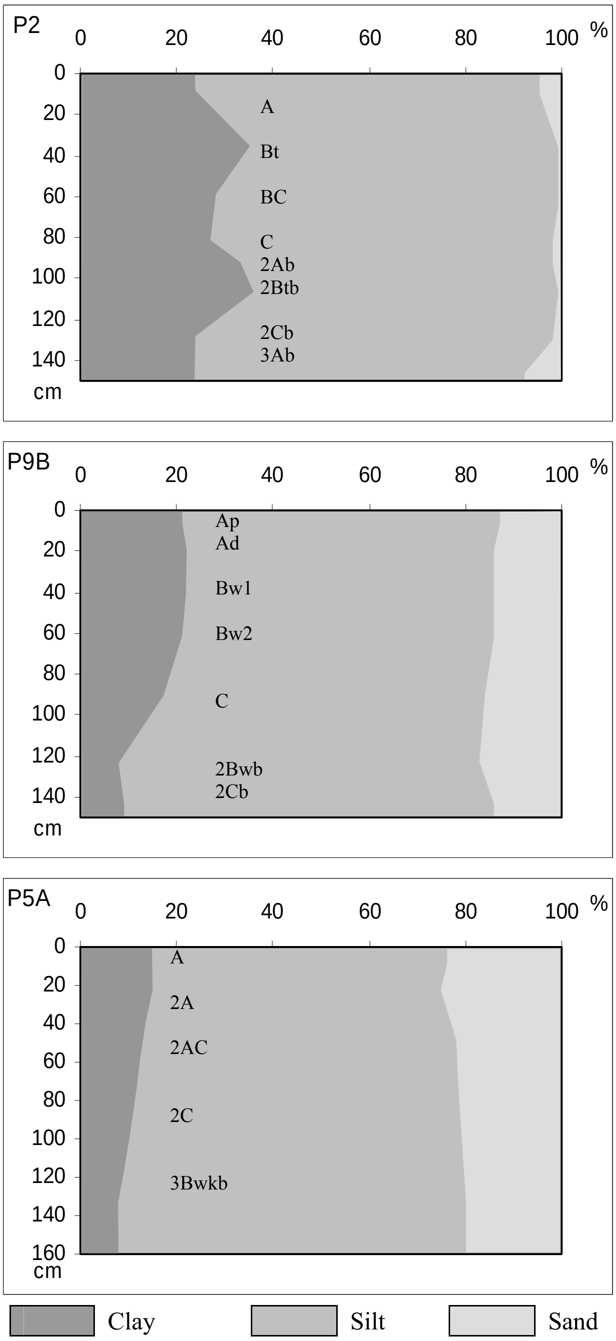


Figure 5.7. Particle-size distributions and genetic horizons of representative pedons from western (P2), central (P9B) and eastern (P5A) strips of the study area.
P2 = Pachic Argiustoll fine silty; Silti-Luvic Phaeozem (Thaptoluvic);
P9B = Typic Haplustoll fine silty; Siltic Phaeozem;
P5A = Pachic (Torriorthentic) Haplustoll coarse loamy; Silti-Pachic Phaeozem.

5.2.3. Buried soils

Buried horizons or complete buried profiles occur in the upper two meters of the soil mantle throughout the study area. They were detected in all deep pedons, mainly from 70-80 cm downwards. Buried soils could seldom be identified in the smaller pedons (supporting profiles <1m deep), but their generalized presence can be inferred from the deep pedons. Compared to the overlying C or AC horizons, the buried

A and B horizons show darker color, higher organic matter content and stronger structural development. The nature of the buried subsoil horizons varies significantly from west to east, with Btb horizons dominating in the western strip, Btb and Bwb horizons in equal proportion in the central strip, and only Bwb horizons in the eastern strip. Thus, the buried soil sequence parallels the cover soil sequence, with comparable members of decreasing development degree from moister west to drier east, as if the current rainfall gradient would have been the same during the past soil formation periods, intercalated between loess influx periods. Frequently, buried soils lack distinct, morphologically recognizable A horizons, in a fashion similar to features observed in the inter-Andean valley of Tafi-del-Valle (Zinck & Sayago, 1999, 2001).

Selected buried soil horizons, all developed from loess parent material, were dated by radiocarbon method and provided the following ages:

- Northwest of the study area, Burruyacú, Finca Lobo, in the piedmont of Sierra de El Campo: a 2Ab horizon (91-97 cm) was dated 2840 ± 60 BP and a deeper 3Ab horizon (140+ cm) was dated 3780 ± 40 BP (Profile P2).
- North-central part of the study area, La Argentina, in the fluvio-eolian plain: a 2Bwb horizon (90-118 cm) was dated 3040 ± 40 BP (Profile P7B).
- Northeast of the study area, Gob. Garmendia, Campo Elías, in the fluvio-eolian plain: a 3Bwb horizon (117-150 cm) was dated 6290 ± 120 BP (Profile P4A).

- Southwest of the study area, La Ramada, in the transition between piedmont and plain: a 2Btb horizon (80-113 cm) was dated 5640 ± 40 BP (Profile P17).
- South-central part of the study area, La Virginia, in the fluvio-eolian plain: a 2BAb horizon (57-88 cm) was dated 4670 ± 60 BP (Profile P10).
- Southeast of the study area, Gob. Piedrabuena, Finca Blasco, in the fluvio-eolian plain: a 2Ab horizon (57-82 cm) was dated 2660 ± 50 BP (Profile P14).

In the northern transect, the main buried soils occur at similar depths, starting at about 90 cm at all three sites, although they are 10 km apart from each other (Figure 5.8). Cover and buried soils are clearly more developed, with Bt horizons, in the moist west. In the drier central and eastern parts of the study area, the cover soils have AC profiles, while the buried soils have Bw horizons but lack distinct A horizons. The last major period of loess influx started around 3000 BP (2840-3040 BP) in the central and western parts. At roughly comparable depths, a buried 3Bwb horizon (117-150 cm) in the east dates 6290 BP, while a 3Ab horizon (140-155 cm) in the west dates 3780 BP, suggesting that loess deposition was more active during the Upper and Middle Holocene in the west, closer to the sub-Andean mountain ranges.

In the southern transect, the cover soils are slightly less thick (about 60-80 cm) and less developed (AC profiles) than in the northern transect (Figure 5.9). Buried soils have Bt horizons in the western and central sectors, and Bw horizons in the eastern sector. At roughly comparable depths (below 60-80 cm), the upper horizons of the buried soils date 2660 BP in the east, 4670 BP in the center and 5640 BP in the west, suggesting that during the Upper and Middle Holocene loess influx was more active in the east than in the west of the area.

The dated horizons spanning 6290-2660 BP indicate that soil formation took place during the Middle and Upper Holocene, generating soils from loess deposits anterior to the most recent and last loess mantle deposition bearing the current cover soils. In general, buried soils show stronger development (ABwC and ABtC profiles) than cover soils (AC and ABwC profiles) because of longer development time and/or moister climate. The last loess influx suggests a drier interval separating the current and former soil formation periods. A similar rainfall gradient from drier east to moister west equally influenced differential soil development during the consecutive soil formation periods. There is no strict correlation between radiocarbon age and depth of the dated buried horizons, indicating that loess accretion did not affect all areas at the same time and/or at the same rate of deposition. Considering the depth-age relationship of the buried horizons, it appears that loess influx increased over time from east to west along the northern transect, while the opposite seems to have happened along the southern transect. A broader analysis of the paleoenvironmental evolution of the area, based on additional stratigraphic and radiocarbon data, is presented in Chapter 3.

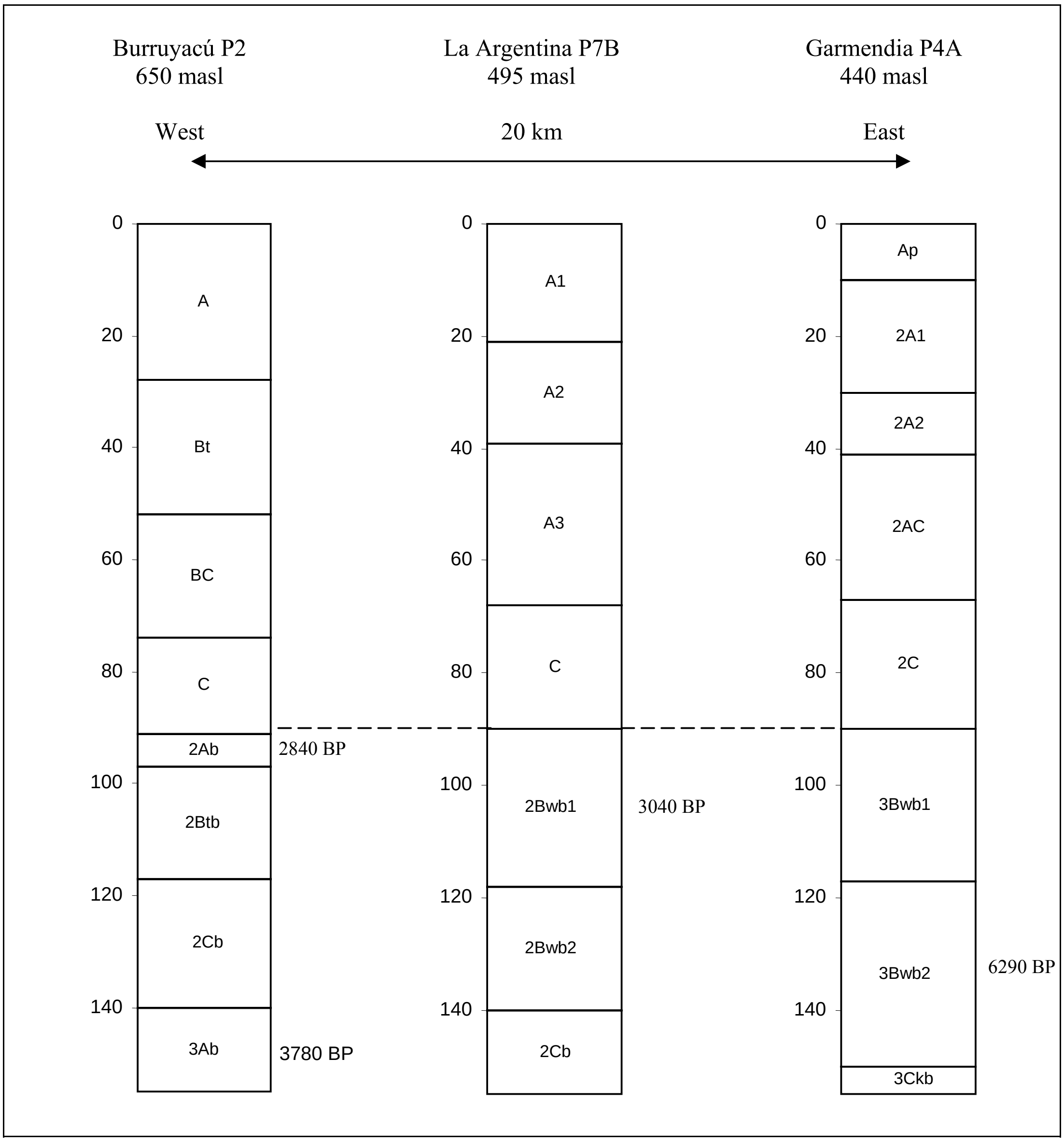


Figure 5.8. Radiocarbon dates of buried horizons along the northern transect (in years Before Present).

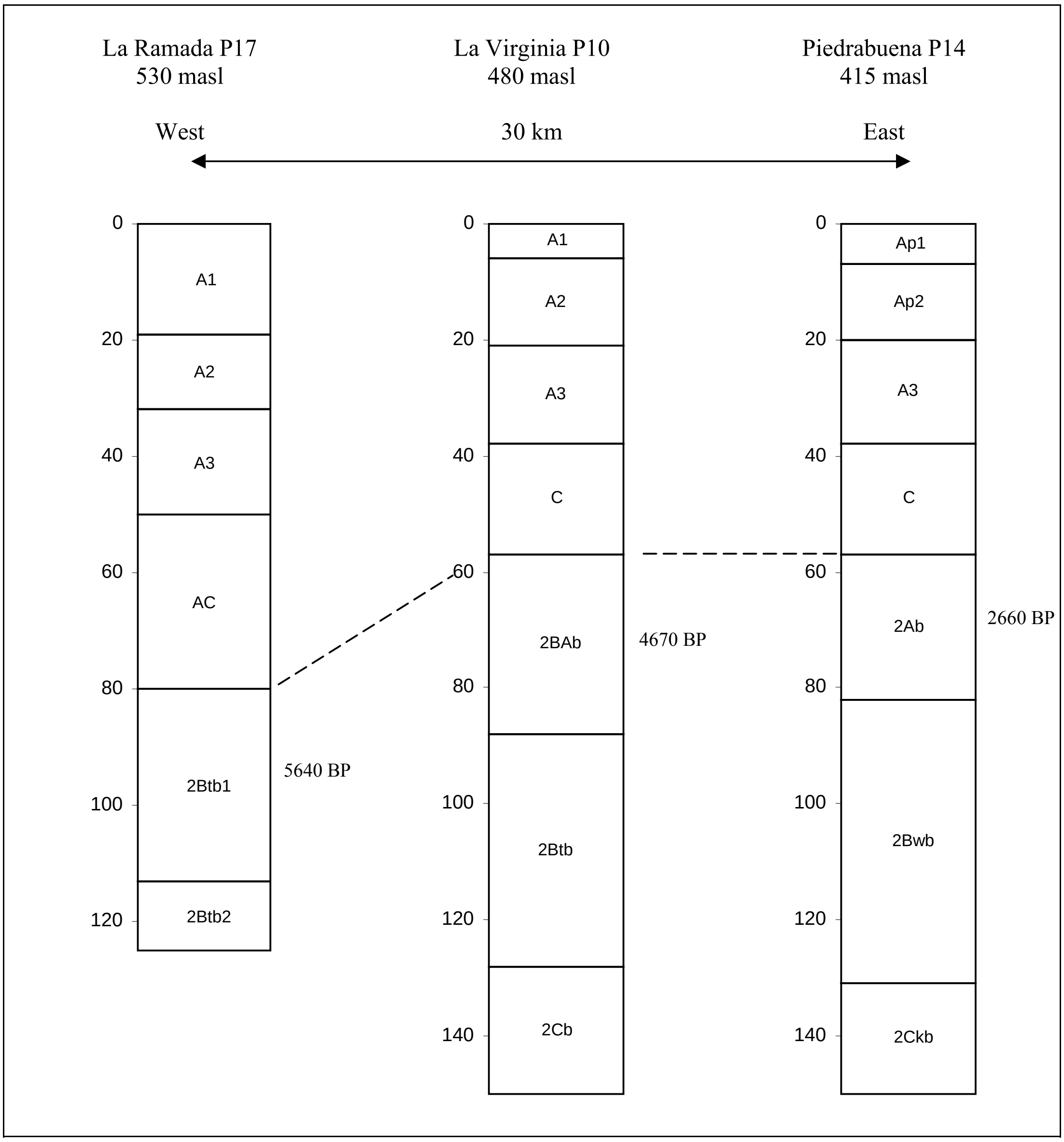


Figure 5.9. Radiocarbon dates of buried horizons along the southern transect (in years Before Present).

5.3. SOIL PROPERTIES

Detailed soil information including profile descriptions and analytical data is reported in Chapter 13. Relevant field and laboratory data describing the morphological, physical and chemical soil properties were averaged and summarized to analyze and highlight soil variations vertically as a function of horizon distribution with depth, and horizontally as a function of spatial distribution between the moist west and the dry east. Properties selected for this purpose include color, texture, structure, sand, silt, clay, bulk density, organic carbon, soil reaction, exchangeable calcium and cation exchange capacity. Topsoil properties in particular are assessed in detail in Chapter 10, with special reference to physical soil degradation and fertility depletion.

Data were aggregated in two ways: (1) per genetic horizons and (2) per rainfall strips. Conventional distinction was made between A, B and C horizons in cover soils and buried soils. Although surface horizons are mainly mollic epipedons, several kinds of A horizons were considered to differentiate between upper forest topsoil (Af), upper farmed topsoil (Ap), plow-pan (Ad) and lower topsoil in general

(A). Subsurface layers include Bw horizons, corresponding mainly to cambic horizons differentiated from parent material by color and structure, and Bt horizons some of which meet the requirements set for argillic horizon. To analyze the effect of the rainfall gradient on soil development and the effect of wind strength on loess influx, data were arranged into three strips from east to west, including a semiarid strip in the east, a sub-humid to semiarid strip in the central part and a sub-humid to humid strip in the west of the study area, in the same fashion as used above (section 5.2.2) for the analysis of the spatial distribution of pedotaxa (Tables 5.4, 5.5, 5.6 and Tables 5.10 to 5.15 in Appendix).

When considering the soil cover as a whole to about two meter depth, regardless of soil stratification and horizonation, the values of some properties appear to be remarkably constant throughout the area, while others vary slightly. Highly generalized benchmark values at regional scale include 65% silt content, bulk density of 1.25 Mg m^{-3}, soil reaction of pH 7 and CEC of 20 cmol(+) kg^{-1} soil. In contrast, the average organic carbon content in the soil mantle decreases from 1.35% in the west to 0.9% in the east, while the overall clay content decreases in the same direction from 26% to 22% to 15% in the three study strips, respectively.

5.3.1. Morphological properties

All soils have formed from Holocene loess parent material. They are moderately developed and moderately thick to thick. All soils are stratified, with multiple small lithological changes, and include frequently one or more buried horizons or complete buried soils. Periodic loess deposition has caused rhythmic soil development.

In general, A horizons are very dark brown, B horizons dark brown and C horizons brown to dark yellowish brown. Vertical color sequences clear up towards the east and in the buried soils. Common structure in the solum is moderate medium sub-angular blocky. Bt horizons have frequently a weak prismatic structure breaking down into blocky. C layers are massive to very weakly structured. The presence of lime in the form of powder and nodules of calcium carbonate is uncommon and occurs mainly in the subsoils and buried horizons of the drier northeast and north-center.

5.3.2. Physical properties

In general, the silt fraction constitutes 60-70% of the particle composition, with dominantly coarse and medium silt (50-60%). The most abundant fraction is coarse silt (0.05-0.02 mm), accounting for 30-40% of the particle composition, with a range of 24-54%. The coarse silt mode dominates all over the area, representing a remarkable feature of sedimentological uniformity. In some C horizons, values of up to 80% silt were registered. The sand fraction is mainly fine and very fine sand. The dominant textural class is silt loam. Loess sediments are finer in the west than in the east. Particle-size families are mainly coarse silty in the east and fine silty in the west, after adding the very fine sand to the silt fraction. There are frequent small vertical variations in silt content.

Bulk density is in general moderately high (1.2-1.4 Mg m^{-3}) throughout the soil cover, with exception of the upper topsoil. Loess material tends naturally to be dense because of high silt content and low structural stability. Af and Ap horizons have the lowest bulk density values (1-1.1 Mg m^{-3}), while Ad horizons (plow-pans) have the highest values (1.3-1.4 Mg m^{-3}). Buried soils are denser than cover soils.

The moisture equivalent, an approximation of water retention at field capacity at about one atmosphere, is in general 20-25% in silt loam materials and 25-35% in silty clay loam materials (data in Appendix 13.2). The effective moisture in the soil at the time of sampling was determined at a selected number of sites during the dry season. Data (70%) represent the situation in the second half of April (1997), corresponding to the beginning of the dry season when average monthly rainfall is 50 mm in the west (Burruyacú) and 40 mm in the east (Garmendia). The rest of the data (30%) represent the situation in the second half of June (1996), corresponding to the middle of the dry season when average monthly rainfall is 10 mm in the west and 5 mm in the east. In the center and east of the study area, the effective moisture in soils under Chaco forest during the dry season can be as low as half the moisture equivalent in the topsoil and even lower in the deeper horizons, while the difference is less pronounced in the west of the area. The gap between moisture equivalent and effective moisture is narrower in cultivated soils than in forest soils, especially in the west where the real moisture content in the soil equals practically the moisture retention capacity. In the central and eastern parts of the area, some sites show significant moisture gaps from topsoil downwards, while others are moisture-deficient only in depth. These results are in agreement with some of the conclusions reached by Zuccardi et al. (1993) through monitoring the soil water dynamics in the same region, especially the difference between forest soils and cultivated soils. The forest cover seems to substantially contribute to depleting the soil moisture during the dry season, while the arable layer in cultivated soils seems to decrease evaporation through the interruption of capillary ascent. Water deficiency, especially in the east, puts at risk farming with annual crops.

5.3.3. Chemical properties

Organic carbon in the upper topsoil (Af and Ap horizons) is in general close to or above 2%, with maxima values of 4-5%. Original A horizons formed under Chaco forest are darker and have more organic matter than cultivated Ap layers, especially in the western strip with on average 4.3% organic carbon in the Af horizon compared to 2.6% in the Ap horizon. This difference tends to attenuate towards the east. In general, organic carbon decreases regularly with depth in spite of the presence of buried A horizons, clearly darker than the overlying C or AC horizons.

In general, pH values are 7-8. Soils are fully base-saturated. Calcium is the dominant exchangeable cation, constituting 60-70% of the CEC in most of the cases, without significant variations between study strips. The range of variation of exchangeable calcium is 56-84% on the basis of 26 horizon averages, regardless of the kind of horizon. CEC varies between 20 and 30 cmol(+) kg^{-1} soil, without conspicuous regional variations. In the few pedons provided with data on exchangeable cations, CEC computed by sum of cations is slightly higher than total CEC. Values recalculated on a clay basis are unusually high, with an average range of variation of 54-190 cmol(+) kg^{-1} clay. Most common values lie between 80 and 120 cmol(+) kg^{-1} clay. As clay content decreases from west to east, CEC on a clay basis increases in the same direction from 77 to 95 to 127 cmol(+) kg^{-1} clay according to the three study strips. High CEC values are related to the presence of zeolites (Zinck et al., in prep.).

Table 5.4. Mean values of selected soil properties in the western strip (14 pedons).

Hor. type	Color moist	Color dry	Text.	Struct.	Sand %	Silt %	Clay %	BD Mg m^{-3}	OC %	pH 1:1 w	Ca exch. cmol kg^{-1}	CECs cmol kg^{-1}	CECc cmol kg^{-1}
Ap	vd(g)b	(g)b	sil	mmsab	14	62	24	1.10	2.61	6.8	17	24	100
Af	vdgb	gb	sil	mmsab	9	66	25	1.06	4.33	7.3	24	30	120
Ad	db	gb	sil	mmplat	14	62	25	1.37	1.50	6.3	14	21	84
A	vdb	b	sil	mmsab	19	58	23	1.22	1.15	6.9	16	19	83
Bw	db	b	sil	mcsab	16	65	21	1.29	0.85	7.1	14	19	90
Bt	(v)db	b	sicl	mp/sab	9	59	32	1.26	0.99	7.1	14	22	69
C	dyb	lb	sil	massive	12	68	20	1.26	0.53	7.3	8	12	60
Ab	vdgb	b	sil	wmsab	2	65	33	1.27	0.64	7.1	10	18	54
Bwb	b	lb	sil	mcsab									
Btb	db	b	sicl	mp/sab	5	64	31	1.36	0.50	7.2	12	19	61
Cb	b	lb	sil	massive	2	74	24	1.28	0.31		9		
Mean					10	64	26	1.25	1.34	7.0	14	20	77

Color: vdgb = very dark grayish brown, vd(g)b = very dark (grayish) brown, gb = grayish brown, (g)b = (grayish) brown, vdb = very dark brown, (v)db = (very) dark brown, db = dark brown, b = brown, dyb = dark yellowish brown, lb = light brown;
Texture: sil = silt loam, sicl = silty clay loam;
Structure: w = weak, m = moderate (first digit); m = medium (second digit), c = coarse; sab =sub-angular blocky, p = prismatic, plat = platy;
BD = bulk density; OC = organic carbon; w = water; Ca exch. = exchangeable calcium; CEC = cation exchange capacity; CECs = CEC per kg soil; CECc = CEC per kg clay.

Table 5.5. Mean values of selected soil properties in the central strip (15 pedons).

Hor. type	Color moist	Color dry	Text.	Struct.	Sand %	Silt %	Clay %	BD Mg m^{-3}	OC %	pH 1:1 w	Ca exch. cmol kg^{-1}	CECs cmol kg^{-1}	CECc cmol kg^{-1}
Ap	vdb	(g)b	sil	mfsab	16	60	24	1.12	1.99	6.5	16	24	100
Af	vdb	(g)b	sil	mmsab	12	60	29	1.12	2.62	5.7	18	29	100
Ad	vd(g)b	b	sil	mcab	19	56	25	1.28	1.50	7.0	16	24	96
A	vdb	gb	sil	mmsab	22	57	21	1.24	1.20	7.2	14	20	95
Bw	db	b	sil	mmsab	19	63	18	1.14	0.67	7.0	14	20	111
Bt	db	b	sicl	mcsab	15	57	29	1.27	0.85	7.7	18	26	90
C	(d)b	(l)b	sil	wmsab	23	60	17	1.24	0.34	7.2	12	16	94
Ab	vdgb	pb	sil	mfsab	12	61	28	1.33	0.31	6.8		19	68
Bwb	b	lb	sil	wmsab	24	63	13	1.33	0.13	7.9	30	17	130
Btb	b	lb	sicl	mp/sab	9	62	28	1.36	0.17	7.3	12	20	71
Cb	sb	lb	sil	wmsab	12	73	15	1.39	0.09	7.8	12	18	120
Mean					17	61	22	1.26	0.90	7.1	16	21	95

Color: vdgb = very dark grayish brown, vd(g)b = very dark (grayish) brown, gb = grayish brown, (g)b = (grayish) brown, vdb = very dark brown, db = dark brown, (d)b = (dark) brown, sb = strong brown, b = brown, lb = light brown, (l)b = (light) brown; pb = pale brown;
Texture: sil = silt loam, sicl = silty clay loam;
Structure: w = weak, m = moderate (first digit); f = fine, m = medium (second digit), c = coarse; sab = sub-angular blocky, ab = angular blocky, p = prismatic;
BD = bulk density; OC = organic carbon; w = water; Ca exch. = exchangeable calcium; CEC = cation exchange capacity; CECs = CEC per kg soil; CECc = CEC per kg clay.

Table 5.6. Mean values of selected soil properties in the eastern strip (17 pedons).

Hor. type	Color moist	Color dry	Text.	Struct.	Sand %	Silt %	Clay %	BD Mg m^{-3}	OC %	pH 1:1 w	Ca exch. cmol kg^{-1}	CECs cmol kg^{-1}	CECc cmol kg^{-1}
Ap	(v)db	b	sil	mmsab	18	65	17	1.13	1.79	7.0	15	21	124
Af	vdb	(v)dgb	sil	mfsab	19	65	16	1.08	2.00	6.6	14	22	138
Ad	db	dgb	sil	mmplat	23	63	14	1.33	1.12	6.4	10	17	121
A	db	b	sil	mmsab	18	65	17	1.18	1.33	7.2	15	21	124
Bw	(d)b	b	sil	mmsab	17	67	16	1.15	0.94	7.0	15	20	125
Bt	sb	sb	sil	mmsab	17	64	17	1.20	1.11		14	21	124
C	b	lb	sil	wmsab	21	66	13	1.24	0.40	7.2	11	16	123
Ab	b	b	sil	mfsab	14	67	19	1.32	0.25	6.8	11	15	79
Bwb	sb	lb	sil	wp/sab	16	70	14	1.32	0.20	7.6	20	17	121
Btb													
Cb	b	lb	sil	wfsab	14	77	10	1.34	0.12	8.1	19	19	190
Mean					18	67	15	1.23	0.93	7.1	14	19	127

Color: (v)dgb = (very) dark grayish brown, dgb = dark grayish brown, vdb = very dark brown, (v)db = (very) dark brown, db = dark brown, (d)b = (dark) brown, sb = strong brown, b = brown, lb = light brown;
Texture: sil = silt loam;
Structure: w = weak, m = moderate (first digit); f = fine, m = medium (second digit); sab = sub-angular blocky, p = prismatic, plat = platy;
BD = bulk density; OC = organic carbon; w = water; Ca exch. = exchangeable calcium; CEC = cation exchange capacity; CECs = CEC per kg soil; CECc = CEC per kg clay.

5.3.4. Mineralogical properties

Clay minerals were determined at two sites provided with radiocarbon dates: site P2 in Burruyacú, northwest of the area, and site P13 in Piedrabuena, southeast of the area. At both sites, there is a common mineral pool including illite, kaolinite and smectite (Tables 5.7 and 5.8). Illite is the dominant mineral in all cases, usually followed by kaolinite. In all horizons, quartz and feldspars are present in weak to moderate proportions. Thus, clay mineralogy is rather uniform throughout the area.

At site P2, clay mineral association in the buried soil includes illite, kaolinite, smectite, chlorite-vermiculite and chlorite, decreasing in this order, in the two tested 2Btb and 2Cb horizons (Table 5.7). These horizons have formed between 3780 BP and 2840 BP, as can be inferred from the age of an immediately underlying 3Ab horizon and an immediately overlying 2Ab horizon The C horizon of the cover soil shows the same mineral association as the buried soil in spite of the lithological discontinuity separating both, while an overlying Bt horizon contains only illite with some kaolinite. This suggests that the loess influx from which the cover soil has formed started by reworking material from the buried soil before being fed by new deposits with different mineralogy. The similarity in mineral composition between the cover and buried C horizons may also be an indication that both had a common source of inherited minerals.

Table 5.7. Clay mineralogy at site P2 in Burruyacú, northwest of the study area.

Depth (cm)	Horizon	Clay minerals	^{14}C date
0-28	A		
28-52	Bt	I>>K	
52-74	BC		
74-91	C	I>K>S=Mx>Ch	
91-97	2Ab		2840 BP
97-117	2Btb	I>K>S=Mx>Ch	
117-140	2Cb	I>K>S=Mx>Ch	
140+	3Ab		3780 BP

I = illite, K = kaolinite, S = smectite, Ch = chlorite, Mx = regular chlorite-vermiculite.

At site P13, clay mineral association in the buried soil includes illite, smectite and kaolinite, in this order of importance, in the two tested 2Bwb1 and 2Cb horizons (Table 5.8). A 2Ab horizon (57-82 cm) dated at a neighboring site (P14) gave 2660 BP, thus an age similar to the age of the 2Ab horizon of site P2 at similar depth. The mineral association of the buried soil is found back in the overlying C horizon of the cover soil, a fact that suggests reworking of the buried soil in the initial phase of the upper loess deposition, while the cover soil bears an association of illite, kaolinite, chlorite-vermiculite, smectite and chlorite in this order. Thus, the clay mineral profile at site P13 is the reverse of the clay mineral profile at site P2.

Table 5.8. Clay mineralogy at site P13 in Piedrabuena, southeast of the study area.

Depth (cm)	Horizon	Clay minerals	^{14}C date
2-0	Oi		
0-8	A1		
8-28	A2	I>K>Mx>>S=Ch	
28-60	A3		
60-80	C	I>>K=S	2660 BP(1)
80-106	2Bwb1	I>S>K	
106-128	2Bwb2		
128-153	2Cb	I>S>K	

I = illite, K = kaolinite, S = smectite, Ch = chlorite, Mx = regular chlorite-vermiculite;
(1) Radiocarbon date determined at neighboring site P14 in a 2Ab horizon (57-82 cm).

There is no difference in clay mineral composition between parent material and overlying genetic horizon in both buried soils. Horizons 2Btb and 2Cb in pedon P2 have the same association of illite>kaolinite>smectite=chlorite-vermiculite>chlorite. Likewise in pedon P13, horizons 2Bwb1 and 2Cb have the same association of illite>smectite>kaolinite. This suggests that soil development did not generate sensible clay differentiation from the original minerals of the parent material and that clay minerals are mainly inherited from the source rocks and sediments from which loess has built up.

In an exploratory study to identify sites suitable for making red pottery, Vece et al. (1987) found that the association of illite-kaolinite (+chlorite) was dominant in the west of the region, while smectite was more abundant in the east. They considered that kaolinite was unlikely to form under the current climate and that clay minerals were mainly inherited from the rocks outcropping in the west. The sandstones of the Río Loro formation would be the source of the association illite-kaolinite and the pelites of the Río Salí formation would be the source of smectite.

These findings agree with our conclusion that clay minerals in the area are rather inherited from parent material than produced in-situ by pedogenic transformation. However, no clear-cut spatial differentiation could be inferred from the minerals identified in pedons located at the four corners of the study area. The association illite-kaolinite-smectite dominates in the northwest (P2), but also in the cover soil of the southeast (P13). The dominant association throughout the area seems to be illite-smectite-kaolinite, with small spatial variations in abundance of the components, but without significant differences between parent materials and genetic horizons, between kinds of genetic horizons and between cover and buried soils (Table 5.9). The relative abundance of kaolinite and smectite may reflect spatial differences in soil moisture, in particular between the moister northwest and the drier rest of the study area.

Because of high CEC values on a clay basis, with common values of 120-150 cmol per kg clay, further investigation in clay mineralogy was conducted leading to the identification of zeolites, with possibly the contribution of the fine silt fraction to CEC (Zinck et al., in prep.). Zeolites may be related to volcanic ash mixed with the loess material.

Table 5.9. Clay mineralogy at selected sites in the northeast, south-center and southwest of the study area.

Pedon-area	Depth (cm)	Horizon	Clay minerals
P4A-northeast	30-41	2A2	I>S>>K
	67-90	2C	I=S>K>Ch
	117-150	3Bwb2	I>S>>K
P10-south-center	38-57	C	I=S>>K
	88-128	2Btb	S>I>>K
	128-150	2Cb	I>S>K
P17-southwest	32-50	A3	I>S>K
	113-125	2Btb2	I>S>K

I = illite, K = kaolinite, S = smectite, Ch = chlorite.

5.4. CONCLUSION

Spatial differentiation of the soil cover in the study area is mainly related to a difference in the degree of soil development that follows the rainfall gradient from drier east to moister west. In the west, clay illuviation takes/took place, leading to the formation of weakly to moderately developed Bt horizons, just meeting the minimum requirements for argillic horizon. Udic and Pachic Argiustolls are the dominant soils. In the east, rainfall scarcity prevents clay illuviation to occur and limits soil development to the formation of weak Bw (cambic) horizons. Aridic and Torriorthentic Haplustolls are the dominant soils. In the central part of the study area, soil development is intermediate between the two former, with the formation of Bw and weak Bt horizons. Haplustolls are the dominant soils with a variety of subgroups. The topsoil throughout the area is mollic, but mollic epipedons are clearly more developed in the west than in the east; they are darker and frequently thick enough to be qualified as pachic.

In spite of property modifications introduced by soil development, all soils throughout the area still reflect the background properties derived from loess, such as particle distribution with high proportion of silt, moderately high bulk density due to the natural tendency of loess material to densify, high cation exchange capacity and dominance of exchangeable calcium. Everywhere soils are strongly stratified with frequent small lithological changes and the occurrence of buried horizons or complete buried soils. From the dated layers, the loess blanket that covers uniformly the area spans the period of the Upper and Middle Holocene. At similar depths, the age of the dated materials is relatively variable, indicating that the same areas were alternatively exposed to deflation and deposition.

5.5. REFERENCES

FAO, 1998. World reference base for soil resources. World Soil Resources Reports 84. FAO, ISRIC and ISSS, Rome, Italy.

García, J.R., 1990. Los suelos de la llanura chacopampeana. Genesis, clasificación y fertilidad. Avance Agroindustrial, Octubre de 1990. S.M. de Tucumán, Argentina.

Gomez, L.A., Ferrao, R.F., Casen, M.L., 1992. Carta básica de suelos del Departamento Burruyacú, Provincia de Tucumán. Instituto Nacional de Tecnología Agropecuaria (INTA), Centro de Investigaciones de Recursos Naturales, Instituto de Suelos. Castelar, Argentina.

INTA, 1996. Atlas de suelos de la República Argentina. Instituto Nacional de Tecnología Agropecuaria. Pergamino, Buenos Aires, Argentina.

ITC, 1997. Integrated Land and Water Information System-ILWIS. International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

Soil Survey Staff, 1996. Soil Taxonomy. Soil Conservation Service, US Department of Agriculture. Washington DC, USA.

Soil Survey Staff, 2003. Keys to soil taxonomy. Natural Resources Conservation Service, US Department of Agriculture. Washington DC, USA.

Vece, M.B., Bossi, G.E., Ovejero, R., Apella, M.C., 1987. Mineralogía y composición química de los limos recientes en el Departamento Burruyacú (Provincia de Tucumán). X Congreso Geológico Argentino, San Miguel de Tucumán, Actas II: 47-50.

Zinck, J.A., Sayago, J.M., 1999. Loess-paleosol sequence of La Mesada in Tucumán province, northwest Argentina. Characterisation and paleoenvironmental interpretation. Journal South American Earth Sciences 12: 293-310.

Zinck, J.A., Sayago, J.M., 2001. Climatic periodicity during the late Pleistocene from a loess-paleosol sequence in northwest Argentina. Quaternary International 78: 11-16.

Zinck, J.A., Van Reeuwijk, P., Sayago, J.M., Huting, J.R.M. High cation exchange capacity caused by zeolites in loess-derived soils in Tucumán province, northwest Argentina (in prep.).

Zuccardi, R.B., Fadda, G.S., 1972. Mapa de reconocimiento de suelos de la Provincia de Tucumán. Publicación Especial 3. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina.

Zuccardi, R.B., Fadda, G.S., 1985. Bosquejo agrológico de la Provincia de Tucumán. Publicación Miscelánea 86. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina.

Zuccardi, R.B, García, J.R., Sanzano, G.A., Giménez, R., 1993. Dinámica del agua edáfica en dos ecosistemas de la región semiárida tucumana. Actas XII Congreso Latinoamericano de la Ciencia del Suelo, Sevilla, España, pp.151-158.

5.6. APPENDIX: SUMMARY STATISTICS OF SOIL PROPERTIES

Table 5.10. Summary statistics of selected physical soil properties in the western strip.

SAND (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	14	9	14	19	16	9	12	2		5	2
Standard deviation	8.0	6.7	8.5	5.9	13.4	6.8	9.0			3.2	
Confidence interval 0.05	4.7	7.5	11.8	4.7	18.6	4.0	10.1			3.1	
Maximum	27	17	20	26	25	19	18			8	
Minimum	3	5	8	9	6	1	2			1	
No. of samples	11	3	2	6	2	11	3	1	0	4	1

SILT (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	62	66	62	58	65	59	68	65		64	74
Standard deviation	8.6	8.1	4.9	5.1	9.9	8.5	3.5			5.6	
Confidence interval 0.05	5.1	9.1	6.9	4.1	13.7	5.0	4.0			5.4	
Maximum	76	71	65	68	72	69	72			70	
Minimum	50	57	58	54	58	43	65			57	
No. of samples	11	3	2	6	2	11	3	1	0	4	1

CLAY (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	24	25	25	23	21	32	20	33		31	24
Standard deviation	5.9	1.2	3.5	4.0	3.5	6.5	6.7			5.9	
Confidence interval 0.05	3.5	1.3	4.9	3.2	4.9	3.8	7.5			5.8	
Maximum	37	26	27	30	23	47	27			36	
Minimum	17	24	22	18	18	23	14			23	
No. of samples	11	3	2	6	2	11	3	1	0	4	1

B. DENSITY (Mg m^{-3})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	1.10	1.06	1.37	1.22	1.29	1.26	1.26	1.27		1.36	1.28
Standard deviation	0.12	0.16	0.01	0.07	0.01	0.19	0.19			0.17	
Confidence interval 0.05	0.07	0.18	0.01	0.06	0.01	0.15	0.21			0.19	
Maximum	1.31	1.22	1.37	1.32	1.29	1.42	1.46			1.49	
Minimum	0.94	0.91	1.36	1.13	1.28	0.98	1.09			1.17	
No. of samples	11	3	2	6	2	6	3	1	0	3	1

Table 5.11. Summary statistics of selected chemical soil properties in the western strip.

ORG. CARBON (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	2.61	4.33	1.50	1.15	0.85	0.99	0.53	0.64		0.50	0.31
Standard deviation	0.71	1.67	0.08	0.56	0.06	0.79	0.37			0.17	
Confidence interval 0.05	0.42	1.89	0.12	0.44	0.08	0.47	0.41			0.16	
Maximum	3.47	5.67	1.56	1.92	0.89	3.03	0.94			0.72	
Minimum	1.56	2.46	1.44	0.5	0.81	0.36	0.23			0.32	
No. of samples	11	3	2	6	2	11	3	1	0	4	1

SOIL REACTION (pH)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	6.8	7.3	6.3	6.9	7.1	7.1	7.3	7.1		7.2	
Standard deviation	0.7	0.1	0.6	0.3		0.4	0.1			0.1	
Confidence interval 0.05	0.5	0.2	0.8	0.3		0.3	0.1			0.1	
Maximum	7.6	7.4	6.7	7.4		7.6	7.3			7.2	
Minimum	5.7	7.2	5.9	6.5		6.4	7.2			7.1	
No. of samples	7	2	2	5	1	7	3	1	0	3	0

CALCIUM (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	17	24	14	16	14	14	8	10		12	9
Standard deviation	4	5		1	1	7	2			3	
Confidence interval 0.05	3	6		2	1	5	2			3	
Maximum	24	27		17	14	25	10			14	
Minimum	11	18		15	13	9	6			9	
No. of samples	6	3	1	2	2	6	3	1	0	4	1

CEC (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	24	30	21	19	19	22	12	18		19	
Standard deviation	6	4	6	4	4	6	3			5	
Confidence interval 0.05	3	5	8	3	5	3	3			5	
Maximum	33	32	25	24	21	30	14			23	
Minimum	15	25	17	13	16	14	9			12	
No. of samples	11	3	2	6	2	11	3	1	0	4	0

Table 5.12. Summary statistics of selected physical soil properties in the central strip.

SAND (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	16	12	19	22	19	15	23	12	24	9	12
Standard deviation	6.3	10.6	13.9	7.6	4.6	5.4	6.1		11.8	2.1	1.7
Confidence interval 0.05	3.6	14.7	12.2	5.2	3.7	4.7	4.0		13.4	2.4	1.7
Maximum	27	19	40	38	27	20	36		38	11	13
Minimum	3	4	2	15	15	8	15		17	7	10
No. of samples	12	2	5	8	6	5	9	1	3	3	4

SILT (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	60	60	56	57	63	57	60	61	63	62	73
Standard deviation	4.2	2.1	7.1	5.4	4.1	3.9	5.3		14.6	3.2	4.3
Confidence interval 0.05	2.4	2.9	6.2	3.7	3.3	3.4	3.5		16.5	3.6	4.3
Maximum	66	61	64	65	67	61	68		75	64	77
Minimum	50	58	45	47	55	52	51		47	58	67
No. of samples	12	2	5	8	6	5	9	1	3	3	4

CLAY (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	24	29	25	21	18	29	17	28	13	28	15
Standard deviation	8.6	7.8	10.4	4.1	6.5	7.0	4.7		4.0	2.5	5.8
Confidence interval 0.05	4.8	10.8	9.1	2.9	5.2	6.1	3.0		4.6	2.8	5.7
Maximum	47	34	42	26	25	39	26		15	31	23
Minimum	14	23	15	15	6	20	10		8	26	9
No. of samples	12	2	5	8	6	5	9	1	3	3	4

B. DENSITY (Mg m^{-3})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	1.12	1.12	1.28	1.24	1.14	1.27	1.24	1.33	1.33	1.36	1.39
Standard deviation	0.14	0.03	0.18	0.14	0.09	0.13	0.12		0.09	0.13	0.09
Confidence interval 0.05	0.08	0.04	0.18	0.10	0.07	0.13	0.09		0.10	0.14	0.11
Maximum	1.37	1.14	1.43	1.52	1.23	1.44	1.45		1.43	1.49	1.50
Minimum	0.93	1.10	1.04	1.11	1.00	1.13	1.12		1.27	1.24	1.33
No. of samples	11	2	4	8	6	4	7	1	3	3	3

Table 5.13. Summary statistics of selected chemical soil properties in the central strip.

ORG. CARBON (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	1.99	2.62	1.50	1.20	0.67	0.85	0.34	0.31	0.13	0.17	0.09
Standard deviation	0.58	0.45	0.61	0.44	0.20	0.23	0.07		0.08	0.01	0.02
Confidence interval 0.05	0.33	0.63	0.53	0.31	0.16	0.20	0.04		0.09	0.01	0.02
Maximum	3.03	2.94	2.55	1.84	0.94	1.13	0.44		0.19	0.18	0.11
Minimum	1.12	2.30	1.04	0.52	0.42	0.58	0.22		0.04	0.16	0.07
No. of samples	12	2	5	8	6	5	9	1	3	3	4

SOIL REACTION (pH)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	6.5	5.7	7.0	7.2	7.0	7.7	7.2	6.8	7.9	7.3	7.8
Standard deviation	0.3		0.5	0.8	0.6	1.6	0.8		0.9	0.4	0.7
Confidence interval 0.05	0.2		0.6	0.6	0.7	2.2	0.6		1.0	0.4	0.6
Maximum	7.0		7.3	8.2	7.7	8.8	8.3		8.6	7.7	8.7
Minimum	6.0		6.4	6.0	6.5	6.6	6.3		6.9	7.0	7.1
No. of samples	7	1	3	6	3	2	7	1	3	3	6

CALCIUM (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	16	18	16	14	14	18	12		30	12	12
Standard deviation	5	8	6	1	2	4	6		20	1	1
Confidence interval 0.05	3	12	5	1	2	5	4		23	1	1
Maximum	28	24	27	15	17	22	27		53	12	12
Minimum	11	12	13	13	12	14	7		15	11	11
No. of samples	9	2	5	5	5	3	8	0	3	3	4

CEC (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	24	29	24	20	20	26	16	19	17	20	18
Standard deviation	4	9	7	4	2	4	3		3	2	2
Confidence interval 0.05	3	13	6	3	1	3	2		3	2	2
Maximum	36	35	37	24	23	31	20		20	22	21
Minimum	19	22	19	14	19	22	12		15	19	15
No. of samples	12	2	5	8	6	5	9	1	3	3	6

Table 5.14. Summary statistics of selected physical soil properties in the eastern strip.

SAND (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	18	19	23	18	17	17	21	14	16		14
Standard deviation	4.3	4.6		2.2	3.0		3.5		5.4		3.3
Confidence interval 0.05	2.2	5.2		1.4	2.2		1.8		4.0		2.9
Maximum	25	24		21	22		26		27		18
Minimum	10	16		15	12		14		11		11
No. of samples	14	3	1	10	7	1	14	1	7	0	5

SILT (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	65	65	63	65	67	64	66	67	70		77
Standard deviation	3.0	5.9		3.2	3.1		2.3		3.0		4.0
Confidence interval 0.05	1.6	6.6		2.0	2.3		1.2		2.2		3.5
Maximum	70	72		70	72		71		73		82
Minimum	61	61		61	63		63		65		72
No. of samples	14	3	1	10	7	1	14	1	7	0	5

CLAY (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	17	16	14	17	16	17	13	19	14		10
Standard deviation	2.8	4.2		3.8	4.3		2.8		3.6		2.6
Confidence interval 0.05	1.5	4.7		2.3	3.2		1.5		2.7		2.3
Maximum	21	21		22	21		17		19		14
Minimum	12	13		12	9		8		8		7
No. of samples	14	3	1	10	7	1	14	1	7	0	5

B. DENSITY (Mg m^{-3})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	1.13	1.08	1.33	1.18	1.15	1.20	1.24	1.32	1.32		1.34
Standard deviation	0.09	0.11		0.15	0.06		0.12		0.04		0.02
Confidence interval 0.05	0.05	0.12		0.09	0.05		0.08		0.04		0.02
Maximum	1.29	1.20		1.55	1.23		1.51		1.37		1.36
Minimum	1.00	0.99		1.03	1.09		1.13		1.26		1.33
No. of samples	14	3	1	10	6	1	8	1	5	0	3

Table 5.15. Summary statistics of selected chemical soil properties in the eastern strip.

ORG. CARBON (%)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	1.79	2.00	1.12	1.33	0.94	1.11	0.40	0.25	0.20		0.12
Standard deviation	0.49	0.66		0.51	0.34		0.13		0.04		0.05
Confidence interval 0.05	0.26	0.75		0.32	0.25		0.07		0.03		0.04
Maximum	2.79	2.58		2.19	1.56		0.64		0.27		0.17
Minimum	0.96	1.28		0.74	0.50		0.21		0.16		0.06
No. of samples	14	3	1	10	7	1	14	1	7	0	5

SOIL REACTION (pH)	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	7.0	6.6	6.4	7.2	7.0		7.2	6.8	7.6		8.1
Standard deviation	0.6	0.8		0.6	0.2		0.5		0.8		0.5
Confidence interval 0.05	0.4	1.1		0.4	0.2		0.3		0.6		0.4
Maximum	8.0	7.1		8.2	7.1		8.1		8.7		8.6
Minimum	6.2	6.0		6.6	6.8		6.3		6.8		7.3
No. of samples	10	2	1	6	3	0	11	1	7	0	5

CALCIUM (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	15	14	10	15	15	14	11	11	20		19
Standard deviation	4	2		2	2		2		15		7
Confidence interval 0.05	2	3		1	1		1		11		10
Maximum	20	17		17	16		14		49		24
Minimum	8	13		12	12		7		11		14
No. of amples	9	3	1	6	5	1	9	1	7	0	2

CEC (cmol kg^{-1})	Ap	Af	Ad	A	Bw	Bt	C	Ab	Bwb	Btb	Cb
Mean	21	22	17	21	20	21	16	15	17		19
Standard deviation	3	1		2	3		2		1		2
Confidence interval 0.05	2	1		1	2		1		1		1
Maximum	26	22		24	22		19		19		21
Minimum	15	21		18	15		12		16		17
No. of samples	14	3	1	10	7	1	13	1	7	0	5

CHAPTER 6

THE CHACO FOREST

J. Remeijn, L. Neder

6.1. INTRODUCTION

Over the last 25 years, large areas covered with forest were cleared in favor of dry-farming. The type of land management applied in the area, in view of the relief and (changes in) the local climate, caused much degradation in terms of soil erosion and depletion of soil fertility, which resulted in decreased crop productivity and even in crop failures (Clark, 1992; Sayago, 1992). One of the specific objectives of the study is identifying trends in the physical, chemical and biological factors and erosion conditions in the cultivated areas, in comparison to the forested areas that are less influenced by human activities.

6.2. THE CHACO BIOME

6.2.1. Origin of the word Chaco

Chaco is a relatively new name, introduced and largely disseminated during the Spanish conquest and the subsequent colonization period until the late 17^{th} century. According to Tissera (1971), "… regions, whole peoples, ethnic groups that had no idea of such a designation, adopted it through time". Pedro Lozano (1733) defines it etymologically as the constellation of nations that populated the region by that time.

The word Chaco has several meanings derived from its quechua origin, the most widely spread and accepted being: "hunting land" or "place where game animals concentrate". It refers to the crowd that gathered when Indians from various places went hunting vicuñas and guanacos. This gathering is called *Chacu* in quechua language. As numerous aboriginal tribes inhabited the region, they were called chacu after that gathering. The word was later turned into Chaco by the Spaniards.

Although the Chaco is comparable, in some aspects, to other regions of the world, it exhibits characteristics of its own, such as the richness of its forests, the behavior of its fauna and flora, its history and its people, which contribute to give this American region a unique and particular profile.

6.2.2. Variations in the Chaco region

The Chaco region in Argentina can be divided into three main types of vegetation cover according to rainfall amount and distribution (Ragonese & Castiglioni, 1970).

(1) Arid Chaco

The arid Chaco encompasses the southeast of La Rioja province and the northwest of Córdoba province, with 300-500 mm annual rainfall. The forest cover is lower, sparser and less diversified than that of the other Chaco types. Forest productivity is low and continuous dry-farming is restricted by low rainfall. Some authors consider this vegetation type different from the real Chaco forest, while others include it because of similarities in climate, resources, uses, land tenure, flora and fauna (Morello et al., 1985; Karlin & Bronstein, 1986; Karlin et al., 1992).

(2) Semiarid Chaco

The semi-arid Chaco covers part of the provinces of Salta, Formosa, Chaco, Santiago del Estero, northeast of Tucumán and north of Córdoba. Annual rainfall is 500-750 mm. The forest cover is higher, denser and more diverse than in the previous type (Saravia Toledo, 1982).

(3) Humid and sub-humid Chaco

The humid and sub-humid Chaco includes the east of Formosa, Chaco, north of Santa Fe and northwest of Corrientes provinces. Annual rainfall varies from 750 to 1200 mm in contrasting seasons, causing alternating flood and drought periods. Dry-farming of cotton, soybean, corn, beans, among other crops, is possible (Ragonese & Castiglioni, 1970).

6.2.3. Tree species

The Chaco forest varies in height, density and diversity according to water availability. In earlier times, three species of the *Schinopsis* genus and one species of the *Aspidosperma* genus, regionally called quebracho, were dominant. The Chaco is known as the "old country of the quebracho", referring to the giant trees of the Chaco forest that require more than 150 years to reach maturity. The resulting wood is very hard and very resistant, hence the meaning of quebracho or ax-breaker.

The quebracho colorado santiagueño or red quebracho (*Schinopsis lorentzii* Griseb.) is the most characteristic species of the semiarid Chaco. It is a large tree, 20-25 m high, with hard wood of difficult workability (specific weight of 1.17 kg dm^{-3}), suitable for turnery, long lasting in open air and water, and a good support for heavy structures. It has a high tannin content (24% tannin for tannery and 62% pure tannin), but it was not used for that purpose because the quebracho chaqueño has a higher tannin content. It was mainly used for railway sleepers, posts and beams. It is also an excellent fuel because of its good calorific properties. Vegetation easily regenerates from seeds if the area is protected from livestock and rodents. The leaves are very palatable for livestock, a fact that threatens seedling re-growth. The tree is suitable for agro-forestry as it sheds the leaves after spring and allows sunlight to get in.

The quebracho blanco or white quebracho (*Aspidosperma quebracho blanco* Schlecht.) is found throughout the Chaco. It is a 7-25 m high tree, with a long straight stem and wrinkled bark. Wood is heavy (specific weight of 0.85 kg dm^{-3}) and not suitable for carpentry because it tends to lose shape. It is used as fuel because it is excellent as coal. The bark contains tannin and is considered to have medicinal properties. This kind of tree is not good for agro-forestry because the young trees have unsuitable crown shape. It easily regenerates from seeds dispersed by wind or from shoots that originate from wounds on surface roots or from recovery after fire.

The quebracho colorado chaqueño (*Schinopsis balansae*) is found in the humid Chaco plains. In the dry and flat places of the west, there are quebrachos colorados santiagueños (*Schinopsis lorentzii* Griseb. and *Schinopsis quebracho colorado* (Schlecht.) Bark. et Meyer), while the quebracho blanco (*Aspidosperma quebracho blanco* Schlecht.) prevails in the most arid areas of the Chaco. The primitive quebracho forests have been strongly deteriorated by human activities.

In the dry Chaco, the most important and representative trees nowadays are the tacos, from quechua "tacku" that means "the tree" by antonomasia. Spaniards called them algarrobo or carob tree, coming from Arabic "al karob", because of the similarity between the taco and the Mediterranean tree (*Ceratonia siliqua* L.), which also means "the tree". The algarrobo blanco or white carob tree (*Prosopis alba* and *Prosopis chilensis* (Mol.) Stuntz.) and the algarrobo negro or black carob tree (*Prosopis nigra* (Griseb.) Hieron. and *Prosopis flexuosa* D.C.) have replaced the quebrachos because of their capacity to easily adapt to the Chaco environment and because of the large dissemination of their seeds by the livestock. The fruits of these hardwood trees are used for human and livestock feeding. They also adapt very well to sylvo-pastoral use and contribute to sustain the pasture productivity through time.

In the semiarid Chaco in the north, there is a variety of trees including:

- the colorful guayacán (*Caesalpinia paraguariensis* (D. Parodi) Burk.), with small ovoid leaves, pale orange flowers, excellent wood quality, edible fruits for livestock and usable tannin;
- the fragrant palosanto or holy wood (*Bulnesia sarmientoi* Lorentz ex. Griseb.), with larger rounded leaves, white flowers, colorful-striped perfumed wood from which essential oils and organic solvents are extracted;
- the palo borracho (*Chorisia insignis* H.B.K.), with a characteristic bottle-shaped stem and soft light wood used for making washtubs, canoes and musical instruments;
- the brea del agua (*Parkinsonia aculeata* L.), with green stem, wide crown, yellow and red flowers and resistant wood;
- the mora amarilla or yellow blackberry (*Clorophora tinctoria* (L.) Gaud.), with resistant flexible wood;
- the palo blanco (*Calycophyllum multiflorum* Griseb.), with very sweet-smelling yellowish white flowers and cylindrical stem of light-striped resistant and flexible hardwood, from which highly valued straight rounded logs can be obtained;
- the tala or hackberry tree (*Celtis spinosa* Spreng.), with edible orange fruits, preferred by birds, and heavy hardwood;
- the sombra de toro or peje (*Jodina rhombifolia* Hook. et Arn.), with thick foliage in winter, reddish fruits, characteristic rhomboidal leaves, soft wood and oil-producing seeds;
- the chañar (*Geoffrea decorticans* (Gill. ex Hook. et Arn.) Burk.) has a stem with detached bark through which the green log can be seen; it flowers in spring and changes aspect as the flowers become dark yellow; the fruits are edible and good for making syrup; the wood is yellowish white, moderately heavy and with medicinal properties; the rooting system expands horizontally, causing large, dense, thorny shrub patches, difficult to penetrate.

6.2.4. Shrub species

The genus *Acacia* is well represented with several species, such as the tusca (*Acacia aroma* Gill. Ap. H. et A.), with edible fruits; the garabato macho (*Acacia furcatispina* Burkart), with white pompon flowers, famous for its bifid thorns; the garabato hembra (*Acacia praecox* Griseb.), with white pompon flowers, providing forage leaves but with hook-shaped thorns, for which reason it is called uña de gato; and the churqui or espinillo (*Acacia caven* (Mol.) Molina), with straight whitish thorns and yellow pompon flowers. The latter two species provide firewood and posts used in fence building.

Other shrub species are also well distributed, including the tala churqui (*Celtis espinosa* Sprengel), an emergency forage; the brea (*Cercidium praecox* (Ruiz et Pavon) Harms), an important species for gum production; the lata or iscayate (*Mimozyganthus carinatus* (Griseb.) Burk.) from which rods of variable sizes are cut; the pichana (*Cassia aphylla* Cav.) used for house roofing; and the poleo used as an aromatic plant.

6.2.5. Plant indicators of environmental conditions

Plants are good indicators of environmental conditions. For instance, the algarrobo blanco and tala trees indicate good water availability, whereas the chañar and the ancoche (*Vallesia glabra* (Cav.) Link) are known to reflect high water table. The presence or absence of red quebrachos indicates large regional variations in the Chaco environment. The quebracho chaqueño is found only in the sub-humid Chaco, while the quebracho santiagueño grows exclusively in the semiarid Chaco and the horco quebracho appears in the highland Chaco. Quebrachos colorados do not occur in the arid Chaco and the absence of the quebracho blanco indicates the beginning of the shrub-type cover (monte).

When salt concentration in the soil increases, tree species in general disappear but the chañar (*Geoffrea decorticans* (Gill. ex Hook. et Arn.) Burk.) and the brea (*Cercidium praecox* (Ruiz et Pavon) Harms) remain, together with some cactus trees such as the cardón (*Stetsonia coryne* (Salm-Dyck) Britton et Rose), the ucle (*Cereus validus* Haw.) and the quimil (*Opuntia quimilo* K. Schum.), and others such as the sacha rosa (*Quiabentia pflanzii* (Vaup) Berger (*Q. Chacoensis* Bak.)) and the carne gorda (*Maytemes vitis-idea* Griseb.). At high salinity levels, halophyte shrubs typically dominate.

6.2.6. Deterioration of the Chaco forest

The tree and grass layers of the Chaco forest have been intensively exploited. Manual and mechanical tree clearing for the main purpose of promoting agriculture has caused soil degradation and biodiversity loss. Dry-farming of beans, corn, soybean, sorghum, among other annual crops, takes place in large parcels, while orchards with or without irrigation are established around farm houses for family consumption. Because of rainfall scarcity and soil nutrient depletion, cultivated fields are soon abandoned and re-colonized by unproductive woody vegetation.

Most of the dry Chaco area has been deteriorated by excessive tree clearing and over-pasturing. After decimation of the upper tree layers, shrubs and annual herbs take over and bare soil spots (peladares) start appearing, turning the area into a bush cover (fachinal) of low productivity and slow recovery. Bush types vary according to region, land use history and the abundance of certain species to which they owe their names. Chañarales, tuscales, garabatales, quimilares and pichanales are some of the local bush varieties, together with grass species and annual herbs. If land use pressure is very high, the bare soil remains exposed or is colonized by healing species such as *Selaginella sellowii* Hieron., yerba del pollo (*Althernanthera pungens* H.B.K.), verdolaga or purslane (*Portulaca oleracea* L.), solo (*Gomphrena martiana* Guillies ex Moq.) and some others. At best, some tree species are planted, including algarrobo, palosanto (*Bulnesia sarmientoi* Lorentz ex. Griseb.) and some other trees of higher productive value.

6.2.7. Land use changes in the 20th century

In the early 20th century, once Argentina was politically and economically consolidated, appropriation and exploitation of the natural resources, especially the forest, went very fast in the central Chaco region that was already settled by then. Wood was transported to consumption centers by train to make railway sleepers and to feed steam machines. Wooden posts and tannins were required in the cattle expansion area of the Pampa, and rods and props were needed in the grape-growing and wine-making areas, in addition to the generalized firewood and coal extraction throughout the region. This contributed to destroying nearly the whole Chaco forest in only 50 years.

Intensive forest exploitation decreased after the 1950s, which favored the beginning of a slow recovery of the forest biomass, but with less valuable forest species and trees with twisted or diseased stems. Livestock kept demanding additional space, thus steadily contributing to soil degradation and limiting the re-growth of trees. The settlement of agro-industries on the Chaco periphery, including sugar factories in the northwest and tannin and cotton activities in the east, required permanent as well as temporary laborers during harvest periods. Because of depending on extra-regional markets, these agro-industries went into temporal crisis, and this contributed to land use diversification with the introduction of citrus crops and horticulture. In spite of bad labor conditions, crop diversification provided more or less stable work that contrasted with the labor scarcity in the dry Chaco.

In the 1960s and 1970s, cattle raising increased due to relatively favorable prices on the international market. Official research and extension agencies experimented with and supported the dissemination of new technology, mostly of foreign origin. The use of wire fences, bulldozers, herbicides and exotic grasses largely spread throughout the region, and new areas were cleared thanks to generous credit facilities. This activity expanded until the 1980s, advancing from the north of Córdoba toward the south of Santiago del Estero, from the eastern and western semiarid Chaco borders toward the interior, and in scattered fields in the rest of the region.

In the mid 1970s, forest clearing started for the cultivation of dry legumes, such as soybean and dry beans, in the moister sectors of the dry Chaco from Salta to the eastern center of Catamarca, south of Santiago del Estero and north of Córdoba (Parodi, 1978). Farming activities in areas with variable rainfall and soils unsuitable for agriculture caused severe erosion problems. Neither the type of agriculture nor the marketing mechanisms brought sustainable regional development; they focused on short-term profits, mishandling the prices of raw and finished products and causing land speculation. In contrast, irrigated agriculture developed in some sectors, using water from the Dulce and Salado rivers in Santiago del Estero. Also, the eastern part of Tucumán province highly contributed to regional development, including areas irrigated with groundwater.

6.2.8. Current activities

Nowadays, the prevailing activity in the region is agriculture, with some livestock areas. Forest subsists in scattered places with impoverished biodiversity on saline soils. Forest exploitation is scarce. Human settlements are small, population density is low, transport facilities are unsuitable; all depends politically and economically on the provincial capital cities. The cancellation of the railway traffic caused the abandonment of villages that had grown around railway stations. Asphalt roads are in bad shape because of poor maintenance that reflects low profitability of the economic activity and scarce population density.

6.3. STUDY AREA

The study area covers 640 km^2, with elevation ranging between 370 m and 560 m. Climate is semi-dry subtropical, with annual rainfall of 600-900 mm, increasing in east-west direction. The dry season is from April till October. The average monthly temperatures vary from 13^{o}C in June to 27^{o}C in January (data of Gobernador Garmendia over the period 1916-1989).

Forest sites were located in such a way that soils could be studied and sampled under forest cover and in nearby agricultural land, to allow comparing and assessing the influence of land management on soil degradation over time after forest clearing for agricultural land use. One survey site is a few kilometers north of Burruyacú at 560 m elevation in the undulating plain that borders the sub-Andean piedmont, while four sites are located in the flat fluvio-eolian plain at La Argentina, Elias, Piedrabuena and La Virginia at elevations ranging from 375 m to 480 m (Figure 6.1).

Remote sensing documents taken over the last 25 years, including satellite imagery (Landsat MSS, Landsat TM and SPOT) and air-photos, reveal a continuous decrease in forest cover in favor of crop cultivation and cattle raising. In the period 1971-1991, forest cover decreased from over 70 % to 22 % of the study area (Figure 6.2).

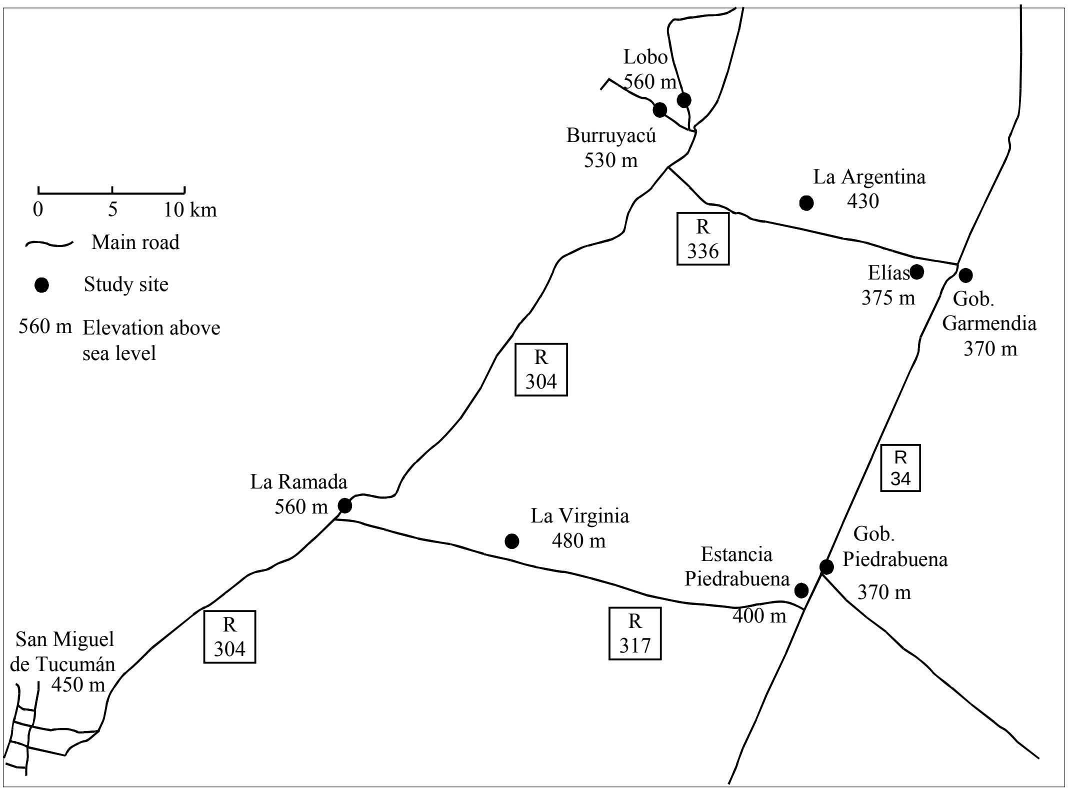


Figure 6.1. Study area and study sites (IGM, 1988).

Indigenous people lived in harmony with the environment, although they burned forest to create pastures. Since colonial times, the Chaco forest served for timber extraction and as a source of fodder for cattle. Timber extraction, especially of quebracho trees for railway sleepers, boomed from the end of the 19th century till about 1925. More recently, the forest, already degraded by timber extraction and cattle browsing, was mainly used as a source of fuel wood, charcoal and tannin for the leather industry, while large areas were slashed, burnt and cleared to create land for agricultural use. Deforestation still continues and only small patches of degraded Chaco forest remain, with significant changes in floristic composition due to grazing and burning. Nowadays, the forest land is mainly used for cattle browsing and for the supply of fuel wood and fence posts (Sayago, 1969; Karlin et al., 1994).

In the original forest, climax tree species such as quebracho colorado (*Schinopsis sp.*) and quebracho blanco (*Aspidosperma sp.*) were very common, while shrubs and small legume trees dominate now in the forest degraded by fire and use (Morello & Toledo, 1959). In this study, the floristic composition of the woody vegetation is described and the productivity of the forest assessed.

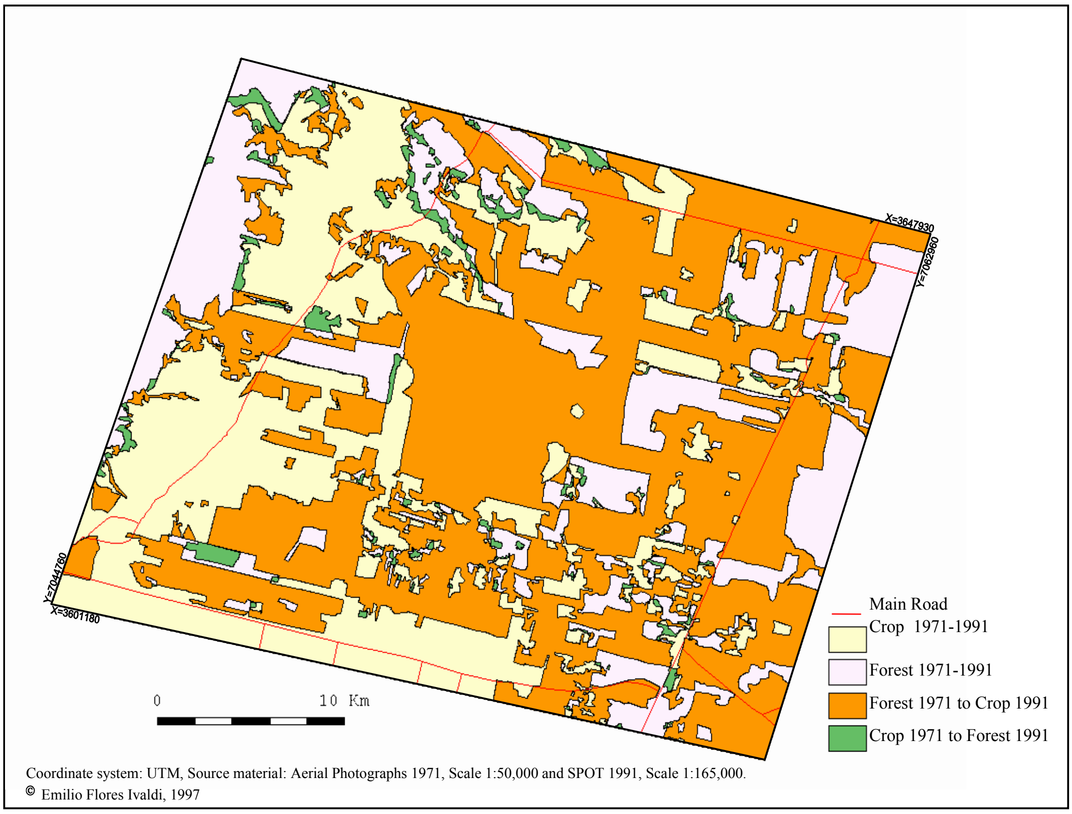


Figure 6.2. Land use changes in the Burruyacú area during the period 1971-1991 (after E. Flores, 1997).

6.4. METHODS

6.4.1. Definitions: tree or shrub?

A tree is a woody perennial plant, typically large, with a well-defined stem, carrying a more or less conspicuous crown. More specifically, a mature tree was considered in this study to have a total height of at least 5 m. For commercial purposes, the stem diameter at breast height (dbh 1.3 m above ground) should be at least 10 cm. A shrub is also a woody perennial plant, but with two or more stems and a crown usually less than 5 m high (Kiyiapi, 1994).

6.4.2. Study sites

Forest patches located close to agricultural fields reclaimed over the last 25 years were identified on remotely-sensed documents. With the help of satellite images of 1971, 1976, 1985 and 1991 and aerial photographs taken at a scale 1:50,000 in 1985, five suitable sites were located for field investigation during the years 1995 and 1996.

- The Lobo site is situated in a slightly undulating landscape, a few km north of Burruyacú town at 560 m elevation.
- The site in Finca La Argentina is 0.8 km north of road 336 and 11.5 km east of the junction with road 304, at 430 m elevation.
- The Elías site is just south of road 336 and west of the graveyard of Gobernador Garmendia, at 375 m elevation.
- The site in Colonia La Virginia is just north of road 317 and 10 km east of the junction with road 304, at 480 m elevation.
- The site in Estancia Piedrabuena is just north of road 317 and 2.6 km west of the junction with road 34, at 400 m elevation.

The Lobo (L), La Argentina (A) and Elías (E) sites form together the northern transect, while La Virginia (V) and Piedrabuena (P) sites form the southern transect (Figure 6.1).

6.4.3. Survey procedure

In each of the selected forest stands, a transect 25 m long and 2 m wide was laid out near the soil study site to describe the floristic composition (physiognomy, structure and taxonomy) of the woody vegetation (Figure 6.3). Types of life form, number of crown canopies, tree and shrub species, tree height, crown diameter and foliage density were recorded. The minimum tree height was 1.3 m and the minimum stem diameter was 2 cm.

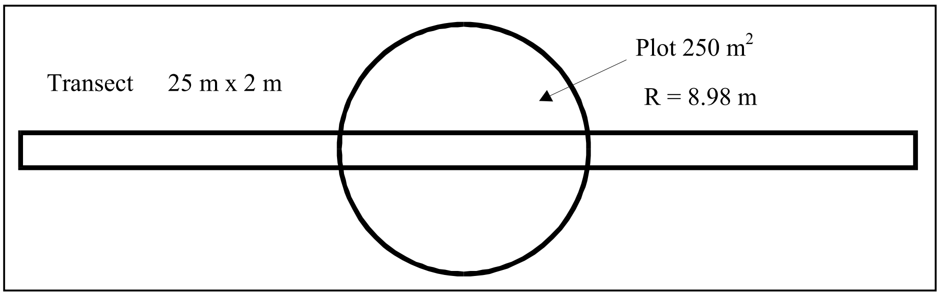


Figure 6.3. Transect and plot layout.

Halfway each transect, a circular plot of 250 m^2 (plot radius of 8.98 m) was surveyed, including determination of terrain slope, number of trees per species, number of stems per tree with a diameter of 2 cm or more at 1.3 m above ground, stem diameters, number of dead trees and stumps, and the area proportions of herbal cover, dry litter and bare soil. Furthermore, signs of past forest fires and of recent cutting and grazing were explored.

For exact location of transects and survey plots use was made of aerial photographs, a Suunto compass and a distance tape. A Magellan GPS recorder was carried along, but readings under forest were not possible because of the generally dense canopy. Elevation above sea level was recorded using a Thommen alti-barometer, which was calibrated in La Ramada. At each site, a sketch map showing the distribution of the vegetation was prepared.

Tree heights and crown diameters were estimated to the nearest 0.5 m. Stem diameters were measured at breast height in 1 cm classes. Increment boring for tree age determination was not carried out mainly because of the dense structure of the stem wood, but also because it was not sure that growth rings would in fact represent annual rings. The age of the shrubs could not be estimated because of frequent coppicing. Locally hired laborers, familiar with the forest situation, assisted in field measurements and supplied the local names of trees and shrubs. Later, the local names were linked to botanical names.

6.4.4. Data collection

The first visit to the area took place during the dry season, in September 1995. After a general reconnaissance through the region, survey concentrated on the Lobo and Elías sites. Practically, all trees and shrubs were leafless by that time, a situation which did not hinder the local assistants from identifying the woody species. The forest presented a quite open appearance, although not enough for the GPS instrument to provide positional coordinates. Dead leaves on the ground were very brittle, and the layer of litter was very thin or absent. There were no traces of forest fire or recent cuttings, while cow tracks were well visible at both sites.

The second visit was in March 1996, after the main rains, when all living trees and shrubs were in full green foliage. Tree species identification was much easier, but the visibility in the forest stands was greatly reduced because of the low height of the forest canopies. Visits were paid to all five sites, allowing for additional measurements at the sites studied in 1995. Cattle browsing the forest were only seen at the Lobo site.

In total, three transects and three plots were surveyed at Lobo and Elías sites, while two transects and two sites were surveyed at La Argentina, La Virginia and Piedrabuena sites.

6.5. SURVEY RESULTS

6.5.1. Abundance and spatial distribution of species

The general types of vegetative life forms present in the area are shown in Table 6.1. Abundance and spatial distribution of woody, liana and cactus species are shown in Figure 6.4 and reported in Tables 6.2 and 6.3. All five sites comprise trees and shrubs, plus one locally representative life form: lianas in the western and central parts of the study area, and cacti in the eastern part, indicating that climate is more humid in the west and drier in the east.

The Lobo site is very rich in woody species (22), followed by La Argentina (15) and Elías (13) in the north, and by Piedrabuena (12) and La Virginia (11) in the south. The Lobo site, situated in an undulating plain bordering the sub-Andean piedmont, is therefore by far the area with the highest woody biodiversity. There is a small decrease in woody species from west to east in the north of the flat fluvio-eolian plain, while the south is in general less rich (Figure 6.4).

Table 6.1. Types of vegetative life forms.

Transect	North			South	
Site	L	A	E	V	P
Tree and shrub species	x	x	x	x	x
Liana species	x	x		x	
Cactus species			x		x

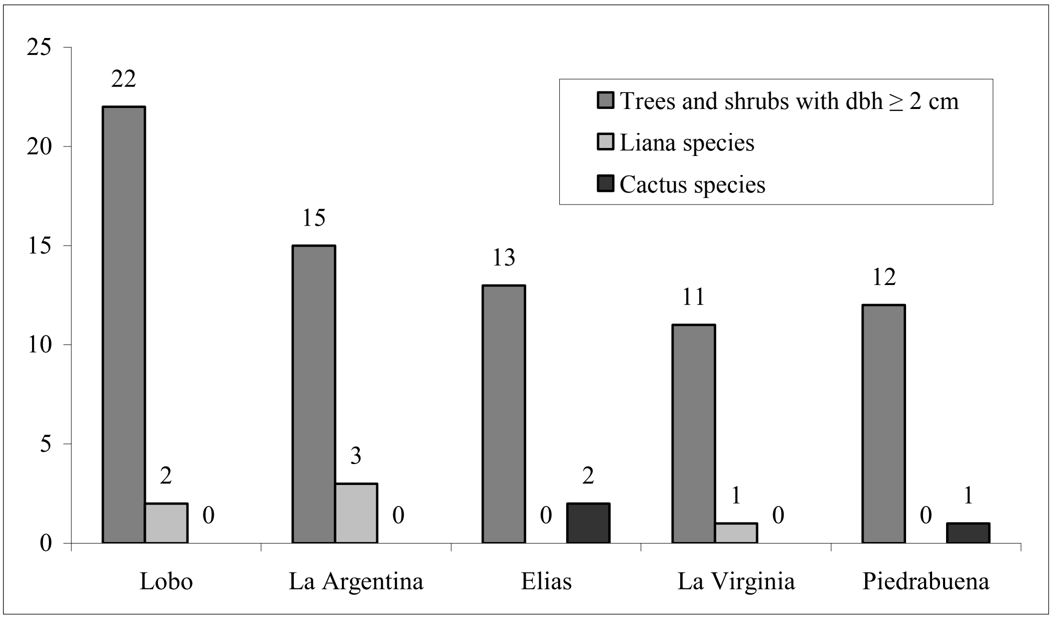


Figure 6.4. Number of species per life form (Y-axis) at the five study sites (dbh: diameter at breast height).

The Lobo site has seven species that do not occur in the other places, whereas the other sites have only one to four exclusive species: three in La Argentina, two in La Virginia and Piedrabuena, and one at Elías. This reflects decreasing biodiversity from west to east. The location-specific trees and shrubs might serve as indicator species for soil and/or climate conditions.

One shrub species (brunagaspe) and two tree species (quebracho blanco and tuscal) are found in four of the five sites. The shrub species brunagaspe does not occur in La Argentina, but is well represented in Elías, La Virginia and Piedrabuena. Quebracho blanco does not occur in Lobo, but is very well represented in Piedrabuena. Tuscal is always present with a few trees, except in Elías.

Two tree species are found at all five sites: mistol (*Zizyphus mistol*) and tala (*Celtis sp*.). Both show their highest concentration at the Elías site. These are probably very tolerant species that do easily survive in poor sites, where more demanding species cannot grow anymore (Figures 6.5 and 6.6).

At all sites except Lobo, one or more species dominate the stands in number of trees: tala in La Argentina with 28 %; brunagaspe, mistol and tala in Elías forming together 83 %; brunagaspe and chalchal in La Virginia with together 63 %; and brunagaspe and quebracho blanco in Piedrabuena with 69 % of all trees. This indicates that biodiversity has been damaged in four out of the five sites.

The number of tree species per plot is practically the same at all sites: six in La Argentina, five in Lobo, Elías and Piedrabuena, and four in La Virginia. The large variation in biodiversity therefore comes from the shrubs.

Table 6.2. Abundance and spatial distribution of woody species. Average number of trees and shrubs per plot with a minimum stem diameter of 2 cm at breast height (1.3 m above ground).

		Transect	North			South	
		Site	L	A	E	V	P
No	Local name	Botanical name					
1	Arrayán	*Eugenia moraviana*	1			1	
2	Algarrobo negro	*Prosopis flexuosa (Prosopis nigra)*		3	5		
3	Ancoche	*Vallesia glabra*	1		1		1
4	Brunagaspe	?	2		18	12	12
5	Chalchal	*Lycium cestroides*	6			25	
6	Churque	*Prosopis ferox*	2	1			
7	Cucharero	*Porliera microphylla*	1				
8	Chebil blanco	?	1	1		5	
9	Chebil negro	?	2				
10	Garabato negro	*Acacia praecox (Mimosa farinosa)*		2	1		3
11	Guarán	*Leguminosae sp.*	1				
12	Guayacán	*Caesalpinea paraguariensis*		1	1		1
13	Lata pobre	*Piper tucumanum*	1				
14	Laurel	*Phoebe porphyria*	1				
15	Lecherón	*Sapium haematospermum*	1				
16	Meloncillo	*Castela coccinea*			1		
17	Mistol	*Zizyphus mistol*	1	1	24	6	7
18	Molle	*Schinus bumelioides (Bumelia obtusifolia)*	1		1		1
19	Morera	*Morus alba*				1	
20	Ortiga	*Urera caracasana*		2			
21	Poleo-montes	?					1
22	Palo blanco	*Prosopis alba*	1				
23	Piquillín	*Condalia buxifolia*	1		1	1	
24	Quebracho blanco	*Aspidosperma Q. blanco*		1	1	1	32
25	Quebracho colorado	*Schinopsis Q. colorado*					3
26	Sacha gochuchu	?	3	1			
27	Sacha huacán	?				1	
28	Siempre-verde	?		1			
29	Sombra-de-toro	*Iodina rhombifolia*	1		1		
30	Sunchillo	*Bocconia pearcei*	1	1			
31	Tala blanca	*Trema micranta (Celtis spinoza)*	1				
32	Tala brava	*Celtis?*	1	8	1	5	1
33	Tala pispa	*Celtis tala*	1		26		
34	Tuscal	*Acacia aroma*	1	3		1	1
35	Viraru	*Ruprechtia apetala*		1			
Mean number of trees and shrubs per plot			32	28	82	59	64
Mean number of woody species per site			22	15	13	11	12
Species exclusive to one specific site			7	4	1	2	2
Dominant species comprising more than 20% of trees present			0	1	3	2	2
Number of tree species (h >5m, dbh >10cm)			5	6	5	4	5

Table 6.3. Presence of liana and cactus species.

	Transect	North			South	
	Site	L	A	E	V	P
Local name	Botanical name					
Liana						
Guaquilla blanca	?	x	x		x	
Sacha guoaska	*Capparis retusa*	x				
Zarza parilla	?		x			
Cactus						
Peinca	*Opuntia quimilo*			x		x
Ucle	*Cereus validus*			x		

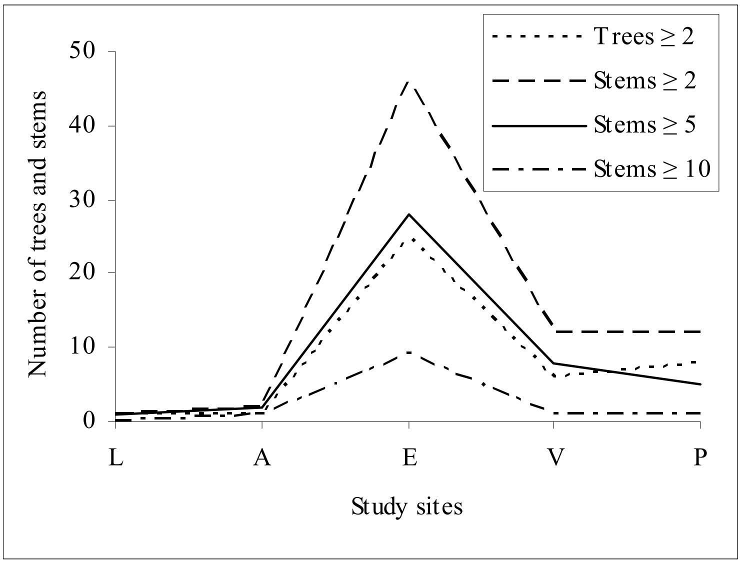


Figure 6.5. Number of trees and stems of mistol at the five study sites (diameter in cm).

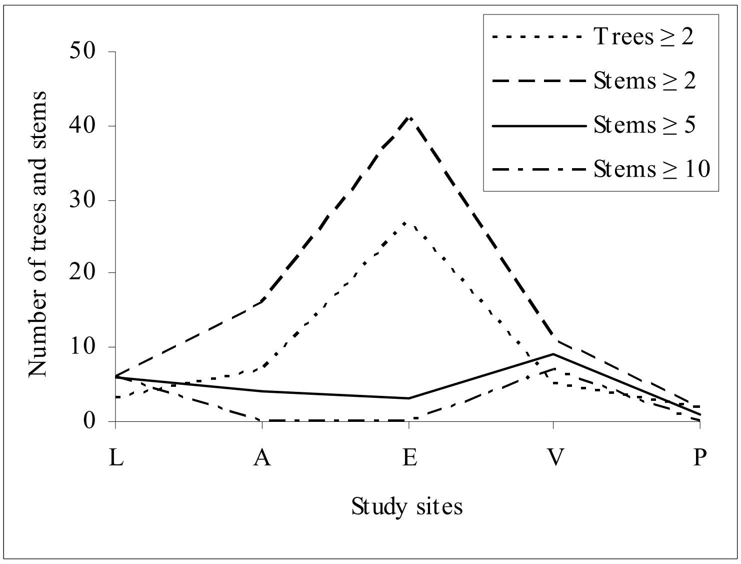


Figure 6.6. Number of trees and stems of tala at the five study sites (diameter in cm).

6.5.2. Density, height and diameter of trees and shrubs

In the Chaco forest, or its degraded remnants, the distinction between tree and shrub per species is often unclear. It is difficult to determine the age of a tree or shrub. Because of the grazing practices and the harvesting of small stems for fuel wood and fence posts, many trees have been coppiced, now appearing as shrubs.

The density of woody plants per plot, including trees and shrubs with stem diameter of 2 cm and more, is lowest in La Argentina (28) and highest in Elías (82), with intermediate values in Lobo (32), La Virginia (59) and Piedrabuena (64) (Figure 6.7). This variation in density is probably related to the proportions of trees (single stems) and shrubs (multiple stems). Strongly degraded forests have usually more shrubs than trees as compared with less degraded forests. In the fluvio-eolian plain, forest degradation increases from west to east and from north to south. However, on basis of the number of trees per plot (dbh >10 cm), with six in Lobo, eight in La Argentina, twelve in Elías, six in La Virginia, and ten in Piedrabuena, tree density increases from west to east, but decreases from north to south (Figure 6.7).

In general, forest canopy is 3-7 m high, with some emerging trees having heights of 10 m (chalchal), 13 m (tala blanca) and 15 m (quebracho). Crown diameter for the smaller shrubs and trees is 1-4 m, while the tall emerging trees (e.g. algarrobo and quebracho) may have crowns up to 12 m wide.

When including woody plants of small diameter (dbh >2 cm), Elías is the site with the largest number of stems per plot (153), with intermediate values in La Virginia (118) and Piedrabuena (116) and with low values in Lobo (59) and La Argentina (60). With increasing stem diameter, the differences between localities gradually disappear. At dbh >20 cm, the number of tree stems is equally low at all sites (Figure 6.8).

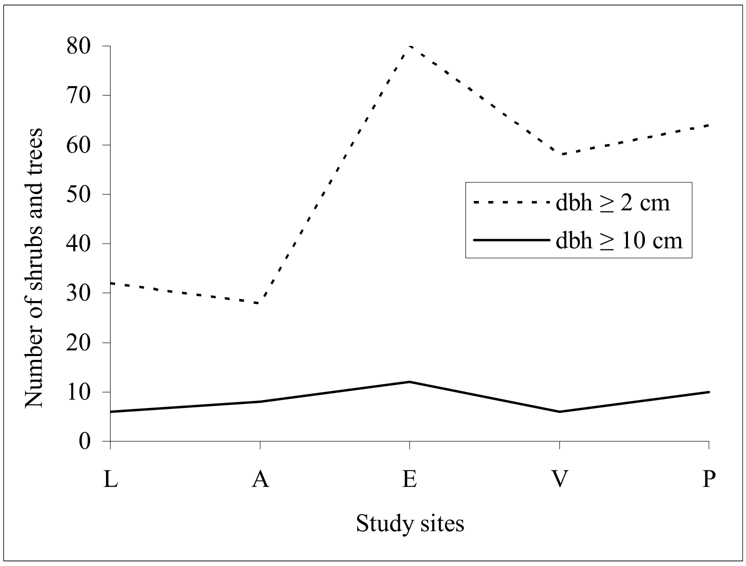


Figure 6.7. Average number of shrubs and trees per plot at the five study sites.

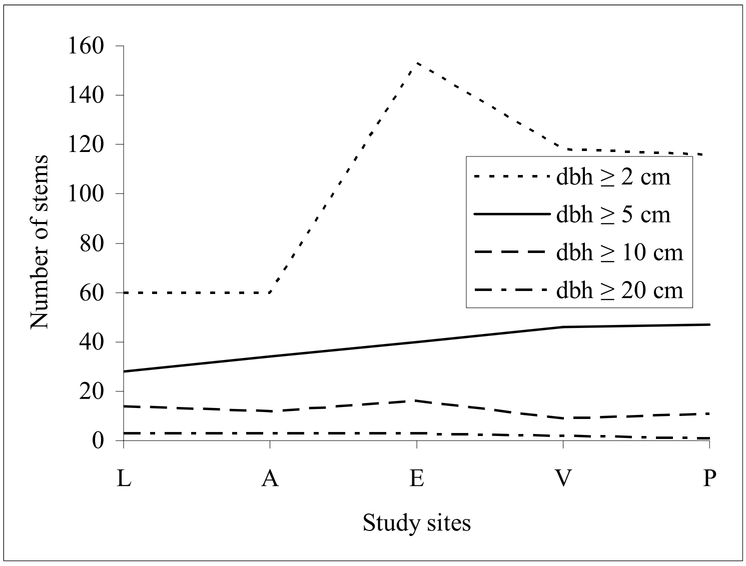


Figure 6.8. Average number of stems per plot at the five study sites.

Stem diameters of 10 cm or more are only found for algarrobo (up to 31 cm), chalchal, churque, lecherón, mistol (up to 32 cm), quebracho (up to 33 cm), siempre-verde, sombra-de-toro (up to 24 cm), tala blanca (up to 40 cm) and tuscal.

Most shrubs have only two stems, just like some of the coppiced trees, but some other woody plants (dbh 2 cm or more) have frequently multiple stems, such as tala brava (9), brunagaspe (6), ortiga (6), siempre-verde (6), tuscal (6) and chalchal (5).

6.5.3. Forest productivity

Forest productivity was assessed using three different criteria: stem diameter, annual growth and woody biomass.

(1) Forest productivity from stem diameter

Stem diameter of 2 cm or more at breast height (1.3 m above ground) is an appropriate indicator for registration of the floristic composition. However, other stem diameter figures are more relevant for assessing the forest potential for fuel wood, charcoal, fence posts and saw timber. Therefore, sites were compared using minimum stem diameters of 5 cm, 10 cm and 20 cm (Table 6.4 and Figure 6.8). From data in Table 6.4, ratios relating number of stems to number of woody plants were calculated for the four diameter classes (Table 6.5).

Table 6.4. Number of plants and stems.

Transect		North		South	
Study site	L	A	E	V	P
Number of woody plants with minimum dbh 2 cm	32	28	82	59	64
Number of stems with minimum dbh 2 cm	59	60	153	118	116
Number of stems with minimum dbh 5 cm	28	35	44	52	54
Number of stems with minimum dbh 10 cm	13	12	16	9	11
Number of stems with minimum dbh 20 cm	3	2	2	2	1

Table 6.5. Ratios between number of stems and number of woody plants.

Transect		North		South	
Study site	L	A	E	V	P
Ratio 1: minimum stem dbh 2 cm	1.84	2.14	1.86	2.00	1.81
Ratio 2: minimum stem dbh 5 cm	0.88	1.25	0.54	0.88	0.84
Ratio 3: minimum stem dbh 10 cm	0.41	0.43	0.20	0.15	0.17
Ratio 4: minimum stem dbh 20 cm	0.09	0.07	0.02	0.03	0.02

From the ratios in Table 6.5, the following conclusions can be drawn. Ratio 1 indicates that, at each site, every woody plant has on average two stems with a diameter of 2 cm or more. From ratio 2, it is clear that not all plants reach the minimum stem diameter of 5 cm in Lobo, La Virginia and Piedrabuena, while stems with at least 5 cm diameter are over-represented in La Argentina and under-represented at Elías site. Ratio 3 shows that, at both Lobo and La Argentina sites, about 40% of the trees have stem diameter of 10 cm or more, while ratio values of 0.15-0.20 at the other three sites in the east and the south indicate that small shrubs dominate in these places. Ratio 4 follows the trend of ratio 3, with a small advantage for Lobo and La Argentina sites.

The potential for heavy timber, with stem diameter over 20 cm, can be better evaluated from the number of stems per plot, a criterion which shows little difference between sites (Table 6.6). Big trees are scarce but represent a considerable proportion of the total woody biomass in each plot.

Table 6.6. Trees with stem diameter of 20 cm and more.

Site	Number of plots	Average number of trees per plot	Average number of stems per plot	Tree species	Max. dbh (cm)
Lobo	3	2.3	3.0	Tala blanca	40
				Tala pispa	40
La Argentina	2	1.0	2.0	Mistol	32
Elías	3	2.0	2.0	Algarrobo	31
				Mistol	21
La Virginia	2	2.0	2.5	Tala	45
Piedrabuena	2	1.0	1.0	Quebracho blanco	28
				Quebracho colorado	20

(2) Forest productivity from annual growth

Neither tree density nor stem density are good forest productivity indicators. Annual growth is a better criterion. The increment in woody biomass can be measured in two ways: (1) by carrying out a survey in two different years and determining the difference in woody volume; (2) by studying the annual growth rings at a cross-section of the stem of a sampled tree. The first method requires a period of preferably 10 years and is therefore not feasible in the present situation. For proper application of the second method, it must be made sure that tree rings, when at all visible, correspond actually to annual growth and not to other factors, which may influence tree growth.

The study of a few cross-sections of felled trees revealed that growth rings are sometimes visible, but not in a distinct pattern. Moreover, the wood is very hard so that the increment borer could not be adequately used. Additionally, felling the few trees present at each site would have heavy impact on biodiversity. Likewise, it resulted difficult to determine the age of shrubs, which occasionally are cut for fuel wood and then sprout out again, leading to multiple stem structure. In conclusion, none of the two methods could be implemented and, therefore, it was not possible to determine the age of the stands investigated.

(3) Forest productivity from woody biomass

The woody biomass of a tree can be obtained from the stem diameter, the tree height and the so-called form factor that measures the rate of decrease of the stem diameter with increasing height above ground. Usually, there is a relationship between stem diameter and tree height per species, although this varies with the quality of the growing site.

The total standing woody volume at the sites can be estimated by determining the basal area, which is the sum of the cross-sectional areas of the stems at breast height as expressed in m^2 per hectare (Figure 6.9). Using this approach, the mean basal area per plot was determined for several minimum stem diameters and converted to basal area per hectare (Table 6.7 and Figures 6.10 and 6.11).

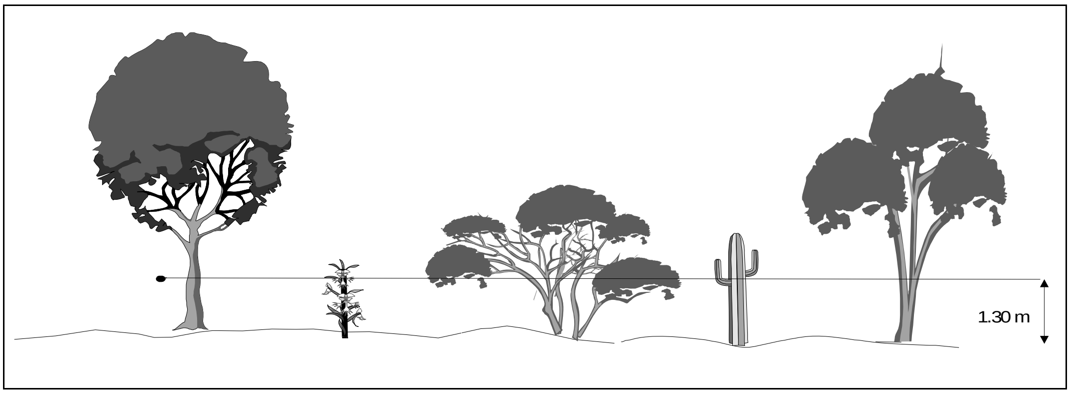


Figure 6.9. Woody basal area as obtained from stem diameter measured at breast height (1.3 m).

Table 6.7. Average basal area per plot (m^2 ha^{-1}).

Transect		North		South	
Study site	L	A	E	V	P
Minimum dbh 2 cm	17.2	13.9	18.1	19.0	13.9
Minimum dbh 5 cm	16.5	13.2	15.4	17.1	12.1
Minimum dbh 10 cm	14.2	9.8	11.5	11.9	6.4
Minimum dbh 20 cm	9.1	3.8	3.6	8.3	1.9

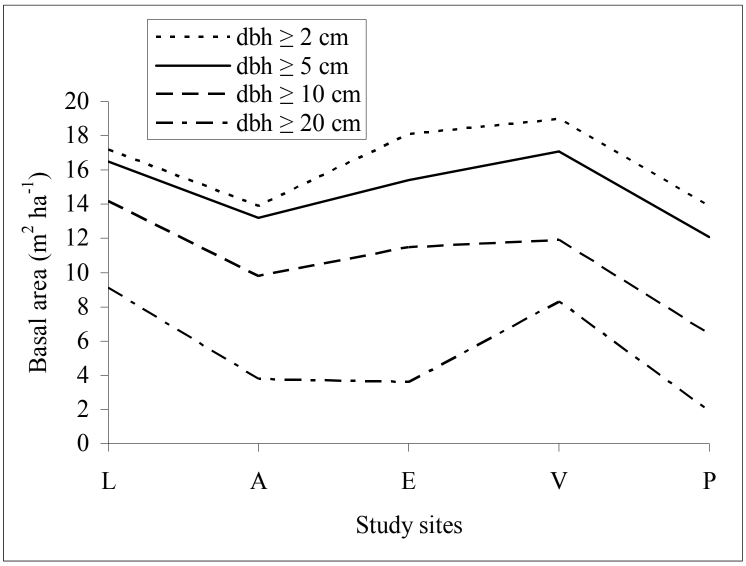


Figure 6.10. Total basal area at the five study sites.

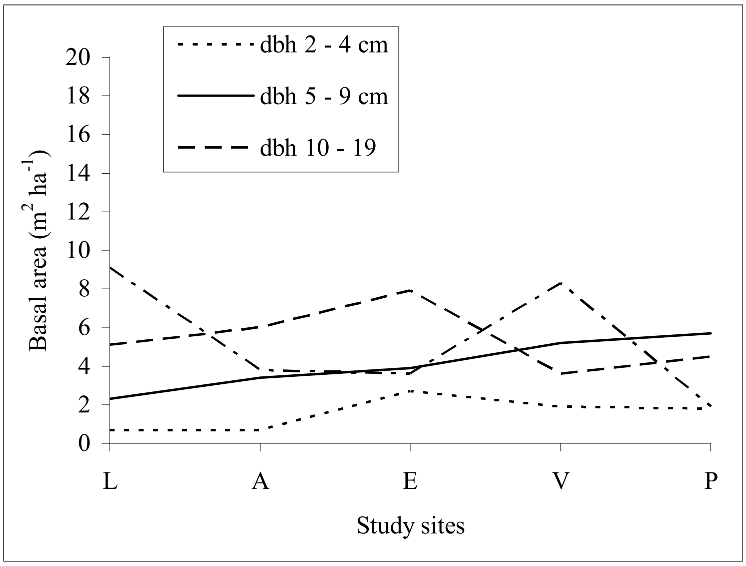


Figure 6.11. Basal area per diameter class at the five study sites.

When considering the 2-cm-dbh data, then Lobo has the best stand together with Elías and La Virginia, while La Argentina and Piedrabuena have a much lower potential. This conclusion applies also to the 5-

cm-dbh data. Probably, the absolute values are controlled by the relative large basal areas of the few big trees present in each plot. An analysis of the basal area values for each stem diameter class may give an answer to this problem (Table 6.8 and Figure 6.11).

Small-size wood (2-4 cm) is hardly found at Lobo and La Argentina sites, but is present in large quantity at Elías site reflecting abundance of shrubs in the northeast. The two southern sites have intermediate values. Medium-size wood (5-9 cm) shows increasing values in basal area from west to east and from north to south. Large-size wood (10-19 cm) increases in quantity from west to east both in the north and south, but the values in the north are much higher than those in the south due to presence of more trees with larger stem diameters. Very-large-size wood (20 cm and more) shows an irregular distribution pattern and is probably controlled by the occasional presence of one or two relatively large trees in the plot.

Table 6.8. Basal area per dbh class (m^2 ha^{-1}).

Transect		North		South	
Study site	L	A	E	V	P
dbh class 2 – 4 cm	0.7	0.7	2.7	1.9	1.8
dbh class 5 – 9 cm	2.3	3.4	3.9	5.2	5.7
dbh class 10 – 19 cm	5.1	6.0	7.9	3.6	4.5
dbh class 20 cm and more	9.1	3.8	3.6	8.3	1.9

6.6. DISCUSSION AND CONCLUSIONS

- The study area includes one site in the northwestern undulating plain (Lobo) and four sites in the flat fluvio-eolian plain (La Argentina and Elías in the north; La Virginia and Piedrabuena in the south). Rainfall decreases from west to east, resulting in a more arid climate at the Elías and Piedrabuena sites.

- The presence of liana species in the three western sites and the presence of cactus species in the two eastern sites indicate a significant climate trend over a relatively short distance, independent of the small elevation differences in the plain, but possibly more closely related to the distance from the nearby mountain ranges.

- Biodiversity decreases from west to east and from north to south. The Lobo site has by far the largest number of woody species.

- The high proportion of shrub species indicates that the Chaco forest has been strongly degraded, resulting from logging of heavy timber in the past and from repeated burning, grazing and cutting for fuel wood in more recent times. Heavy rainfall causing erosion may also play a role.

- Except in Lobo, a few species (1 to 3) dominate the stands in proportions of 28-83% in the north and 63-69% in the south. This is an indication of relatively low biodiversity.

- Density of trees and shrubs increases from west to east, mostly due to the increment of shrubs. This can be seen as a decrease in site quality.

- Often the stand height is considered to be a good measure of site quality. This criterion is not applicable here, because all sites have an average stand height of about 5 m, while the height of the taller trees is not relevant as their age cannot be determined.

- On average, shrubs and coppiced trees at all sites have two stems of at least 2 cm diameter per plant. Multiple stems (up to six) are found for brunagaspe, chalchal, mistol and tala pispa.

- The number of stems per plot increases from west to east and from north to south for stem diameters >2 cm and >5 cm, respectively. For dbh >10 cm, stem density slightly increases from west to east, but decreases from north to south. Apparently, the high number of shrubs in the poor southern sites is at the expense of the number of trees.

- The basal area, as a measure of biomass, is highest at Lobo site when taking into account the stems with dbh >10 cm. However, biomass trend is apparently better indicated by the basal area of the stem diameter class 5-9 cm. In general, basal area is controlled by the occasional presence of a few big trees in the plots, such as algarrobo, mistol, quebracho and tala. Basal area values increase from west to east and from north to south, which means that shrubs with small stem diameters play an increasing role in the biomass in southeastern direction.

- Briefly, life forms change from west to east according to decreasing rainfall and biodiversity decreases in southeastern direction together with an increase in shrub vegetation. The total biomass at dbh >2 cm shows an irregular pattern, since the data are obscured by the occasional presence of large trees in the sample plots. The diameter class 5-9 cm shows increasing biomass in southeastern direction, while the diameter class 10-19 cm gives an increase from west to east and a decrease from north to south.

6.7. RECOMMENDATIONS

- The above conclusions are based on a few sample plots per study site. Present result trends should be confirmed by additional observations to increase the reliability of the statistical analysis.

- The short visits in 1995 and 1996 did not allow studying the history of the stands investigated. Interviews with forest owners and forest users may give more insight in the past and present use of the forest land. Detailed information on forest fires, grazing intensity, wood cutting and harvesting is needed for better appreciation of the differences between the five sites, especially in view of the survey objective to establish relationships between the productivity of the forest land and that of the surrounding agricultural land.

- For further vegetation studies in this type of forest, it is recommended to enlarge the surface area of the transects (here 2 m x 25 m) to cope with the presence of a few large-crown trees.

- The 250 m^2 circular plots were laid out to quantify the woody vegetation. Instead of taking 2-cm-dbh as minimum stem diameter, the work can be facilitated by accepting 5-cm-dbh as lower limit. Biomass trends would not be considerably altered.

- A few species could not be identified with their botanical names, partly caused by misunderstandings and lack of consistency deriving from the local names collected with the help of different field workers. For further studies, hiring of a qualified forester with adequate taxonomic knowledge is recommended.

6.8. REFERENCES

Clark, C., 1992. Empirical evidence for the effect of tropical deforestation on climatic changes. Environmental Conservation 19 (1): 39-47.

Flores, E., 1997. Monitoring land use changes and comparing soil physical properties between arable and forest land use in the western Chaco plain, NW-Argentina. MSc Thesis. ITC, Enschede, The Netherlands.

IGM, 1988. Mapa topográfico San Miguel de Tucumán, Hoja 2766-II. Instituto Geográfico Militar, República Argentina.

Karlin, U.O., Bronstein, G., 1986. Caracterización de los sistemas de producción del árido subtropical Argentino. V Reunión de Intercambio Tecnológico en Zonas Aridas y Semiáridas, La Rioja, pp.439-448.

Karlin, U., Catalan, L., Coirini, R., 1994. La naturaleza y el hombre en el Chaco seco. Facultad de Ciencias Agropecuarias, Universidad de Córdoba, Argentina.

Karlin, U.O., Coirini, R., Pietrarelli, L., Periña, E., 1992. Caracterización del Chaco árido y propuesta de recuperación del recurso forestal. En: Sistemas agroforestales para pequeños productores de zonas áridas. UNC-GTZ, Córdoba, pp.7-12.

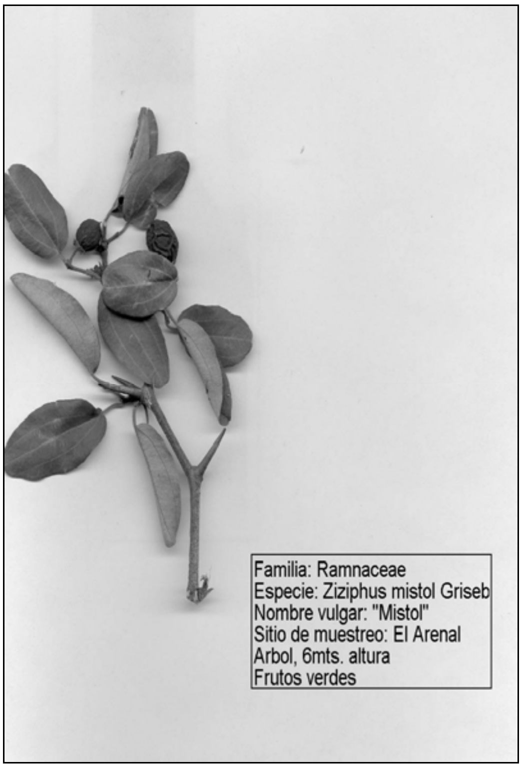
Kiyiapi, J., 1994. Structure and characteristics of Acacia tortilis woodland on the Njemps Flats. Advances in Geoecology 27: 47-69.

Lozano, P., 1733. Descripción corográfica del Gran Chaco Gualamba. Re-edición 1989, Dpto. Investigaciones Nacionales, UNT, Publicación 288, Tucumán.
Morello, J.H., Toledo, C.S., 1959. El bosque chaqueño. Revista Agronomía del Noroeste de Argentina III (1): 5-79, III (2): 209-258.
Morello, J., Protomastro, J., Sancholuz, L., Blanco, C., 1985. Estudio macroecológico de los Llanos de La Rioja. Administración de Parques Nacionales, Serie del Cinquentenario 5, Buenos Aires, 53 pp.
Parodi, L., 1978. Enciclopedia argentina de agricultura y jardinería. Tomo I. Descripción de las plantas cultivadas (1º y 2º volúmenes), 3º edición. Editado ACME S.A.C.I., Buenos Aires, Argentina.
Ragonese, A.E., Castiglioni, J.C., 1970. La vegetación del Parque Chaqueño. Boletín Sociedad Argentina de Botánica 11 (Supl.): 133-160.
Saravia Toledo, C., 1982. Chaco semiárido. Conservación de la vegetación natural en la República Argentina. XVIII Jornadas Argentinas de Botánica, Tucumán, pp.35-40.
Sayago, J.M., 1969. Estudio fitogeográfico del Norte de Córdoba. Boletin de la Academia Nacional de Ciencias 46 (2, 3, 4): 267-280.
Sayago, J.M., 1992. El deterioro del ambiente en el Noroeste Argentino. Estudios Geográficos, Public. 208: 543-567.
Tissera, R., 1971. Chaco Gualamba, historia de un nombre. Ed. Cultural Nordeste, Resistencia, Argentina, 67 pp.

6.9. APPENDIX: SELECTED PLANT SPECIES OF THE CHACO FOREST


Familia: Anacardinaceae.
Especie: Schinopsis haenkeana Engl.
Nombre vulgar: "Horco quebracho".
Sitio de Muestreo: La Tuna
Arbol, 1 mt. altura


Familia: Apocinaceae
Especie: Aspidosperma quebracho blanco Achltdl.
Nombre vulgar: "Quebracho blanco"
Sitio de muestreo: Rincón Grande
Arbol, 7mts. de altura, frutos grandes (6 cm)


Familia: Ramnaceae
Especie: Ziziphus mistol Griseb
Nombre vulgar: "Mistol"
Sitio de muestreo: El Arenal
Arbol, 6mts. altura
Frutos verdes


Fam. Leguminosae. = Fabeceae.
Especie: Acacia visco. Lorentzap, Griseb
Nombre vulgar: "Visco", "Arca", "Viscote
Sitio de muestreo: La Tuna
Arbol, altura: 7 mts.

CHAPTER 7

LAND USE CHANGES

E. Flores, J.A. Zinck

7.1. INTRODUCTION

Agricultural land use changes can be monitored by using remote sensing (Cygul et al., 1977; ESA, 1989; Dennis & White, 1991; Singh, 1992). Sometimes, the only data source on past land covers is imagery. These data can be used for monitoring land use changes, as ESA (1989) showed for large parts of Europe.

Cygul et al. (1977) state that using Landsat imagery is an economic method for monitoring land use changes in comparison to traditional survey methods, but they anticipate problems related to differences in imagery scales. Dennis and White (1991) used data from land use maps derived from aerial photographs (1976) and SPOT multispectral imagery (1986) for mapping cropland changes in a GIS. They assessed the use of GIS techniques to quantify land use changes over a 10-year period within a test area covering approximately 282 km^2 in the lower Indus Valley, Pakistan.

Ram and Kolarkar (1993) identified land use changes in various parts of arid Rajasthan using multidate data, which allowed them to identify a shift from traditional rain-fed agriculture to irrigated agriculture. During the last three decades, the net sown area increased by 36%, while short- and long-term fallows declined by 29% and 41%, respectively. The net irrigated area increased by 140%. Forest and pastures became highly degraded, although their areas increased to some extent.

Singh (1992) has used remote sensing and GIS for monitoring land use changes in both natural and anthropogenically modified geosystems in the Himalayan region. The results show a changing forest distribution and provide a classification of land suitable for agriculture.

7.2. LAND USE HISTORY

In the past, the Chaco forest was used for fodder and timber. After Spanish colonialists introduced cattle into the area, cattle browsing became the first step of resources degradation in the Chaco forest. Starting by the end of the 19^{th} century, timber extraction concentrated on the selective removal of quebracho trees for railway sleepers. The Chaco forest was also a source of tannin. Following cattle expansion, leather production was reported as an important economic activity in the Burruyacú area in the last century, while becoming raw material for handicraft in more recent years (La Gaceta, 1996). Nowadays, the degraded remnants of the Chaco forest are used for cattle browsing.

At present, crop production is the main economic activity in the Burruyacú area. The most important crop is soybean, followed by maize, wheat and vegetables. Soybean and maize are summer crops, whereas wheat is cultivated in winter (Zuccardi & Fadda, 1985). The first data about soybean production in Tucumán province were recorded in the early 1960s (Table 7.1). According to Hemsy (1970), yields were high in spite of poor management knowledge in those days.

Currently, different farming systems are implemented in the Burruyacú area, depending mainly upon the economic wealth of the farmer. No-tillage, irrigation and fertilizers are applied on some large farms, such as La Argentina and the Giordano farm. In the rest of the area, traditional farming is still common.

Since the 1970s, there has been an increase in annual rainfall. This climatic bonanza, together with good market prices, led to a rapid expansion of the agricultural production and also an increasing demand for new land (Vicini, 1984; Minetti & Sierra, 1984; Minetti & Poblete, 1989). Local institutions promoted the use of new crops in the 1960s and early 1970s (Hemsy, 1970). Because the area was suitable for soybean, the Agricultural Experimental Station of Tucumán and the University of Tucumán started a promotional program in 1967. Over a period of five years, farmers were advised on and taught adapted farming and soil management techniques. Trials of soybean varieties were conducted and the quality of the soybean produced in the area was monitored. As a consequence, production and yields substantially increased (Table 7.2 and Figure 7.1).

Farmland rapidly expanded at the expense of the forest cover, resulting in a drastic reduction of the Chaco forest. Mechanized deforestation replaced the traditional, less harming hand-clearing. Trees were felled using heavy machinery, usually a set of two bulldozers connected by a chain.

Table 7.1. Soybean production in Tucumán province (Hemsy, 1970).

Year	Production (tons)	Area (ha)	Yield (kg ha^{-1})
1961-62	2,177	1,500	1,497
1962-63	1,690	1,400	1,300
1963-64	1,220	1,140	1,305
1964-65	2,210	2,312	1,079
1965-66	2,400	2,230	1,204
1966-67	2,700	2,350	1,277
1967-68	10,200	8,900	1,146

Table 7.2. Soybean production in the east of Tucumán province (Hemsy, 1970).

Year	Production (tons)	Area tilled (ha)	Area harvested (ha)	Yield (kg ha^{-1})
1965-66	2,400	2,230	1,994	1,204
1966-67	2,700	2,350	2,114	1,277
1967-68	9,454	6,815	6,815	1,387
1968-69	16,515	12,550	12,550	1,316
1969-70	4,685	5,750	4,555	1,029
1970-71	8,930	7,400	6,900	1,294
1971-72	4,465	8,500	6,350	703
1972-73	20,850	15,000	15,000	1,390
1973-74	46,690	26,610	26,610	1,755
1974-75	27,841	24,000	21,500	1,295
1975-76	44,300	24,900	24,900	1,779
1976-77	62,700	36,000	35,700	1,756
1977-78	98,000	54,500	54,500	1,798
1978-79	155,250	75,000	75,000	2,070
1979-80	132,600	84,569	78,000	1,700
1980-81	155,000	84,404	76,166	2,035
1981-82	130,770	72,171	68,371	1,913
1982-83	145,000	76,250	73,600	1,970
1983-84	156,200	83,970	81,870	1,908
1984-85	166,250	85,395	83,825	1,983
1985-86	145,500	75,000	74,000	1,966
1986-87	84,330	84,759	84,759	995
1987-88	167,200	84,000	83,600	2,000
1988-89	39,000	40,000	23,000	1,696
1989-90	161,700	81,400	78,400	1,063
1990-91	190,000	82,000	79,000	2,405
1991-92	191,210	87,130	86,330	2,215
1992-93	190,050	92,000	90,000	2,112
1993-94	173,200	90,000	88,400	1,959

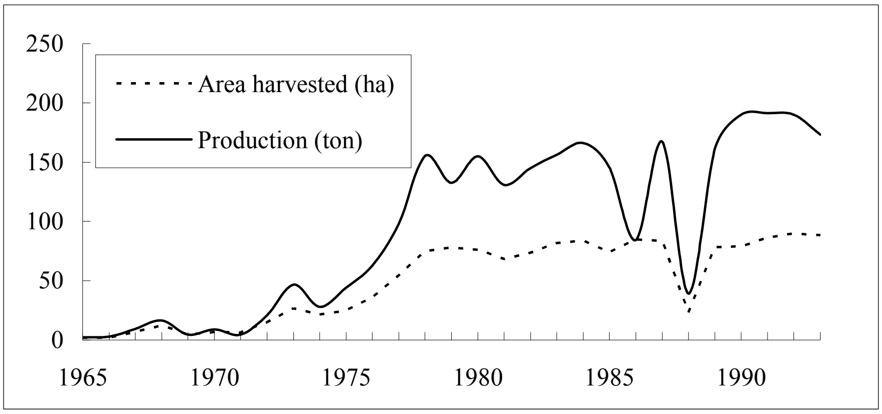


Figure 7.1. Soybean production and harvested area in the east of Tucumán province during the period 1965-1993 (ha and ton in thousands).

7.3. EXTENT OF FOREST AND CROPLAND AT DIFFERENT DATES

A time series of available remote sensing documents ranging from 1971 to 1991 was used to determine the extent of forest cover and cropland at five consecutive dates separated by irregular time intervals (Table 7.3). Data were of variable nature (including aerial photographs, photomosaics and hardcopies of satellite images) and of variable scale (ranging from 1:50,000 to 1:500,000). This large data variety caused problems in terms of interpretation of the remote sensing documents, comparison between land use interpretation maps, and reduction of the latter to a common cartographic base. The remote sensing documents were visually interpreted at their respective original scales to separate forest and crop areas. After conversion from vector to raster format, the visual interpretation maps were georeferenced to a topographic base map at 1:250,000 scale to calculate the extent of forest and crop areas at each selected date. After choosing a window common to all files, histograms were established for each file, showing the amount of pixels for each pixel value in each file. From the known pixel size (10 m^2), the areas of both cropland and forest at the selected dates were calculated (Table 7.4 and Figure 7.2).

Table 7.3. Dates and scales of available imagery.

Date	Source document	Scale
1971	Photomosaic	1:50,000
1972 September	Landsat hardcopy	1:250,000
1976 March	Landsat hardcopy	1:500,000
1985	Aerial photographs	1:83,000
1991 March	SPOT hardcopy	1:165,000

Table 7.4. Cropland and forest areas at different dates.

Date	Land use	Number of pixels	Pixel size (m^2)	Area (m^2)	Area (%)
1971	Crop	3,293,993	10	32,939,930	31.0
	Forest	7,335,074	10	73,350,740	69.0
1972	Crop	2,839,477	10	28,394,770	26.7
	Forest	7,805,481	10	78,054,810	73.3
1976	Crop	3,972,554	10	39,725,540	37.3
	Forest	6,672,404	10	66,724,040	62.7
1985	Crop	7,910,317	10	79,103,170	74.4
	Forest	2,721,766	10	27,217,660	25.6
1991	Crop	8,312,294	10	83,122,940	78.1
	Forest	2,332,664	10	23,326,640	21.9

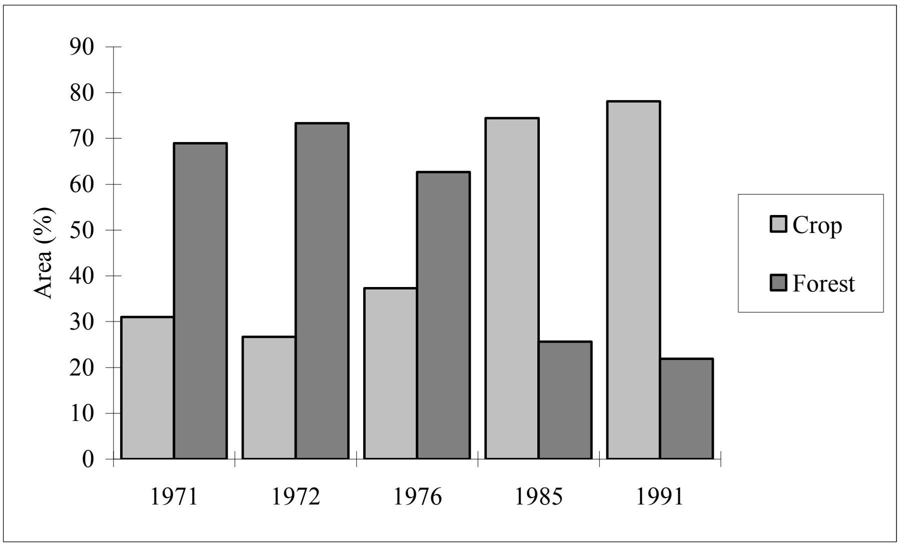


Figure 7.2. Land use changes in the Burruyacú area from 1971 to 1991.

The cumulative curves of cropland areas versus forest areas are shown in Figure 7.3, indicating a steady reduction of the forest cover between 1972 and 1985. The increase in forest area from 1971 to 1972 is an artifact attributed to the inaccuracy of image interpretation because of scale differences between the documents used (photomosaic at 1:50,000 for 1971 and hardcopy of Landsat image at 1:250,000 for 1972). The forest area should be obviously less in 1972. Land use changes at the selected dates are shown in Figures 7.4 to 7.7.

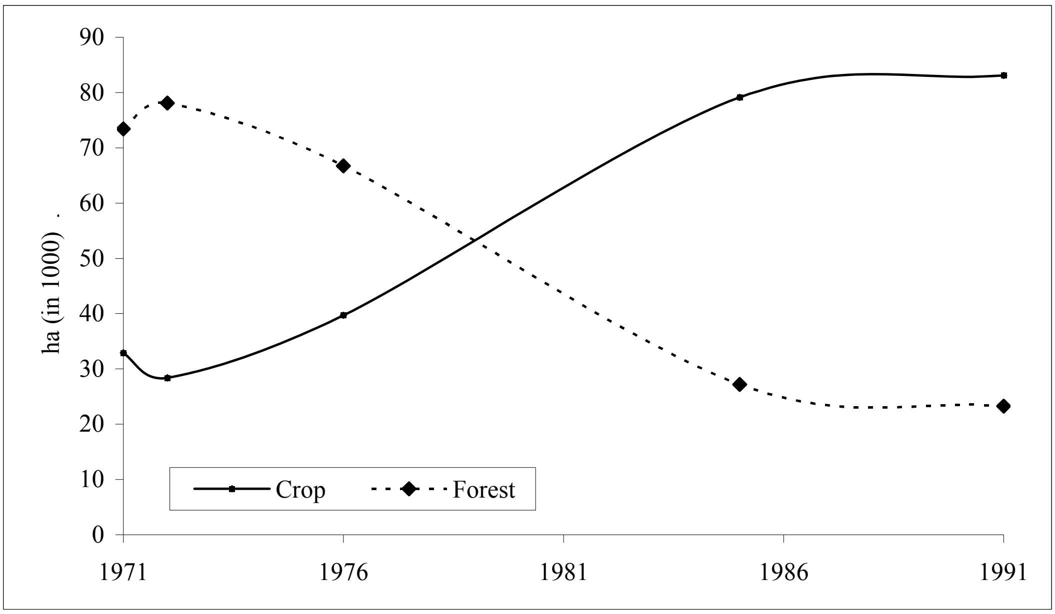


Figure 7.3. Land use changes in the Burruyacú area during the period 1971-1991.

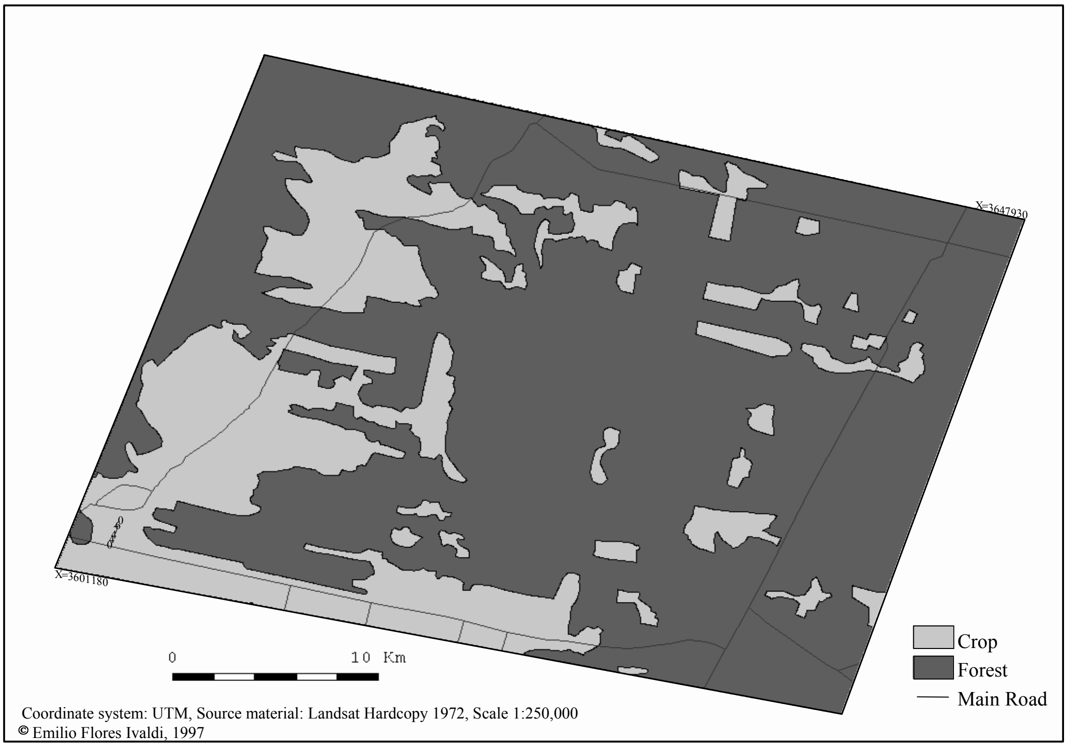


Figure 7.4. Land use in the Burruyacú area in 1972.

Figure 7.5. Land use in the Burruyacú area in 1976.

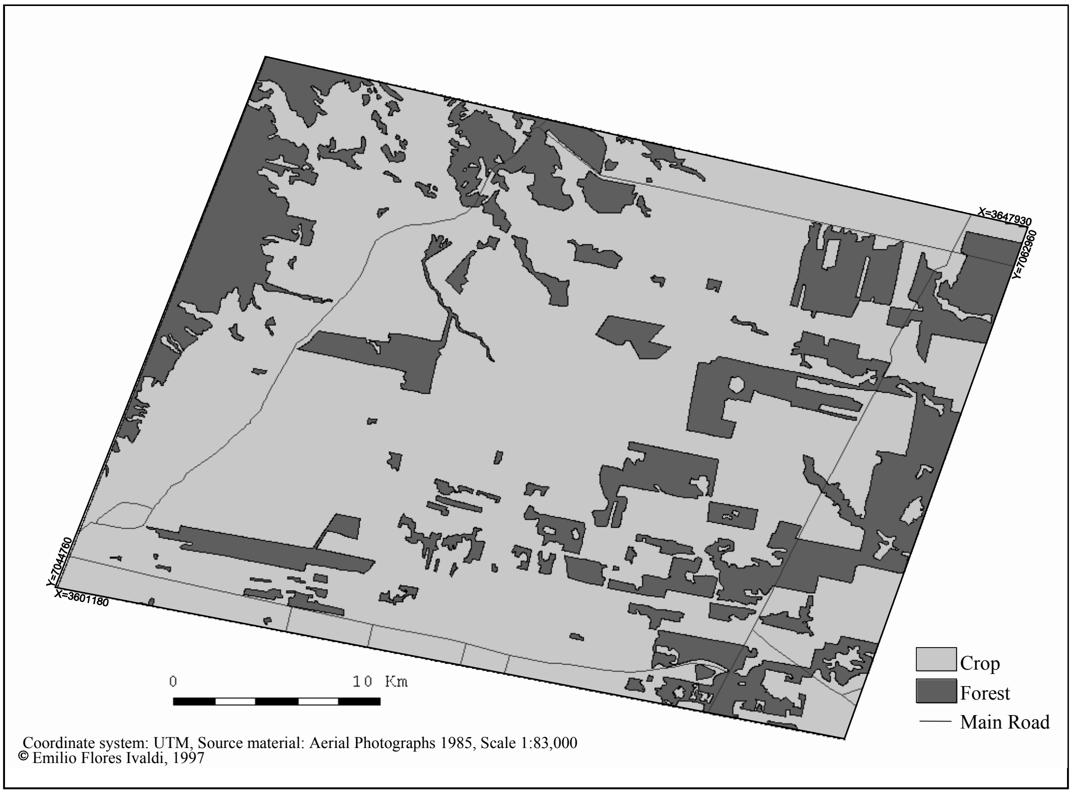


Figure 7.6. Land use in the Burruyacú area in 1985.

Figure 7.7. Land use in the Burruyacú area in 1991.

7.4. MODELLING LAND USE CHANGES

The visual interpretation image maps and the topographic map were digitized using the ILWIS software (ITC, 1997). The topographic map was used as base map for georeferencing the visual interpretation maps. As the visual interpretations covered different areas, a window matching all of them was selected. This window area was cut out of each original raster map, using the following equation for mapcalculation in ILWIS:

mcalc make85{byte}: = if(mask,vi85,-32767)

The above equation creates a new file called make85 that has the same area as the mask file. The number -32767 stands for an undefined pixel value and is assigned to each pixel outside the mask area. The equation was applied to all original raster files using a batch file. All files have the same size of 10,632,083 bytes.

The land use changes between 1971 and 1991 were modelled using mapcalculation and colour-composite modules of the ILWIS software. Visual image interpretations were overlaid after conversion to raster files. Mapcalculation and colour-composite modules of ILWIS were applied for making maps of land use changes, according to the following steps. First, the two oldest data set files, corresponding to 1971 and 1972 respectively, were overlaid. The resulting file, called 1971-1972 results, shows the land use changes taking place in the period 1971-1972. Then, the 1971-1972 results file and the file of the next land use data available, i.e. 1976, were overlaid. A new file was obtained, which was called 1972-1976 results. This method was applied successively to the rest of the available imagery. A final cumulative land use changes map was obtained. The different steps in both mapcalculation and colour-composite modules are explained with more details hereafter. The final maps were exported from ILWIS to Surfer TIF file format for making annotations.

For mapcalculation, three procedures were implemented: (1) a simplified procedure, (2) a non-simplified procedure, and (3) an extreme-dates procedure. The formula used for overlaying the different interpretation images (one per date) was as follows:

newmap:= tablename [1st mapname, 2nd mapname]

As a result, a new map was obtained, which was used as input in the next step (Figure 7.8).

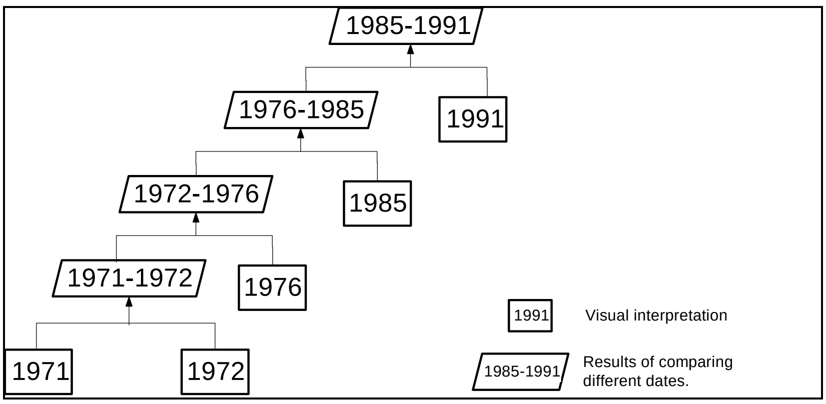


Figure 7.8. General scheme of overlaying files in the simplified and non-simplified procedures.

7.4.1. Simplified mapcalculation procedure

In this approach, the assumption was made that forest would not return after a piece of land is totally cleared for agriculture. Thus, pixels interpreted as crop on an earlier image and as forest on a subsequent one were finally assigned to crop. For instance, to model the land use changes between 1971 and 1972, the following four logical statements were implemented:

(1) when pixel in 1971=crop and pixel in 1972=crop, then pixel in newmap=crop; original crop remains crop, then pixel value 1 remains 1.

(2) when pixel in 1971=crop and pixel in 1972=forest, then pixel in newmap=crop;
it is impossible to get forest after cropping, then pixel value 1 remains 1.

(3) when pixel in 1971=forest and pixel in 1972=forest, then pixel in newmap=forest;
original forest remains forest, then pixel value 2 remains 2.

(4) when pixel in 1971=forest and pixel in 1972=crop, then pixel in newmap=crop;
original forest becomes crop in 1972, then pixel value 2 becomes 3.

The possible pixel values in the new map are 1, 2 and 3, where 1 is constant crop, 2 is constant forest and 3 is a change from forest to crop.

In this way, four two-dimensional tables were created in ILWIS for overlaying the different files (Table 7.5.). The example given above corresponds to the two-dimensional table Simple1. In the two-dimensional tables, the numbers 1 and 2 are pixel values corresponding to original crop and forest in 1971, respectively. The other numbers represent the land use changes between the different dates.

Table 7.5. Tables used in the simplified procedure for identifying land use changes.

Simple1				Simple2				Simple3				Simple4			
		1972				1976				1985				1991	
	0	0	0		0	0	0		0	0	0		0	0	0
	0	1	1		0	1	1		0	1	1		0	1	1
1971	0	3	2	1972	0	4	2	1976	0	5	2	1985	0	6	2
					0	3	3		0	3	3		0	3	3
									0	4	4		0	4	4
													0	5	5

In the simplified procedure, the formula sequence was applied in a batch file as follows:

simp7172:= simple1[i71,i72]
simp7276:= simple2[simp7172,i76]
simp7685:= simple3[simp7276,i85]
simp8591:= simple4[simp7685,i91]

Using this procedure, four land use change maps were created to show land use changes between consecutives dates. The final cumulative map obtained with the simplest criterion, i.e. no forest after cropping, recapitulates all land use changes that occurred between 1971 and 1991, period per period (Figure 7.9). The legend entries have the following meaning:

C71-91: original crop use remains.
F71-91: original forest use remains.
C71-72: land use changes from forest to crop between 1971 and 1972.
C72-76: land use changes from forest to crop between 1972 and 1976.
C76-85: land use changes from forest to crop between 1976 and 1985.
C85-91: land use changes from forest to crop between 1985 and 1991.

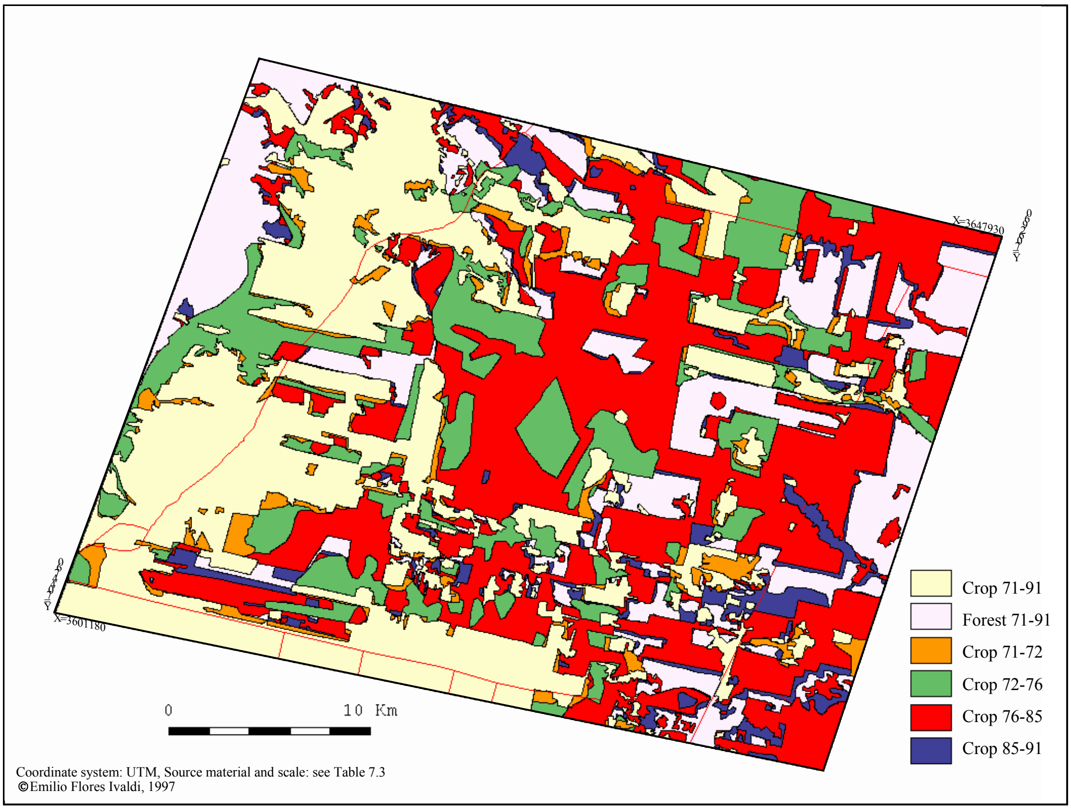


Figure 7.9. Land use changes in the Burruyacú area during the period 1971-1991 using the simplified procedure.

7.4.2. Non-simplified mapcalculation procedure

In this procedure, the following two assumptions were made:

- It is not possible to obtain forest after cropping when comparing the interpretations of 1971 and 1972 and when comparing the 1971-1972 results with the interpretation of 1976.
- It is possible to obtain forest after cropping when comparing the 1972-1976 results with the interpretation of 1985 and when comparing the 1976-1985 results with the interpretation of 1991.

The above criteria are based on the hypothesis that abandoned cropland cannot be recolonized by forest or shrub at short-time intervals. A five-year interval was selected as a time threshold. Thus, the two-dimensional tables Simple1 and Simple2 are equal to the tables Nsimple1 and Nsimple2 (Table 7.6).

Table 7.6. Tables used in the non-simplified procedure for identifying land use changes.

Nsimple1				Nsimple2				Nsimple3				Nsimple4			
		1972				1976				1985				1991	
	0	0	0		0	0	0		0	0	0		0	0	0
	0	1	1		0	1	1		0	1	6		0	1	8
1971	0	3	2	1971-72	0	4	2	1972-76	0	5	2	1976-85	0	7	2
					0	3	3		0	3	6		0	3	9
									0	4	6		0	4	9
													0	5	9
													0	10	6

Similarly to the previous procedure, the mapcalculation module was executed using the following equations in a batch file:

cros7172:= Nsimple1[i71,i72]
cros7276:= Nsimple2[cros7172,i76]
cros7685:= Nsimple3[cros7276,i85]
cros8591:= Nsimple4[cros7685,i91]

Likewise the simplified procedure, this procedure also generated four land use change maps to highlight land use changes between consecutive dates. The final cumulative map, which recapitulates all land use changes that occurred between 1971 and 1991, period per period, is shown in Figure 7.10. The legend entries have the following meaning:

C71-91: original crop use remains.
F71-91: original forest use remains.
C71-72: land use changes from original forest to crop between 1971 and 1972.
C72-76: land use changes from original forest to crop between 1972 and 1976.
C76-85: land use changes from original forest to crop between 1976 and 1985.
C85-91: land use changes from original forest to crop between 1985 and 1991.
F76-85: land use changes from original crop to forest between 1976 and 1985.
F85-91: land use changes from original crop to forest between 1985 and 1991.
C76 F91: land use changes from crop in 1976 to forest between 1976 and 1991.
F85 C91: land use changes from forest in 1985 to crop between 1985 and 1991.

Figure 7.10. Land use changes in the Burruyacú area during the period 1971-1991 using the non-simplified procedure.

7.4.3. Extreme-dates procedure

In the extreme-dates procedure, only the earliest (1971) and the most recent (1991) interpretation maps were compared to detect land use changes. Forest regeneration was assumed to be possible because of 20 years difference between the dates. A two-dimensional table, called cros7191, was created in ILWIS to overlay the interpretations corresponding to the two extreme dates (Table 7.7).

Table 7.7. Two-dimensional table used in the extreme-dates procedure.

Cros7191	1991		
	0	0	0
1971	0	1	1
	0	3	2

The formula used in mapcalculation was as follows:

simp7191:= cros7191[i71,i91]

The map obtained is shown in Figure 7.11. The legend entries have the following meaning:

C71-91: original crop use remains.
F71-91: original forest use remains.
F to C: original forest changes to crop in 1971-1991.
C to F: original crop changes to forest in 1971-1991.

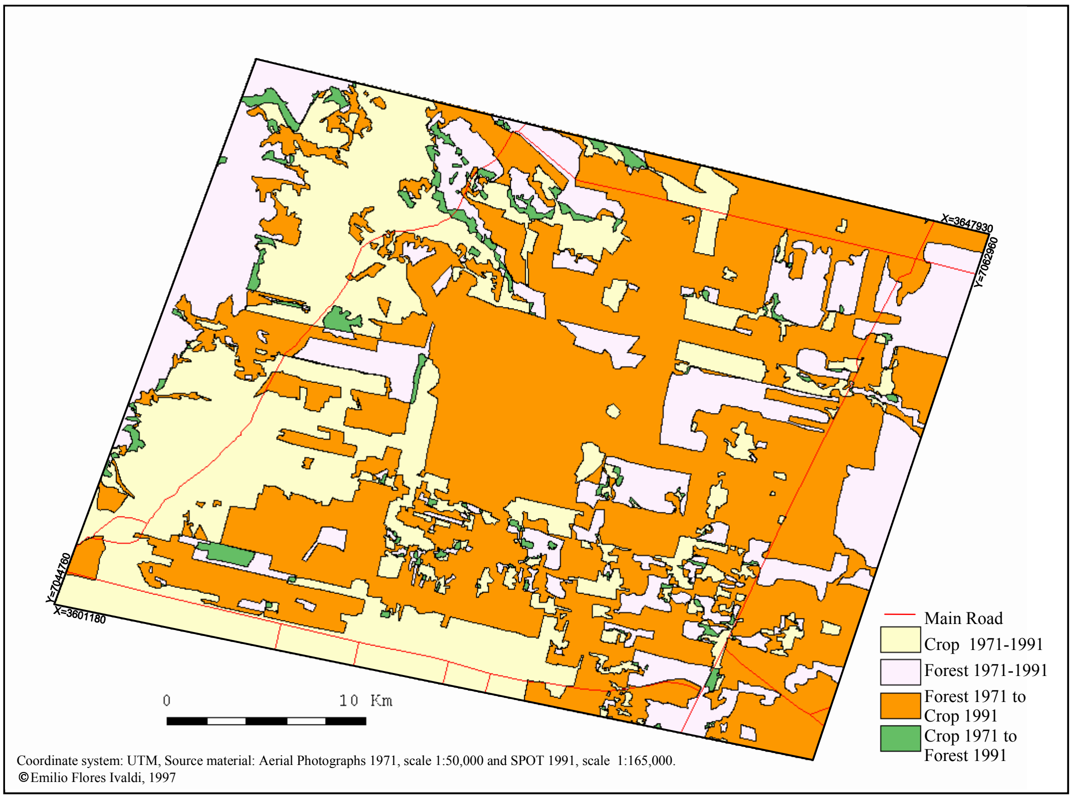


Figure 7.11. Land use changes in the Burruyacú area during the period 1971-1991 using the extreme-dates procedure.

7.4.4. Colour-composite procedure

A fourth procedure, called colour-composite procedure, was applied to the interpretation maps showing land use changes in the Burruyacú area. Three dates were chosen: 1971, 1985 and 1991, on the basis of comparable image scales and time intervals. The images of 1971 (1:50,000), 1985 (1:83,000) and 1991 (1:165,000) have larger scales than those of the images of 1972 (1:250,000) and 1976 (1:500,000). The years 1971 and 1991 are the end-members of the time span for which remotely-sensed data are available, while 1985 is a convenient intermediate date.

Each image was assigned a colour such as: red for 1971, green for 1985 and blue for 1991. When a composite image is created in ILWIS, each file is stretched and a colour is assigned to each band, corresponding to a specific date in this case. Thus, after stretching the files, the forest pixel value is equal to 0 and the crop pixel value is equal to 255. Each image having only two pixel values, the number of possible combinations in the final image is 2^3. It means that there are only eight pixel values or eight different colours in the final product.

Red (R), green (G) and blue (B) are the additive primary colours. By mixing these primary colours, complementary colours are produced, including magenta (M), yellow (Y) and cyan (C). According to the additive colour theory, when all three primary colours are added, the resulting colour is white. On the other hand, if colours are not added, the resulting colour is black or absence of colour. Using these eight colours, a colour-composite map was obtained (Figure 7.12). The eight possible combinations of pixel values for the chosen dates are shown in Table 7.8.

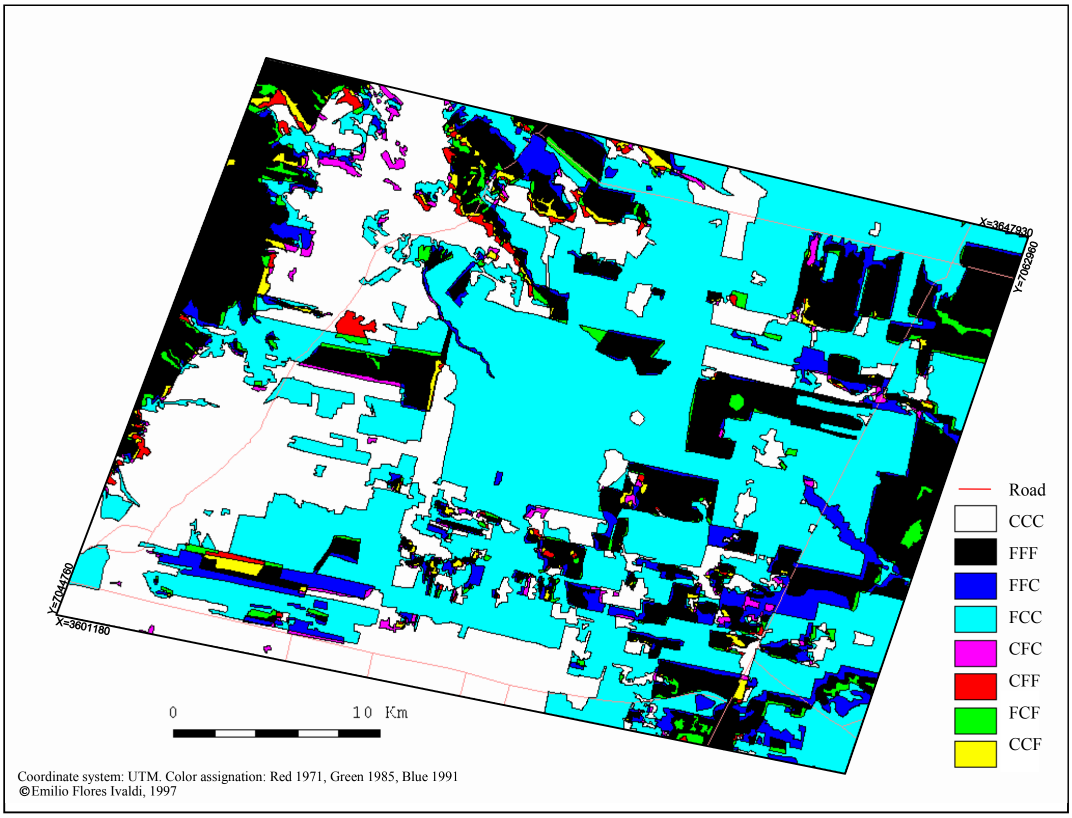


Figure 7.12. Land use changes in the Burruyacú area during the period 1971-1991 using the colour-composite procedure (C: crop; F: forest).

Table 7.8. Eight possible combinations of land uses in the colour-composite procedure.

1971	1985	1991	Colour	Sequence of land uses (1971/1985/1991)
255	255	255	White	CCC = Crop Crop Crop
0	0	0	Black	FFF = Forest Forest Forest
0	0	255	Blue	FFC = Forest Forest Crop
0	255	255	Cyan	FCC = Forest Crop Crop
255	0	255	Magenta	CFC = Crop Forest Crop
255	0	0	Red	CFF = Crop Forest Forest
0	255	0	Green	FCF = Forest Crop Forest
255	255	0	Yellow	CCF = Crop Crop Forest

(0 means forest and 255 means crop)

7.5. MAGNITUDE AND RATES OF LAND USE CHANGES

The areas corresponding to all identified land uses and land use changes were calculated using the simplified, non-simplified, extreme-dates and colour-composite procedures. For that purpose, the histogram function of ILWIS was applied to each final map. Numbers of pixels, areas in hectares and areas in percentages were calculated (Table 7.9 and Figures 7.13 to 7.16).

Deforestation rates were calculated by using the simplified procedure data and dividing the land use change area (in ha), from forest to crop, by the number of years (Table 7.10).

After adding up the changes detected during the four selected periods, each procedure gave a total figure of the magnitude of the land use changes that occurred over the whole time span 1971-1991, such as follows: 53.6% by the simplified procedure; 57.1% by the non-simplified procedure; 49.4% by the extreme-dates procedure; and 55.3% by the colour-composite procedure. The best approach is the simplified procedure, because it takes into account all the imagery available and operates with a limited number of six land use change classes, which allows easy interpretation. The extreme-dates procedure, which uses only four land use change classes and two images, provides the lowest land use change figure. The colour-composite procedure, easy and fast to apply, is suitable to show land use changes over three dates. The non-simplified procedure is the most complicated approach, but also the only one that considers the possibility of forest regeneration. The advantages and disadvantages of the different procedures are listed in Table 7.11.

Table 7.9. Extent of land uses and land use changes.

Land use changes	Number of pixels	Area (ha)	Area (%)
Simplified procedure			
Crop 1971-1991	3,291,112	32,911	31.0
Forest 1971-1991	1,626,581	16,266	15.3
To crop 1971-1972	439,184	4,392	4.1
To crop 1972-1976	1,445,408	14,454	13.6
To crop 1976-1985	3,316,963	33,170	31.2
To crop 1985-1991	496,971	4,970	4.7
Non-simplified procedure			
Crop 1971-1991	2,924,847	29,248	27.6
Forest 1971-1991	626,581	16,266	15.3
To crop 1971-1972	358,319	3,583	3.4
To crop 1972-1976	1,137,675	11,377	10.7
To crop 1976-1985	3,126,337	31,263	29.5
To crop 1985-1991	496,971	4,970	4.7
To forest 1976-1985	331,142	3,311	3.1
To forest 1985-1991	110,676	1,107	1.0
Crop 1976 to forest 1991	245,522	2,455	2.3
Forest 1985 to crop 1991	258,149	2,581	2.4
Extreme-dates procedure			
Crop 1971-1991	3,054,528	30,545	28.7
Forest 1971-1991	2,084,251	20,842	19.6
Forest to crop 1991	5,250,823	52,508	49.4
Crop to forest 1991	239,465	2,394	2.3
Colour-composite procedure			
CCC	2,927,036	29,270	27.5
FFC	627,628	6,276	5.9
FCC	4,623,195	46,232	43.5
CFC	127,492	1,275	1.2
CFF	111,368	1,114	1.1
FFF	1,829,626	18,296	17.2
FCF	254,625	2,546	2.4
CCF	128,097	1,281	1.2

Pixel size: 10 m^2; C: crop; F: forest; CCC: crop in 1971, crop in 1985, crop in 1991.

Figure 7.13. Changes from forest to crop in the period 1971-1991, using the simplified procedure (% of the total area).

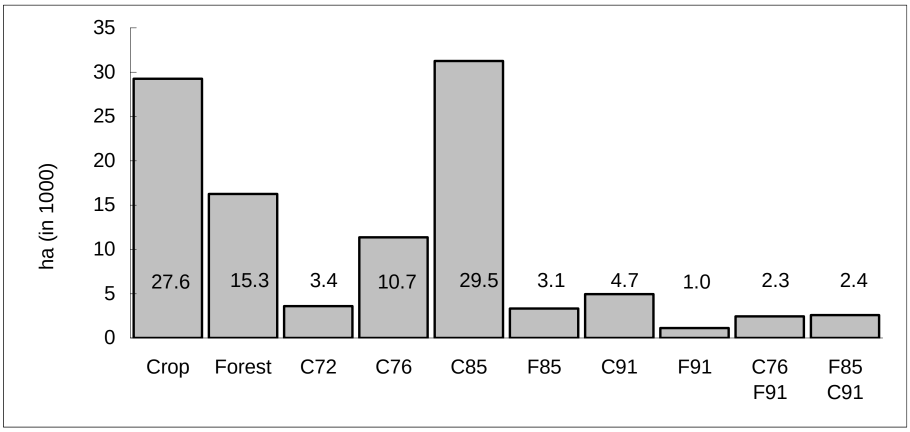


Figure 7.14. Land use changes in the period 1971-1991, using the non-simplified procedure (% of the total area) (C: crop; F: forest).

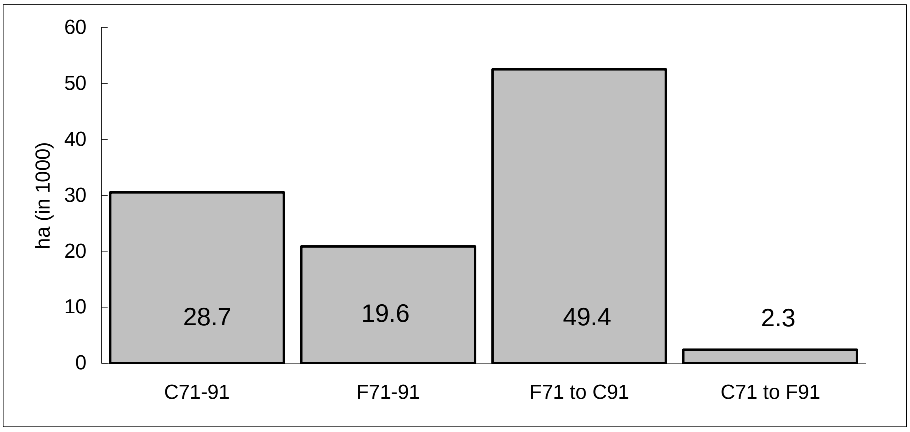


Figure 7.15. Land use changes in the period 1971-1991, using the extreme-dates procedure (% of the total area) (C: crop; F: forest).

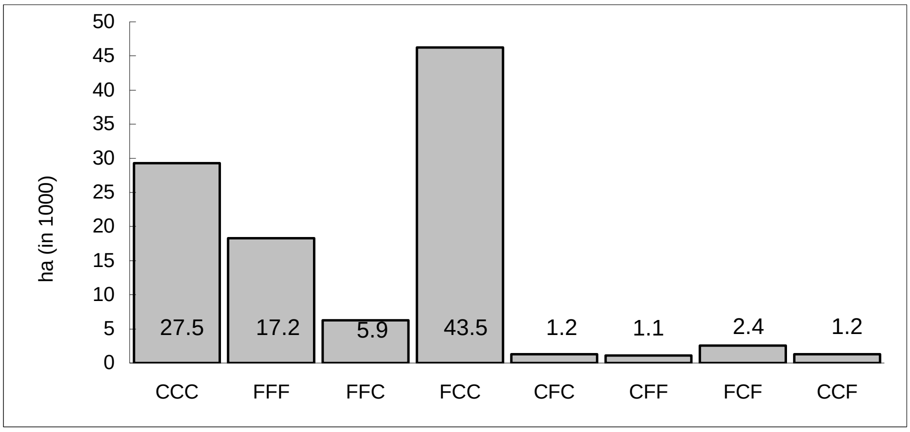


Figure 7.16. Land use changes in the period 1971-1991, using the colour-composite procedure (% of the total area) (C: crop; F: forest; CCC: crop in 1971, crop in 1985, crop in 1991).

Table 7.10. Deforestation rate (ha year^{-1}) from 1971 to 1991.

Time interval	Deforested area (in % of forest land in 1971)	Surface area (ha)	Interval length (years)	Deforestation rate (ha year^{-1})
1971-1972	5.9	4,392	1	4,392
1972-1976	19.7	14,454	4	3,614
1976-1985	45.2	33,170	9	3,685
1985-1991	6.8	4,970	6	828
1971-1991	77.7	56,986	20	2,849

Table 7.11. Advantages and disadvantages of the various land use change detection procedures.

Procedure	Advantages	Disadvantages
Simplified	• Less units, thus easy to read • All images exploited, thus more data for comparison	• Large scale differences between data source documents • Dissimilar source data (aerial photographs and satellite images) • Four tables needed • Four steps in ILWIS
Non-simplified	• All images exploited, thus more data for comparison • Considers the possibility of forest regeneration after cropping	• Large scale differences between data source documents • Dissimilar source data (aerial photographs and satellite images) • More land use changes, thus more difficult to read. • Four tables needed • Four steps in ILWIS
Extreme-dates	• Less land use change classes, thus easy to read • Use of comparable scale data • Only one step in ILWIS	• Only two images used
Colour-composite	• Less land use change classes, thus easy to read • Use of comparable scale data • Easy and fast procedure • Only one step in ILWIS	• Only three images used

7.6. LAND USE CHANGE FACTORS

According to data from Burruyacú, La Ramada and Gobernador Garmendia stations, annual rainfalls fluctuated considerably around a long-term regional mean of 867 mm over the largest part of the last century (1916-1989). However, from the beginning of the 1970s, rainfall consistently increased, especially in the western and southern parts of the study region (Figures 7.17 and 7.18) (Minetti & Sierra, 1984; Minetti et al., 1985; Minetti & Poblete, 1989; Minetti, 1994; Minetti & Lamelas, 1996). This is reflected in the land use changes of the years 1971 and 1972, when crops developed in areas with high rainfall and good accessibility, thus mainly in the west, along the piedmont, and in the south, along road 304.

Cropland substantially increased in the west of the study region during the period 1972-1976. Two large areas, without connection in 1972, had already merged in 1976. The 1976 land use interpretation map shows that the cropland area slightly increased by comparison to 1972. This can be related to increasing rainfall in the period 1972-1976, but also to land tenure in the Burruyacú area, where a few large farms (e.g. La Argentina and Budeguer) increased cropland along secondary roads.

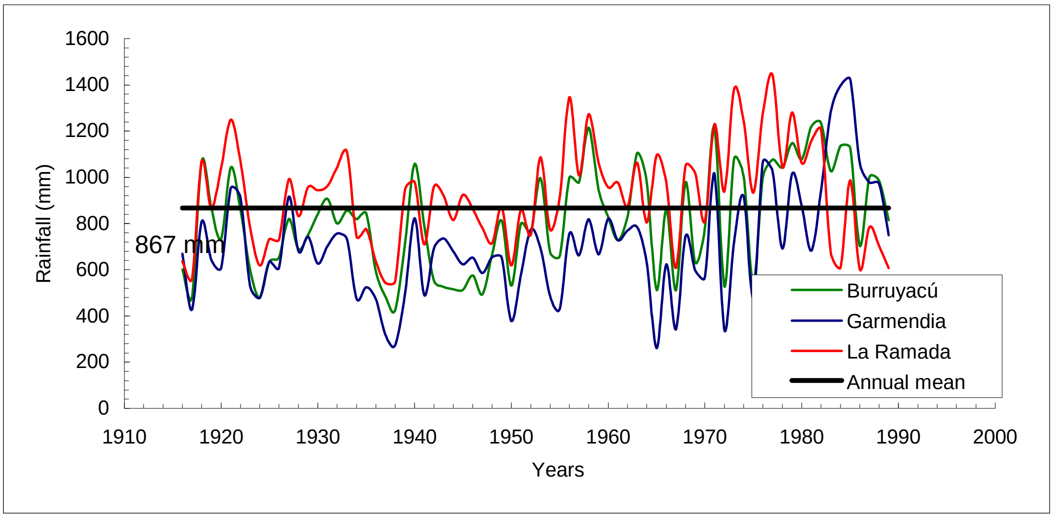


Figure 7.17. Annual rainfalls and mean rainfall at three stations in the Burruyacú area during the period 1916-1989.

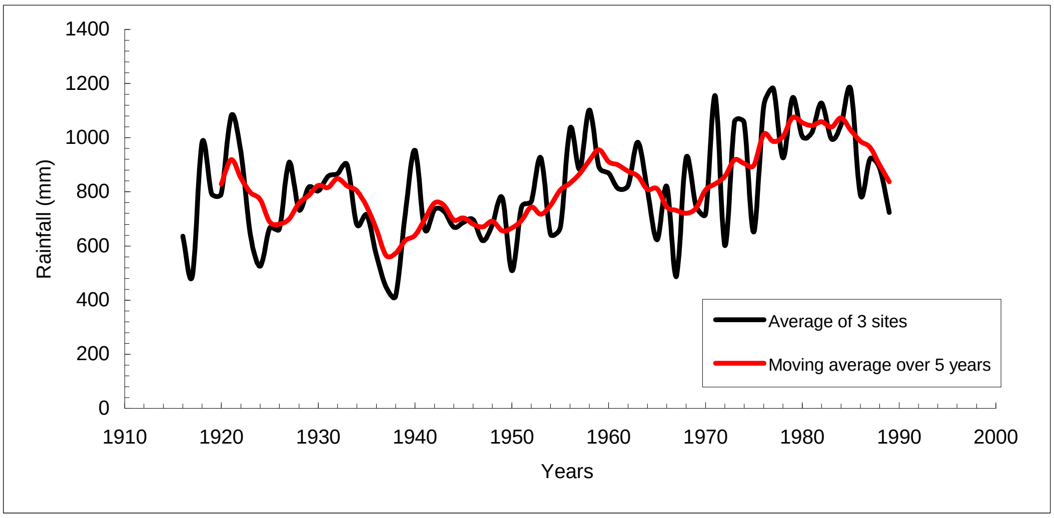


Figure 7.18. Average and moving average of annual rainfalls at three stations (Burruyacú, Garmendia and La Ramada) of the Burruyacú area during the period 1916-1989.

The most important land use changes took place in the period 1976-1985. Although this interval is longer than the previous one (1971-1976), increasing rainfall played an important role in promoting cropland expansion (Figure 7.18). Large forest patches survived only in the eastern part of the study region because of less rainfall and unpaved access ways. West of road 304, forest subsisted because of sloping piedmont relief. In the following period (1985-1991), land use changes became less significant, with the incorporation of fewer areas into cropland, mainly along road 34 and in the central part of the study region.

Annual rainfall is strongly variable not only in the drier east of the area (Gobernador Garmendia) but also in the moister west (Burruyacú, La Ramada). Rainfall varies practically from year to year, with large differences per sets of 2-3 years, making crop planning hazardous. In spite of this inter-annual variability, trends appear after normalizing the annual rainfall data by means of 5-year moving averages (Figure 7.18). Multi-annual periods of lower and higher rainfall succeed each other in coarse cycles of 10-20 years. The development of soybean cultivation in the early 1970s roughly coincided with the beginning of a cycle of relative rainfall abundance, which started declining again in the late 1980s. The lack of data for the decade 1990-2000 does not allow extending the correlation soybean-rainfall into recent years. But rainfall decrease certainly puts at risk soybean cultivation in the drier east of the study area and will much likely slow down the expansion of the agricultural frontier eastwards.

7.7. CONCLUSION

Over the 20-year period considered (1971-1991), the main factors that played a role in cropland expansion were: increasing rainfall, suitable soils, attractive market price for soybean, easy accessibility, and favourable land tenure with large farms. Land use changes were substantial in the period 1971-1985, but less in the period 1985-1991. Although data in Figures 7.13 to 7.16 are not fully comparable, depending upon the procedure used for detecting land use changes, they show a trend towards sustained conversion of forest to cropland. From the total forest area in 1971, forest clearing was 6% in 1971-1972 (3% per year), 20% in 1972-1976 (5% per year), 45% in 1976-1985 (5% per year) and 7% in 1985-1991 (1% per year), at an average annual rate of 2850 ha. According to the deforestation rates reported in Table 7.10, the period of more land reclamation was 1971-1985, coinciding with increasing rainfall in the area of Burruyacú (Figure 7.18). Eastward, the station of Garmendia shows a remarkable rainfall peak in the mid-1980s (Figure 7.17), corresponding to the incorporation of new areas to agriculture (Figure 7.16).

After completion of this project, Busnelli continued tracing the pace of deforestation in the area using Landsat data of 1997 and 2003. Additional 5,296 ha (4.8% of the area) were cleared in the period 1991-1997 and 4,588 ha (4.2%) in the period 1997-2003. By 2003, only 10,650 ha representing 9.6% of the original Chaco forest remained, mainly as small fragmented patches spread all over the area. Cropland ascended from 33,512 ha (30.3%) in 1971 to 99,880 ha (90.4%) in 2003 (Busnelli, 2003). Thus, deforestation has now reached a critical threshold where the remaining forest tracts are unable to play any role as environmental regulator or as backup resource (Casas & Michelena, 1983).

7.8. REFERENCES

Busnelli, J., 2003. Land use changes in the Burruyacú district, northwest of Argentina. Instituto de Geociencias y Medioambiente, Universidad Nacional de Tucumán. S.M. de Tucumán, Argentina (unpublished).

Casas, R.R., Michelena, R.O., 1983. La degradación de los suelos y la expansión de la frontera agropecuaria en el Parque Chaqueño Occidental. IDIA-INTA, Buenos Aires. Suplemento 36: 141-146.

Cygul, J.T., Hariston, J.E., White, F.C., 1977. Land use change detection from satellite imagery. Proceedings of AAEA Meeting.

Dennis, R.A., White, J.C., 1991. Land use monitoring in the lower Indus Valley, Pakistan. Bulletin Société Française de Photogrammétrie et de Télédétection 121: 62-66.

ESA, 1989. Using topographical maps to improve classification results from satellite imagery. European Space Agency. Earth Observation Quarterly 25: 6-8.

Hemsy, V., 1970. El cultivo de la soja en Tucumán: trabajos experimentales y estudios realizados. Revista Agronómica del Noroeste de Argentina VIII (1-2): 141-144.

ITC, 1997. Integrated Land and Water Information System (ILWIS). International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

La Gaceta, 1996. El riego como alternativa de desarrollo del Este. Artículo publicado 30-06-1996. S.M. de Tucumán, Argentina.

Minetti, J., 1994. Régimen de variabilidad de la precipitación en el Este de Tucumán y Oeste de Santiago del Estero. III Parte: el salto climático de la década de 1950 en la precipitación mensual. INTA, Reporte interno. Tucumán, Argentina.

Minetti, J., Lamelas, C.M., 1996. Respuesta regional de la soja en Tucumán a la variabilidad climática. Revista de la Estación Experimental Obispo Colombres 72.

Minetti, J., Poblete, A.G., 1989. El salto climático de la década de 1950 en Tucumán: análisis de diagnóstico y consecuencias. Rev. Ind. y Agric. de Tucumán 66 (1): 119-136.

Minetti, J., Sierra, E., 1984. Expansión de la frontera agrícola en Tucumán y el diagnóstico climático. Rev. Ind. y Agric. de Tucumán 62 (2): 109-126.

Minetti, J., García, A.I., Dora de Desjardins, N.S., Suarez, L., 1985. Exploración pluviométrica en la cuenca del río Tajamar y zonas adyacentes, Depto. Burruyacú, Provincia de Tucumán. Rev. Ind. y Agric. de Tucumán 62 (2): 69-77.

Ram, B., Kolarkar, A.S., 1993. Remote sensing application in monitoring land-use changes in arid Rajasthan. International Journal of Remote Sensing 14: 3191-3200.

Singh, R.B., 1992. Remote sensing and GIS as decision support systems in the Himalayas. Annals of the National Association of Geographers 12. New Delhi, India, pp.1-2.

Vicini, L., 1984. La cobertura boscosa de los Departamentos de Burruyacú, Cruz Alta y Leales, Provincia de Tucumán, Argentina. Informe interno INTA, Banda del Río Salí, Tucumán, Argentina.

Zuccardi, R.B., Fadda, G.S., 1985. Bosquejo agrológico de la Provincia de Tucumán. Miscelánea 86. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. S.M. de Tucumán, Argentina.

CHAPTER 8

SOIL AND LAND MANAGEMENT ASPECTS

E. Bergsma, L. Neder

8.1. INTRODUCTION

Sustainable development is a concept that integrates several criteria relating nature to society. From an ecological viewpoint, sustainability requires that development be compatible with the maintenance of ecological processes, biological diversity and elementary resources. From a social standpoint, development should strengthen community identity and be economically effective and equitable within and between generations. Geographical sustainability involves a harmonious process among environmental systems, attenuating the dysfunctions of the territory, promoting its capabilities and limiting its vulnerability (Casas, 1998).

The fast and intensive agricultural development in the study area over the last two decades does not seem to match these criteria and raises the question of its sustainability. The expansion of the agricultural frontier incorporated new areas into farming and current technology achieved higher crop production. But technological advance masks ongoing land degradation, including soil fertility loss and physical deterioration. New land management and farming practices are needed to minimize the unfavorable impacts of sprawling agricultural development. In this chapter, aspects of soil and land management are analyzed, from land reclamation to land use.

8.2. FACTORS INFLUENCING LAND USE AND LAND MANAGEMENT

Land use is determined by the decisions made by land users, taking into account the possibilities and limitations of the natural environment, but also considerations related to infrastructure, markets and governmental policy (Figure 8.1). The farmer's decision on land use is based on the interaction of many factors as shown in Table 8.1. Some factors have a household character, others relate to soil degradation aspects of physical, chemical and biological nature. The relation between soil characteristics and crop growth conditions is best shown by looking at groups of soil characteristics that determine certain soil qualities for crop growth. Soil qualities describe fundamental conditions necessary for specific land use types, such as for instance arable land use. Soil qualities are frequently used in the evaluation of land for its suitability. The relation between soil characteristics and main soil qualities for plant growth is shown in Table 8.2. Soil characteristics that require laboratory data can be approximated from related soil characteristics, observable or measurable in the field, using pedo-transfer functions. The soil qualities of Table 8.2 are the five important ones that are often used in land evaluation. For more detail, several more land qualities can be used.

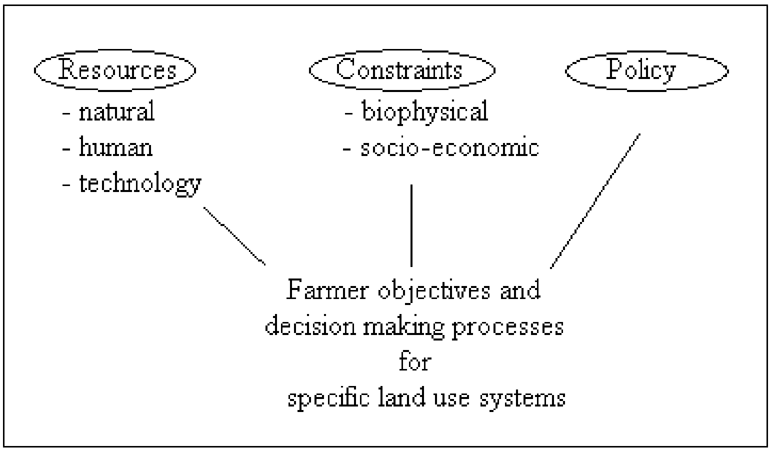


Figure 8.1. Factors influencing farmer's decision making.

Table 8.1. Factors influencing farmer's land use decisions.

- Deforestation and climate change*
- Household perspectives
- Transportation cost and infrastructure
- Risks:
    - political risk or policy failure
    - crop production risk*
    - agricultural trade risk
    - food price risk
    - employment risk
    - health risk
- Soil degradation versus sustained use, alternative systems of land use *
- Soil degradation and soil characteristics:
  - Soil physical dynamics:*
    - compaction and hard-setting
    - erosion
    - decrease of organic matter
    - dryer soil moisture regime
    - less favourable soil structure for plant growth
  - Soil chemical dynamics, especially fertility depletion through:
    - harvest
    - erosion and runoff *
    - leaching
    - decrease in CEC through loss of organic matter
    - acidification
    - toxicity
  - Soil chemical dynamics through analysis of*:
    - the nutrient stock in the soil
    - K, Mg, Ca, nitrate and sulphate
    - loss by erosion
    - loss by runoff
    - loss by leaching
    - recycling in the soil => replenishment
  - Soil biological dynamics as an integral part of the soil system:
    - decline in soil organic matter
    - reduction in soil macro- and micro-flora
- Integrated pathways to sustainable systems

** = Subjects which received special attention in this project*
Based on: Lal & Stewart (1990); Ellis & Mellor (1995); Brady (1996)

Table 8.2. Soil characteristics and main soil qualities for plant growth

Soil characteristics	Soil qualities				
	Availibility of nutrients	Availibility of oxygen	Availibility of water	Possibilities of mechanization	Resistance to erosion
Soil texture	+		+	+	+
Soil structure, porosity, rooting	+	+	+	+	+
Topsoil clay type	+		+	+	+
Weatherable minerals	+				
Organic matter	+		+		+
Base saturation / pH	+			+	+
Soil depth	+		+	+	+
Gravel content	+		+	+	+
Colour and mottling		+	+		
Soil sealing / crusting	+	+	+		+
Drainage		+		+	
Slope steepness and form				+	+
Size, shape and access of land unit	+		+	+	+
Stoniness, rockiness	+		+	+	+

\+ *= characteristic important for a given soil quality*

8.3. LOCAL FARMING PRACTICES

Data and information on farming practices applied in the study region were collected by L. Neder from interviews and personal communications with farmers and extension officers (Neder, 1995).

8.3.1. Evolution of agricultural development

Manual forest clearing for agricultural land use started in the early 1960s. Soybean cultivation began between 1963 and 1965; the crop was harvested manually and threshed in bags. From 1973 onwards, herbicides started being used, harvest was carried out with a threshing machine, and tree clearing was done mechanically. Around 1980, the chisel plough was introduced and uneven terrains were leveled out. In undulating fields, conservationist farming was put into practice with contour ploughing. Some producers began to implement direct sowing. From 1985, new crop varieties were used with post-emergent herbicides that markedly increased yields due to genetics rather than to soil fertility. In 1990-1991, the PROPECO Project was created, providing access to modified heavy-duty machinery designed to avoid soil compaction. Fertilizers were used and direct sowing was implemented. In 1995, an insect-resistant soybean variety provided by INTA (Instituto Nacional de Tecnología Agropecuaria) was introduced. Further, new soybean varieties requiring high doses of herbicides and insecticides were recommended to farmers.

8.3.2. Conservationist farming

Traditional horse-powered farming has practically disappeared by now. Over the last years, farmers have replaced the conventional blade plough that returns and inverts the arable layer, by the chisel plough that affects the soil structure to a lesser degree and leaves crop residues on the terrain surface. Some farmers intend to apply the principles of conservationist agriculture and try to overcome the traditional way of agricultural production by means of an integral management of resources to attain a larger and better production (Gargicevich & Massoni, 1991).

8.3.3. Crop rotation

Crop rotation, essential to soil management, consists of a series of crops and agricultural practices used on the same soil and arranged in the course of time, while monoculture is the repetition of a certain crop in the same place. Crop rotation allows farmers to maintain or even improve soil fertility, control plant diseases, vary stubble type and quality, make efficient use of available water, and reduce climatic risks. But it also leads to soil exhaustion, pest proliferation and propagation of the diseases proper to each crop included in the rotation system (Casas, 1998).

In the study region, the most frequent crop combination is soybean with wheat, which allows obtaining higher profits from two annual harvests, keeping the soil covered most of the year and preventing excessive depletion of soil nutrients. Both crops are sown in rows but with different spacing, so that soybean can be seeded immediately after harvesting the winter wheat.

8.3.4. Direct sowing

Direct sowing is a technology applied to a production system as a whole rather than a particular technique for a certain crop. It is based on the interaction between crops and the management of water, soil, weeds, diseases and the use of agrochemicals. Direct sowing implies working only on a narrow land strip where seeds are sown on the previous cultivation stubble with no soil removal, generating higher profits in the short term. In 1995-1996, this technology was applied on about 60,000 ha in the province of Tucumán. Nowadays, 95% of the producers use direct sowing.

Direct sowing contributes to the sustainability of the production system, because it is accompanied by balanced fertilization, crop rotation, integrated management of pests and diseases, weed control, improved use of water, protection against erosion, improvement in soil biological activity, and increased organic matter content. Altogether, it leads to higher yields.

For farmers, direct sowing means efficient use of time and decrease in the amount of machinery, labor and fuel as compared with conventional sowing systems. Fertilization is necessary, since there are essential crop nutrients that cannot be replaced naturally such as phosphorus and potassium, and others that are scarce because they are used up by the crops such as nitrogen (Carmona, 2001).

Crop rotation is essential to the development of the root system because of morphological differences between species. It improves soil porosity, thus favoring water and air storage in the soil, and increases the organic matter content and microbiological activity in the arable layer. Stubble preservation on the soil surface contributes to increasing organic matter and nutrients (Lorenzetti, 2004).

Disadvantages of direct sowing include a strong dependence on chemicals, such as fertilizers and herbicides, and the appearance or increase of pests. It needs strong control in the use of chemicals in order to minimize the margin for error.

8.3.5. Regional variations in production systems

(1) Northern transect

In the western sector, direct sowing has proven to be more effective with fertilizer application, including urea-ammonium phosphate or a triple fertilizer. Yields with and without fertilizers differed in about 400 kg/ha. Phosphorus content in the soil under forest was about 25 mg/kg, but on average 2 mg/kg were lost every year after forest clearing and, after 10 years of cultivation, fertilizers were needed.

After deforestation, an adjustment in soil moisture took place leading to high soybean yields. During the following seven years, yields remained high with the use of herbicides and insecticides. In the first years of cultivation, soybean yielded 2500 kg/ha and maize yielded 5000-6500 kg/ha in summer. Winter wheat also provided good production levels. To the south and west of the study area, production was higher due to more favorable rainfall. In soils with long clearing time, soybean production with direct sowing was low.

In La Argentina, a maize field located at the entrance of the Heguy farm (P6B site) had a clearing time of over 25 years. It was allowed to rest eight years with pastures and, in 1995, was sown with soybean that produced yields of 2000-2500 kg/ha. In another field of the same farm, close to the silos place (M1 site), soybean was sown after eight years of rest under pasture, yielding 2000 kg/ha. Maize production was 6000-6500 kg/ha.

On the San Arturo farm (Rogríguez farm), several fields managed with zero-tillage produced on average 2400 kg/ha soybean. Under conventional tillage, low-quality soybean was obtained, with a yield of 1400 kg/ha.

(2) Southern transect

In La Ramada, different varieties of soybean were grown with direct sowing and abundant herbicide application, generating good yields. Before 1971, the Zavaleta farm was raising 1800 cattle, mainly Creole and Charolais, together with 400 horses and 200 mules, on an area of over 700 ha. In 1983, the farm was converted to agriculture. The most recent clearing ridges are still visible on the field.

On the Vece farm, bean production did not show significant differences between plots with and without fertilization. On this place, harvest residues are not burnt. A yield of 600 kg/ha beans is considered a profitable harvest. In the first years after forest clearing (1973), yields were substantially higher than later.

8.4. LOCAL LAND MANAGEMENT EXPERIENCE

8.4.1. Land management and land degradation

General farm information and yield data have been collected by the Agro-Industrial Experiment Station of Tucumán through on-farm surveys and interviews conducted between 1972 and 1985, with particular attention to the effect of Chaco forest reclamation on soil properties and its consequences on crop yield. More specific information was obtained from personal communication with N. Dantur (Tucumán, 1995) and J. Molina (Buenos Aires, 1995), knowledgeable experts in agricultural issues of Tucumán province.

In Chapter 9 of this report, it is shown that improving soil structure and its stability is crucial for the reduction of erosion and increase in yield. Increased infiltration for plant available water and reduction of overland flow would result. Soil degradation can be reversed by incorporating plant residues. This is easier under sugar cane cultivation, but it should also be possible with suitable rotations including for instance soybean, pasture and other crops. This is the fundamental approach to the problem of soil degradation and its consequences on erosion and inundation. For instance, the transformation of cellulose to organic matter has been observed under rotation of soybean-maize-pasture in Santiago del Estero, next to our study area (Molina, 1995). Deterioration of soil structure occurred already after three years of cultivation with residues removed from the field. When sugar cane residues were incorporated without burning, rapid improvement of soil structure took place, leading to higher crop yields.

Some changes in land management were introduced already during the 1980s (Zuccardi et al., 1987b). Decrease in agricultural production and evidence of water erosion led to new tillage practices, change in agricultural machinery and improvement in pest and disease control. The cultivation of products for export increased, while the cultivation of sugarcane in winter and spring decreased. In general, the occurrence of wetter years than average stimulated the extension of agricultural activities in the area.

8.4.2. Regional conditions for agricultural development

Zuccardi and Fadda (1985) describe the Chaco-Pampean plain, which covers a quarter of the Tucumán province. The plain extends eastward into the province of Santiago del Estero and southward to the province of Catamarca. In general, the relief is flat with slopes below 1%, while it is undulating with slopes up to 4% in the north and northeast. Low ridges occur with a SW-NE direction and decreasing height towards the southeast. Main rivers are the río Urueña and the río Tajamar, but the general drainage system is not well defined.

The area of Tucumán has several advantages for agricultural production, but some of the factors are not fully operating in our study area. There are also natural constraints to farming, compounded by poor soil management (Zuccardi et al., 1989).

(1) Locational and natural advantages

The range of influence of S.M. de Tucumán on the surrounding region might be about 50-100 km from the city. Our study area is somewhat further away. General access roads have been improved over the last years, but local access by secondary roads and farm tracks is still poor. A railway at the eastern border is not operative. There are a few small towns near the study area and scattered farms. The largest town is Burruyacú in the northwest.

Soils derived from loess have good natural fertility under forest cover, but forest has been cleared in patches since 50 years, increasing in rate of reclamation in the last 20-30 years. As a consequence, the natural cycle balancing nutrient supply and loss has been discontinued, and chemical loss has become dominant (Zuccardi et al., 1987a; Zuccardi et al., 1989). Also physical degradation, including plough-pan formation and topsoil densification, increased.

General topography is flat, although there are incisions of ephemeral streams that cut the land to a depth of several meters and, in a few cases, form vales of about 10-20 m deep with colluvial sides. There are also low hilly ridges running SW-NE.

(2) Unfavourable conditions

Weather variability from year to year and between series of drier and wetter years represents a risk for farmers. Ongoing soil degradation is not halted or reversed by better practices to allow incorporation of sufficient quantities of organic residues. This would improve the soil structure and thereby water infiltration, but the change may take a few years. Crop rotation is not widely accepted. Zuccardi (2000) discusses the possibilities for improvement and recovery of the agriculture from a growing decline, especially over the last 15 years, and summarizes the negative impacts of reclamation and poor management on land productivity, as follows:

- mineralization of organic matter, causing a loss of 33 ton carbon per hectare in 25 years;
- decreased cation exchange capacity;
- loss in soil water storage capacity;
- decrease of physical space for root development due to plough-pan formation;
- depletion of soil fertility by continuous removal of nutrients without replacement, with a loss of N, P and K estimated at US$ 72 million per hectare in 10 years;
- widespread erosion as a sign of land management crisis.

(3) Regional variations in cropping conditions

To describe the cropping conditions, a subdivision of the Chaco plain in the study area was made based on climate (Table 8.3). Dairy is mentioned for the central part of the plain and forage crops for the eastern part. The occurrence of strings of years with more or with less rainfall affects the suitability of the land in the central zone. Arable use of the land is successful without irrigation in wetter periods. Water reservoirs are helpful for small fields with high revenue crops in the central plain.

Table 8.3. Cropping conditions in the study area.

Characteristics	Western sector subhumid-humid	Central sector dry-subhumid	Eastern sector semi-arid
Area proportion (%)	14	44	42
Rainfall (mm)	750-1000	650-750	500-650
Pot. evapotranspiration (mm)	900-950	950-1000	>1000
Frost (days per year)	12	12-15	12-15
Soil parent material	eolian	eolian	eolian
Soil profile horizons	ABtC	ABwC	AC
Epipedon	Mollic	Mollic	Ochric (Mollic)
Texture	Silt loam	Silt loam	Silt
Soil classification	Typic Argiustolls	Typic Haplustolls	Typic Ustorthents (Entic Haplustolls)
pH	+/- 7	+/- 7 (higher in subsoil)	Calcareous below 60 cm
Use limitations	Dry summer Frost Rain erosion on slopes Plough-pan	Drought Frost Rain erosion on slopes Plough-pan	Drought Subsoil salinity Water salinity Rain erosion (sheetwash and trail-gullies)
Irrigated crops	Sugar cane* Citrus Figs	Sugar cane* Tobacco* Alfalfa Wheat Soybean	Alfalfa Wheat
Rain-fed crops	Soybean* Maize* Sorghum French beans Wheat Bastard saffron	Soybean* Sorghum* French beans* Maize* Wheat Bastard saffron	Natural pasture* French beans Sorghum Soybean Maize
Management practices	Chisel ploughing	Coarse tillage Rotation for residue and soil cover	Water storage
Suitability	Arable crops	Irrigated crops (Rain-fed crops) Forage for cattle Dairy	Mixed farming (dairy + crops for forage/market)

*Adapted from: Zuccardi & Fadda (1985); * = main crop*

8.4.3. Factors influencing land management

(1) Farming practices

One major farming improvement in the area is the use of chisel plough. It allows vertical tillage, where seed is put in a narrow slit cut across residues, as part of a no-till / minimum-till system. This contributes to breaking plow-pans in old arable land, improving biological activity and increasing stable macroporosity. The system avoids the use of turn-plowing and thus eliminates exposing the deeper topsoil to the direct sunlight, preserving better the soil organic matter. The residues give protection against the rain and thus help reduce erosion. This farming method includes the application of chemical fertilizers and implies the use of herbicides.

(2) Rain infiltration

Rain infiltration has been studied at the Agro-Industrial Experiment Station of Tucumán. Using double-ring infiltrometer, infiltration was measured during one hour. This measuring period is longer than the period we used in field tests of infiltration. For most showers, the decline of infiltration between 30 and 60 minutes into the rain-shower became very gradual and low in a variety of soils. In most cases, it seems that infiltration can be well approximated from the data of the first half-hour.

Most (erosive) rains are shorter than the four-hour infiltration time required as a standard for determining the infiltration rate. For erosion studies, it is not the basic infiltration rate but rather the infiltration velocities during the rain that are of interest. The infiltrated volume in the first half-hour or hour is often decisive for the occurrence of overland flow. In the area of Tucumán, 5-7 rainstorms cause about 50% of the annual soil loss. These heavy showers, with rain intensity above 30 mm/hour, last about 1-2 hours.

In the early stages of annual crops, such as wheat, the infiltration under splash is of dominant importance. This is the way infiltration is measured by the ITC Soil Division. In the later stages of crop growth, the infiltration as measured by the double-ring method is also a good parameter. The aim of the Experimental Station, however, was not to imitate the rain effect, but to establish a basis for comparison between soils and cultivation practices.

(3) Available soil water

Available moisture in a soil can be estimated in a very simple way that has proven to be effective, even for predicting yield (Molina, 1995). This method is based on a 30-year work experience in large areas (for instance, areas of 100,000 ha) in Argentina (Salta), Brazil, Venezuela, Cuba and Colombia. These are areas with relatively low rainfall and prolonged dry season. For instance in Salta, the annual precipitation is 1200 mm and the dry season lasts six months.

The procedure of the test is the following: one kneads the soil as it is found in the field. When the imprint of the fingers is left behind on the soil, enough moisture is available. This check is made at soil depth of 0, 30, 60 and 90 cm. It appears that conclusions from these observations, for the cases where water is limiting the yield, allow harvest prediction.

(4) Organic matter content

A relevant property that varies with the time since reclamation from the Chaco forest is the organic matter content of the soil (Dantur, 1995). It declines during about 2-4 years and then stabilizes. Organic matter content is important for aggregate stability, which in turn, in these soils with low clay and high silt content, determines water infiltration and soil stability against wetting and splash.

8.4.4. Conservation practices

Views on the adequacy of conservation practices in the study area were obtained from personal communications provided by N. Dantur in Tucumán (1995) and J. Molina in Buenos Aires (1995). The Agro-Industrial Experiment Station of Tucumán has put in a lot of effort to stimulate contour farming, but this practice is in itself inadequate for the problem of the area. It is not the storing of the overland flow and the reduction of the flow velocity that is the key factor for soil conservation, but the aggregate stability and the infiltration that should be increased. Then, the crops would have more water and there would be less erosion.

At present, on fertile land with an annual rainfall of 800-1200 mm, crop residues have enough mass to help maintain a good level of organic matter and, consequently, infiltration is high. But when the rainfall is less, residues become also less, and infiltration is inadequate to deal with the rain-showers. In addition to the problem of surface sealing, ploughing causes compaction at the foot of the plough layer, which limits infiltration. Though the top of the plough layer may be opened up to the rain through tillage and then acquire increased macroporosity, the compacted soil pan that results from repeated ploughing to the same depth prevents deeper percolation. Less permeable topsoil causes surface water stagnation and increases overland flow. Flow resulting from surface sealing and from topsoil saturation contributes to inundation in the flat low-lying areas.

An obvious question is how to find improvement. Is deep ploughing a solution to break the compacted and dense subsoil? It is expected that, on soils with high silt content, the improvement of porosity and permeability to favour infiltration by deep ploughing would be of short duration (Dantur, 1995). Deep ploughing would only be recommendable on soils richer in clay content, where the effect would be more durable. It might be of practical significance to do research on the question of which soils would profit, on at least the medium term, from deep ploughing. The cost of the practice would have to be balanced by increased benefits and reduction of other costs.

The average yield of wheat in the area is 2000 kg/ha. When conservation practices are applied, this level can go up to 3000 kg/ha. Production cost is balanced by a yield of 1500 kg/ha. Therefore, the margin of the farmers is small. Moreover, the yields are not stable but vary from year to year. In the Tucumán area, arable land under production is about 150,000 ha. The average size of the farms is 200-400 ha. A stable, sustainable farm requires a size of more than 300 ha.

8.5. SOIL PROPERTY CHANGES UPON RECLAMATION

8.5.1. Effect of forest clearing on the topsoil

Clearing of a subtropical forest on Typic Haplustalfs in eastern Bolivia, using bulldozers and straight blades, was investigated to assess resulting soil degradation and reduction in corn yield (Barber & Romero, 1994). Several clearing methods were compared, including (1) conventional bulldozer felling and windrowing with a straight blade; (2) bulldozer felling with a straight blade, tree pusher and rake windrowing; (3) chain felling with a tree pusher and straight blade windrowing; (4) chain felling with a tree pusher and rake windrowing; and (5) undisturbed forest (control).

All four clearing methods caused severe physical soil degradation. Bulk density increased by 20% in the 0-20 cm layer; the soil surface was lowered by 3 cm due to compaction; cumulative 30 min infiltration decreased from 15.1 cm to 4.4 cm water; and exchangeable calcium increased from 7.7 to 11.6 cmol kg^{-1} in the topsoil as a result of forest burning. Penetrometer resistance increased linearly from 3.5 cm depth downwards, but became constant from 45 cm onwards. No significant changes in yield were found between clearing methods. It can be noted that the rooting depth in the crop field reached to about 40 cm and there was no sign of compaction within this depth. The effect of the clearing methods on the soil depends also on the skill of the operators.

8.5.2. Effect of burning on the soil surface

The Chaco forest vegetation that has been removed is put in heaps or lines and burned. The effect of burning and heating the soil at different temperatures has been studied by Giovannini and Luchesi (1997). Soil temperature was measured at various depths in the surface soil. The passage of fire stimulated the aggregation of clay particles into sand-size particles, which were more resistant to disruption by water.

The pH decreased at temperatures up to 395ºC, but increased at higher temperatures because of transformation of clay to coarser particles. Cation exchange capacity and organic matter content decreased continuously with increasing temperature, resulting from the loss of organic matter and transformation of the clay particles. Total nitrogen content remained surprisingly constant, while ammonium nitrogen peaked at 184ºC. Organic phosphorus decreased continuously, whereas available mineral phosphorus increased from mineralization of organic matter. Porosity decreased and bulk density increased because of the burning of the organic fraction.

Changes took place during the fire because of the temperature but affected only a shallow top layer of the soil. In the layer between 2.5 and 5 cm depth, temperature increase was very small and did not result in appreciable changes of soil properties.

In total, the fire had two effects: an immediate one resulting in strong changes, another one of delayed changes derived from the simultaneous modification of soil, plant cover and biological life. Delayed changes could be traced by repeated observation over time, with the difficulty of separating delayed effects of the fire itself from other effects that act later.

8.5.3. General effects of land reclamation on soil properties

General effects of reclamation on soil properties were collected via personal communications with N. Dantur (1995) and J. Molina (1995). The soil organic matter content decreases after deforestation and then stabilizes. In areas with sufficient rainfall for biomass production, the soil structure does not deteriorate. When rain is insufficient (in amount or in distribution) for a good biomass production, soil organic matter declines. In that case, soil structure deterioration occurs soon, after 2-4 years, limiting rain infiltration into the soil. This causes further decline in vegetative production with increased negative effect on the soil condition.

A similar influence on soil structure can be caused by a change in land use to crops with less biomass production or farming practices that give less plant material back to the soil. Periodic burning of residues ("quema") can cause a decline in soil structure in a few years, because less organic matter becomes available to support aggregation. Without the binding effect of organic matter, loess soils can become compact in only a few years.

Even on compacted soils, avoiding the burning of residues allows organic compounds to infiltrate downwards and improve aggregation. This effect can become noticeable in 1-2 years already. In the case of sugar cane cultivation, for instance, residues have proven to be effective, just as other types of residues in comparable quantity.

Tillage has great influence on compaction. Disk-ploughs and turn-ploughs are not recommended. The single tine plough that only tears the soil is the best. Seeding directly into the stubble of the previous crop is recommended.

8.5.4. Short- and long-term changes in topsoil properties

(1) Observations in Chaco forest and in arable fields 5 and 25 years after reclamation

A comparison of topsoil properties under Chaco forest and in arable land used for 5 and 25 years has been made by Zuccardi et al. (1987a). Since reclamation, the hydraulic properties of the soil declined in quality, increasing the risk of flooding by stagnant water because of poor external drainage and increasing the hazard of erosion due to lower rainfall acceptance in the soil (Table 8.4). The drop number in the aggregate stability test is the number of drops necessary to destroy surface soil aggregates of 5 mm diameter by splash impact in a standard test of aggregate stability (McCalla, 1944).

The same authors provide another case of structural decline in loess soils after reclamation that also shows a rapid increase in apparent density after reclamation and a subsequent slow increase between 10 and 20 years of arable use. Land users reported a decrease in yield, and soil analyses indicated a gradual decrease in soluble phosphorus content. Biological activity of micro- and macro-organisms is important for the mineralization of organic compounds. The biological activity indicated by the glucose index showed a 50% decline after Chaco forest removal and a marginal recovery (0-10%) in the data of 10 and 20 years of arable use.

Table 8.4. Changes in topsoil properties after reclamation.

Soil properties	Original soil under forest	Reclaimed soils after	
		5 years	25 years
Hydraulic conductivity K (cm h^{-1})	3.05	1.33	0.34
Infiltration rate (cm h^{-1})	35	1	0.2
Bulk density (Mg m^{-3})	0.83	1.05	1.22
Aggregate stability (drop number)	36	--	9
Organic matter (%)	2.8	2.5	2.2
Total phosphorus (% P_2O_5)	0.034	0.030	0.026
Soluble P (mg kg^{-1})	52	33	7
pH	6.1	6.5	6.4

From: Zuccardi et al. (1987a)

(2) Observations in Chaco forest and in arable fields 1 and 40 years after reclamation

In our study area, changes in physical and chemical properties of loess soils under Chaco forest and in arable fields one year and forty years after reclamation to cultivation of soybean and other annual crops were identified (Table 8.5).

The thickness of the A horizon decreases from 28 cm to 17 cm and 13 cm after, respectively, 1 year and 40 years reclamation of the forest cover. However, when the thickness of the A horizon becomes equal to the thickness of the Ap layer reflecting the ploughing depth, further reduction of thickness may not have been noted. This further change would have to be recognized not by thickness but, for instance, by a break in the profile of organic matter content below the Ap.

Some physical and chemical soil properties that are important for arable land use, have deteriorated with time after reclamation. The decline is very rapid at first, such as in the first year after reclamation, and slows later down to reach a new equilibrium. Another effect is the gradual homogenization of the arable topsoil.

Table 8.5. Effect of deforestation and duration of arable land use on physical and chemical topsoil properties in the Burruyacú area (Lobo farm).

Topsoil properties	Chaco forest	Arable land use after reclamation of	
		1 year	40 years
Thickness (cm)	28	17	13
Texture	Heavy silt loam	Silt loam	Heavy silt loam
Colour	10YR4/1d,3/3m	10YR3/2m	10YR5/2d,7.5YR3/2m
Structure	abk, md, co	sbk, md, fn	sbk, md, co
Plough-pan	--	--	13 - 15 cm deep
Organic matter (%)	7.3	5.9	4.3
pH water	6.7	6.6	6.8
Ca (cmol kg^{-1})	19	18	13
Mg (cmol kg^{-1})	4	3	4
K (cmol kg^{-1})	2	2	2
Na (cmol kg^{-1})	0.3	0.3	0.3
P sol (mg kg^{-1})	30	15	5
P total (%)	0.1	0.1	0.06
NO_3 (mg kg^{-1})	11	3	2
N total (%)	0.3	0.3	0.2
CEC (cmol kg^{-1})	33	20	18
Bulk density (Mg m^{-3})	1.1	0.9	1.1

Values are averages of several (3-5) determinations; Colour: d = dry, m = moist; Structure: abk = angular blocky, sbk = subangular blocky, md = moderate, co = coarse, fn = fine.

8.6. SOIL PROPERTY CHANGES UNDER FARMING

8.6.1. Effect of tillage on bulk density and soil water

An experiment with soybean (variety Stuart) was conducted on a Typic Haplustoll near Canetes, area of La Ramada, during 1984-1985. The purpose was to assess the effect of tillage on the cultivated soil as compared to the original soil under Chaco forest (García & Giménez, 1987). At the two investigated dates, bulk density in the arable chisel-ploughed plots was lower than in the forest at 10-20 cm depth, equal or lower at 20-35 cm, and equal or higher at 35-50 cm (Table 8.6). It appears that the effect of chisel-ploughing is only partial or occurs only in certain parts of the field. The higher bulk density values in the upper subsoil could reflect the presence of a denser B horizon. This was also the case in our study area, where the use of heavy farm machinery may have contributed to higher bulk density below the topsoil.

Table 8.6. Effect of chisel-ploughing on bulk density (Mg m^{-3}).

Observation depth (cm)	Original forest soil	Chisel-ploughing after reclamation			
		Early June		Late September	
		min.	max.	min.	max.
10-20	1.22	1.16	1.18	1.14	1.20
20-35	1.33	1.23	1.35	1.24	1.30
35-50	1.24	1.24	1.30	1.26	1.27

From: García & Giménez (1987)

The effect of chisel-ploughing on water storage in the soil profile was also studied. The fallow parcel accumulated less water (260 mm or 70% of field capacity) than the chisel-ploughed field (325 mm or 86% of field capacity). No significant difference was found for hydraulic conductivity and basic infiltration. However, the effect of chisel-ploughing on hydraulic conductivity seems to wear off during the cropping season (Table 8.7).

Table 8.7. Effect of chisel-ploughing on saturated hydraulic conductivity (cm h^{-1}).

Observation depth (cm)	Original forest soil	Chisel-ploughing after reclamation	
		Early June	Late September
10-20	2.16	15.06	13.25
20-35	1.42	5.42	5.79
35-50	2.28	6.10	4.72

From: García & Giménez (1987)

Chisel-ploughing increased basic infiltration from 0.5 cm h^{-1} in the Chaco forest soil to 5 cm h^{-1} in early June and 4 cm h^{-1} in late September in the cultivated field. As infiltration of rainwater is crucial for plant available water in the soil, as well as for reducing overland flow volume, the effect of chisel-ploughing on soil water storage became a subject of research (Zuccardi et al., 1993). Chisel-ploughing was successfully introduced in the study area and became widely used.

It appears that saturated hydraulic conductivity and basic infiltration rates are much increased by tillage. This is logical because macroporosity is increased. However, the permanence of this improvement strongly depends on the structural stability of the topsoil. Loess soils are notorious for their sealing sensitivity. It is therefore possible that the infiltration experiment has been performed by ponding infiltration and not by infiltration under rain splash that would lead to sealing more easily.

8.6.2. Effect of cultivation on plant available water

In the area of La Virginia and Las Cejas, in the southern part of the study area, soil moisture of a Haplustoll formed from loess has been recorded at depths of 30, 60 and 100 cm from September 1987 up to June 1990, every fortnight or monthly, for parcels in forest and under permanent cultivation of soybean (Zuccardi et al. 1993). It was concluded as follows:

- The amount of soil water held down to 1 m depth in the cultivated soil is greater than under forest. In periods of drought, the amount is the same.
- In the wetter periods, the water content in the cultivated parcel includes plant available water, while the soil water under forest is available for plants only with difficulty. Water is estimated 325 mm at field capacity and 170 mm at wilting point. The division between readily available and slowly available soil water is at about 225 mm.
- In the forest, periods with soil moisture content below wilting point occur for many months. Under soybean, the soil moisture content is below wilting point for half this number of months, while the other half has slowly available water. It follows that crop cultivation is subjected to risk of drought.
- Monthly evapotranspiration varies between 25 mm and 170 mm, while monthly rainfall varies between zero and 140 mm. Rainfall equals evapotranspiration only in February and March. It would

be, however, erroneous to infer the moisture supply to the soil from the distribution of rainfall and evapotranspiration. The supply depends strongly on the infiltration velocities during the rains, controlled by macroporosity and structural stability. Soils sensitive to sealing, such as loess soils when devoid of plant or residue cover, may become semi-impervious in a few minutes of rain, while the rainwater may be transformed in overland flow, lost for the plants.

In the study area, it was observed that in the more western part, with higher rainfall, a promising land use is that of orchard. This land use may compensate declining revenues from land where soil degradation cannot be reversed.

8.6.3. Effect of fertilizer application on crop yields

In a fertilizer trial, P_2O_5 was applied in four amounts, that is 0, 11, 22 and 42 kg ha^{-1} (Zuccardi et al., 1993). A subdivision was made in the application of carbonates with 0 and 1100 kg of $Ca(OH)_2$ per ha, respectively. The trial used four replications in a latin square lay-out of the plots. Results showed significant to highly significant difference in yield between the original soil and the fertilized parcels in combination. The difference in yield between limed and non-limed parcels was highly significant.

8.7. CONCLUSIONS

- Water retention can be increased by incorporating plant residues in the topsoil instead of burning them. This would improve yields and reduce erosion.
- Surface storage and flow diversion are probably insufficient to reduce erosion and improve yields.
- On older arable land, the risk of flooding and inundation, rather than soil loss, is probably the most important land use limitation resulting from soil degradation.
- Periods of drier years may restrict yields and make it difficult to incorporate enough mulch and crop residues. Periods of wetter years may encourage cultivators to extend their activities eastwards and incur greater risk of drought.
- In most topsoils, clay content is 20-30 %, while silt content is 45-55%. In La Ramada and La Cruz, in the western part of the study area, some topsoils have silt content of 30-40%. These textural differences may result in differences in water holding capacity.
- In the transition area from sub-humid to semiarid climate, exists a vague boundary where dairy land use becomes a better option than arable land use, if extensive grazing is possible.
- Perennial crops may have a future, if irrigation can be applied with limited water use. Careful salt control will be needed. There are already some orchards in the western part of the study area.
- Monitoring the land use from satellite data, supported by aerial photographs and field inspection, could help planners follow trends of cropping and assist agriculture.

8.8. REFERENCES

Barber, R.G., Romero, D., 1994. Effects of bulldozer and chain clearing on soil properties and crop yields. Soil Science Society of America Journal 58:1768-1775.

Brady, N.C., 1996. Alternatives to slash-and-burn agriculture: a global imperative. Agriculture, Ecosystems & Environment 58 (1): 3-11.

Carmona, D., 2001. Plagas emergentes en siembra directa. Revista Visión Rural, Argentina.

Casas, R., 1998. Los procesos de degradación y la conservación de suelos de la República Argentina. La Argentina Ambiental: naturaleza y sociedad, pp.139-174.

Dantur, N., 1995. Personal communications. Estación Experimental Agro-Industrial, Tucumán, Argentina.

Ellis, S., Mellor, A., 1995. Soils and environment. Routledge, London, UK.

García, J., Giménez, R., 1987. Influencia del cincelado en la conservación del agua y en las propiedades físicas del suelo. XI Congreso de la Asociación Argentina de la Ciencia del Suelo. Río Negro, Argentina.

Gargicevich, A., Massoni, S., 1991. Manual de agricultura conservacionista. INTA, Fundación Producir Conservando. Buenos Aires, Argentina.

Giovannini, G., Luchesi, S., 1997. Modifications induced in soil physico-chemical parameters by experimental fires at different intensities. Soil Science 162 (7): 479-486.

Lal, R., Stewart, B.A., 1990. Soil degradation. In: Stewart, B.A. (ed.), 1990. Advances in Soil Science 11. Springer Verlag, Berlin, Germany.

Lorenzetti, S., 2004. Importancia de la siembra directa y la rotación de cultivos. Seminario AAPRESID (Asociación Argentina de Productores de Siembra Directa). Tucumán, Argentina.

McCalla, T.M., 1944. Waterdrop method of determining stability of soil structure. Soil Science 58: 117-123.

Molina, J., 1995. Personal communications. Buenos Aires, Argentina.

Neder, L., 1995. Field information collected from farmers and extension officers (Candela, Heguy, Los Pempa, Rodríguez, Vece). Tucumán, Argentina.

Zuccardi, R.B., 2000. La expansión de fronteras agrícolas, 20 años después. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán, Argentina.

Zuccardi, R.B., Fadda, G.S., 1985. Bosquejo agrológico de la Provincia de Tucumán. Publicación Miscelánea 86. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán, Argentina.

Zuccardi, R.B., Molina, N.C., Cáceres, M.R., 1987a. Problemas de fertilidad en suelos loessicos de Tucumán. XI Congreso de la Asociación Argentina de la Ciencia del Suelo. Río Negro, Argentina.

Zuccardi, R.B., García, J.R., Molina, C., Cáceres, M., Bleckwedel, C., Giménez, D., Sanzano, A., 1987b. La expansión de fronteras agropecuarias y los impactos sobre el sistema edáfico. Actas XIII Reunión de la Sociedad Argentina de Ecología. Bahía Blanca, Argentina.

Zuccardi, R.B., García, J., Giménez, R., Sanzano, A., Cáceres, M.R., 1989. La ampliación de las fronteras agrícolas y la sobreexplotación de los recursos naturales. Los impactos al sistema edáfico. Documento inédito. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán, Argentina.

Zuccardi, R.B, García, J.R., Sanzano, G.A., Giménez, R., 1993. Dinámica del agua edáfica en dos ecosistemas de la región semiárida tucumana. Actas XII Congreso Latinoamericano de la Ciencia del Suelo. Sevilla, España, pp.151-158.

CHAPTER 9

THE SOIL SURFACE

E.Bergsma, L.Neder

9.1. INTRODUCTION

This chapter covers the study of the soil surface properties that relate to soil degradation and land management. Though these soil properties have influence on crop growth, crop cultivation and farming practices are discussed in Chapter 8. The soil surface is analyzed with reference to soil erodibility, including resistance to detachment by splash and scour, and rainwater infiltration, and with reference to erosion hazard. Attention is also paid to soil compaction, deterioration of soil structure and decline of soil fertility

9.2. SOIL ERODIBILITY AND LAND DEGRADATION

9.2.1. Role of erosion, components and tests

Soil erodibility can be seen as the combination of soil detachability by splash and scour with the generation of overland flow from rain, as influenced by the properties of the soil cover (Figure 9.1). The position of the soil in the landscape influences its erodibility. Divergence and convergence of subsurface flow may cause local saturation and generate overland flow. Soil erodibility is controlled by a set of soil characteristics, which make a given material erodable and intervene in the production of overland flow.

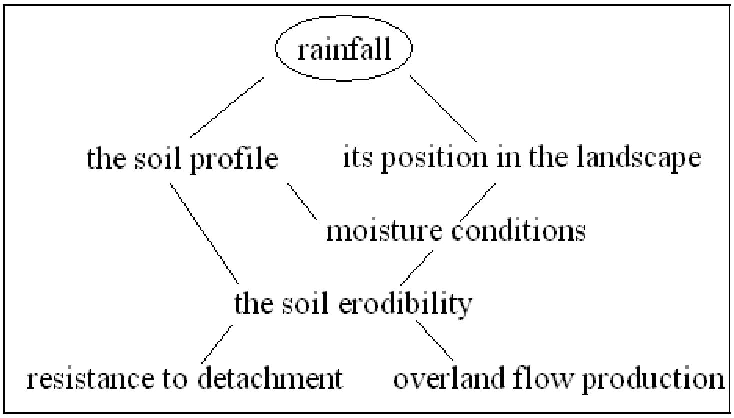


Figure 9.1. The place of soil erodibility in the soil erosion process.

Erodable material depends on soil texture, soil surface structure (strength, stability, type and size), surface gravel and other factors such as the amount of exchangeable sodium (ESP) and the content of electrolytes in runoff water. The erodable material may be fine primary particles, aggregate fragments or small aggregates, and results from the detachment processes taking place at the soil surface (Figure 9.2).

The volume of overland flow production depends on surface sealing, infiltration rate, surface storage and profile storage capacity as influenced by macro-porosity, rapidly permeable depth, external and internal drainage condition, slope configuration, run-on and seepage flow. The erosive capacity of the flow depends on other hazard factors such as topography (slope form, steepness and length), surface roughness and basal plant cover.

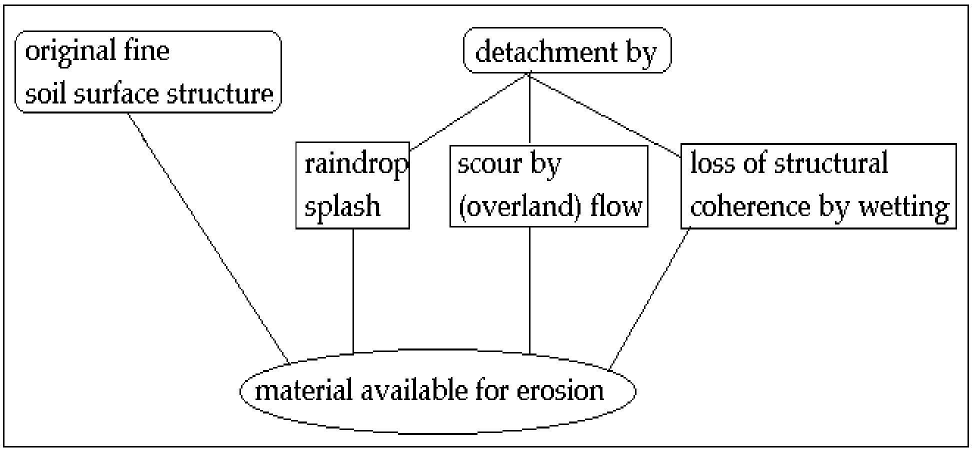


Figure 9.2. Sources of available erodable material.

Field tests were used to characterize the main components of soil erodibility (Table 9.1). They were designed to be simple and cheap and to give similar results when done by different operators (Bergsma, 1986a). The same tests can be used for monitoring temporal variation of erodibility. Land management (e.g. tillage, weeding) and climate seasons are common causes for temporal variation in erodibility.

Table 9.1. Components of erodibility measured using field tests and soil profile study.

	Soil profile	Crumb test	Field pinhole test	Manipu-lation test	Rainfall accept. test	Soil loss test	Rilling test	Torvane test
Soil surface structure	+ <>				/			/
Structural stability	/	+	+ *	+	/	/	+ *	+ *
Sealing/ Infiltration	/	/		/	+	/		
Permeability	/				/			
Rain storage capacity	+				/			
Interrill erodibility	/					+		
Rill erodibility		-	+	+	+	/ **	+ *	+ *

*+ = strong evidence <> = surface gravel * = scour sensitivity ** = flow volume produced*
/ = some evidence

9.2.2. Bulk density

Bulk density is an important soil characteristic because it is related to the resistance against detachment and the intake of rainwater. Detachment by splash or by scour from flow is often stronger when the soil aggregates are more porous and have a lower apparent density. Compact soil is often more coherent and resists detachment more.

Infiltration velocity during the rain depends strongly on the volume of macropores and thus on bulk density. The difference between infiltration velocity, which by various causes declines during the rain, and the varying rain intensity determines the production of overland flow at a site. Adsorption of rain on dry soil and partial filling of the micropore volume by infiltrating rain take place also and modify this difference.

The method used for forest reclamation modifies the bulk density of the topsoil and affects thus soil properties of importance for infiltration of rainwater and, consequently, for the amount of water in the soil profile that is available for crop growth (Table 9.2). In the Tucumán area, the method of forest clearance has changed over the years from using hand-operated equipment to the use of bulldozers and clearing by chain-ball. Thus, differences found in the topsoil of the study area may be partly due to the clearing techniques, in particular differences in infiltration characteristics between parcels of different age of reclamation. Dense horizons occur also frequently deeper than 20 cm in our study area. This suggests the use of very heavy equipment or the influence of other factors affecting compaction, such as exposure to intensive and repeated wetting and drying down to the wetting front in the soil profile.

Table 9.2. Soil bulk density (Mg m^{-3}) as influenced by forest clearance.

Soil depth (cm)	Original forest soil	Soil after clearance by	
		Slash-and-burn	Bulldozer
0-5	0.8	0.8	1.3
5-10	1.0	1.0	1.2
10–15	1.1	1.1	1.2
15-20	1.1	1.1	1.2

(adapted from Ellis & Mellor, 1995).

9.2.3. Surface gravel

The presence of gravel on the soil surface strongly influences soil erodibility. Graphical relation between surface gravel and erosion intensity has been published in the USDA Handbook 537 (Wischmeier & Smith, 1978). Research on the same subject conducted in southern Germany shows a linear relationship (Schwertmann, 1986), while research from Ivory Coast shows a parabolic curve (Collinet & Valentin, 1984). In our study area, the amount of surface gravel is generally low.

9.2.4. Temporal changes in erodibility

Erodibility changes over time. Seasonal variations are due to physical, chemical and biological changes in the soil over the seasons. Soil erodibility may also undergo changes over a number of years because of changing land use, for instance after forest reclamation. In such a case, erodibility increases through loss of root mat and decrease in soil organic matter. Conversely, soil erodibility may decrease over the years, under cultivation of annuals, by the development of a pavement of resisting coarse material through selective remotion of the finer particles in the plough layer (Lal, 1976).

9.2.5. Tillage condition

The tillage condition of the soil surface strongly influences soil erodibility. In Indonesia, Bergsma (1987) found that loose tilled topsoil had a lower erodibility than bare compact topsoil. The difference was estimated as one or two classes of erodibility out of five classes. The opposite was found in Pa Sak, Thailand, where loose tilled topsoil was easier eroded than a compact untilled soil, probably because of lower permeability in the subsoil (ITC, 1988-1990).

9.2.6. Effect of cropping on loess soil properties over time

In the past, the reclamation of the Chaco forest was done by slash-and-burn. Nowadays, bulldozers are used for the removal and collection of the vegetative matter. Alternatives to such a system are discussed by Brady (1996), though in relation to a different environment.

Scott et al. (1994) investigated the effect of cropping on loess soil properties with respect to variation within fields and variation with time. Samples were taken monthly from 0-5 cm and 5-10 cm depth. The soils were a Typic Albaqualf and a Typic Glossudalf. Average particle size distribution was 17% sand, 69% silt and 14% clay. The sites included prairie vegetation and three arable fields that had a history of agricultural use of 3, 14 and 32 years. Crops were rice, soybean and wheat. Soil properties studied were bulk density, saturated hydraulic conductivity, total porosity, total carbon, pH in water and pH in $CaCl_2$.

Statistical analysis showed that soil properties varied with cropping, depth, and sampling time within the year. The highest ratio of within-field variability over monthly variability was 26 for total carbon; the lowest ratio was 0.52 for saturated hydraulic conductivity. Most of the investigated soil properties had ratio values between 1.7 and 2.8, which tended to be higher in the upper depth interval. For the various soil properties, the different sources of variation were statistically analyzed for their significance (Table 9.3).

Table 9.3. Statistical significance of effects of in-field variation, time and soil depth (Scott et al., 1994).

Soil characteristic	Field	Depth	Time
Saturated hydraulic conductivity	**	*	*
Bulk density	**	*	**
Total porosity	**	*	**
Total carbon	NS	NS	**
pH water	***	NS	**
pH $CaCl_2$	**	NS	**

, **, * = significant respectively at 0.05, 0.01, 0.001*
NS = not significant

The findings of the study led to the following conclusions:

- The effect of land use (crops and prairie) was highly significantly correlated with a change in soil properties, except for total carbon.
- The effect of depth is somewhat less significant, being not significant for total C and pH.
- A significant change in total C is only reached on the long term.
- The effect of the number of years in arable use was highly significantly correlated with a change in soil properties.

The in-field variability of soil properties related to water retention was investigated by Shouse et al. (1995). The scale of spatial influence for the water retention function parameters and the measured physical characteristics of the soil in intervals of 30 cm were all similar: approximately 15-30 m. It was suggested that field size may be the dominant factor that determines the range of influence. Antecedent effects of land use probably play this role here. About 50% of the variability was attributed to experimental error.

9.3. METHODS AND TECHNIQUES

9.3.1. Observation sites

The landscape is an undulating plain, grading eastward into a flat plain. From the seven dates of existing satellite and airphoto coverage spanning the period from 1970 to 1996, several dates were selected for monitoring purposes, taking into account available representative forest remnants and arable land plots of corresponding age. The sites where soil surface observations and tests took place are listed in Table 9.4

and their location is given in Chapter 13. Sites were selected to reflect the rain gradient from drier east to wetter west, with only 20 km distance between the isohyetes of 700 mm and 900 mm.

Table 9.4. Field tests of soil erodibility applied at selected locations.

Site	Soil profile	Reclamation period	Detachability dcr	pin	man	Infiltration	Shear strength
Lobo	P1A	<1970	x	x	x	x	x
	P2	Forest	x	x	x	x	x
Salim	P4A	<1970	x	x	x	x	x
	P5A	Forest	x	x	x	x	x
Blasco	M26	1985-1991				x	
	M12	1976-1985	x	x	x	x	
	P13	Forest	x	x	x	x	
La Argentina	P9B	1991-1996	x	x	x	x	
	P6B	<1970	x	x	x	x	
	P7B	Forest	x	x	x	x	
La Virginia	P11	1991-1996	x	x	x	x	
	P12	<1970	x	x	x	x	
	P10	Forest	x	x	x	x	
Deschamps	M27	1970-1976	x	x	x	x	
La Ramada	M18	1970-1976	x	x	x	x	
	M20	1976-1985	x	x	x	x	
	M17	<1970	x	x	x	x	
	P17	Forest	x	x	x	x	

dcr = crumb test; pin = field pinhole test; man = manipulation test

9.3.2. Field tests of soil erodibility components

For the evaluation of the soil erodibility, the following field tests were used: crumb test, pinhole test, manipulation test, rainfall infiltration test, torvane test and hand-penetrometer test.

- Crumb test: rating the behaviour of a dry crumb submerged in water. The test gives a measure of the structural stability of the dry soil against wetting and an indication of the sensitivity to sealing by wetting of the dry soil. The procedure is modified from Loveday and Pyle (1973), taking into account the experience of Greenland et al. (1975) and Jungerius (1982).

- Field pinhole test: rating soil sensitivity to dispersion and suspension. Water is led through a tiny hole in a soil ball. The test measures shear resistance or scour sensitivity. The procedure has been adapted from that of Sherard et al. (1976) for use as a field method.

- Manipulation test: rating soil coherence from kneading of moist soil into a defined shape of maximum complexity. The rating is modified from Charter (1949) to give emphasis on material coherence of standard soil textural classes. The rating takes into account the relationship with the water drop test (De Bont & Van der Poel, 1976).

- Rainfall infiltration test: measuring the water volume infiltrating between 2 and 30 minutes into artificial rain, under splash, with limited ponding. The procedure has been developed during many field studies of soil erodibility. Infiltration from frequent small rain applications is distinguished from that of fewer, larger rain applications. Some of the references that were consulted are Bouwer (1962), Gifford and Bushy (1974), Munn and Huntington (1976), Hachum and Alfaro (1977), and Roth et al. (1985).

- Shear vane test: measuring the shear resistance of the upper layer of the topsoil by a torvane apparatus. It has extra wide vanes of 4 cm height and 2 cm width. It is pressed 1 cm deep into the soil surface at near saturation such as can be expected during prolonged rain. The pressure needed to rotate the blades through the soil is indicated on a scale. The test produces an indication of the

resistance to scour by overland flow, such as occurs in rill erosion. For reference, see the torvane operation instruction and basic principles at:
http://www.civil.port.ac.uk/geotechnics/level2/week1b.doc.

- Hand penetrometer test: measuring the compressive strength of a soil by a spring-operated penetrometer. A 5 mm diameter rod is pushed into the soil to about 1 cm depth. Figures on a scale can be translated to a resistant force in kg per cm^2. Measured strength relates to bulk density and shearing resistance. It also provides an indication of sealing when surface observation is compared to observation on the immediate subsurface. Operation is easy and repetition is 10 times. Moisture condition is critical, as the test is made near saturation. For reference, see the operating instruction at:
http://www.forestry-suppliers.com/product_pages/view_catalog_page.asp?id=3044

The torvane and hand-penetrometer tests are proxies of bulk density, which is a pedotransfer parameter for shear resistance. They were applied only at some Chaco forest sites. Loose topsoil prevented the meaningful use of these tests at arable sites.

Full description of the tests for their use in the field is available from Bergsma at bodem@wanadoo.nl and also from Farshad@itc.nl or Shrestha@itc.nl. The field guide explains how the results of the field tests can be combined (1) to arrive at a relative soil erodibility ranking, (2) to establish absolute classes of soil erodibility, and (3) to determine values of an "equivalent K-factor" of soil erodibility. The tests have been developed during fieldwork in various countries, on a variety of soils (Bergsma, 1986a, 2002). A general description of the factors involved in structural stability and rainfall infiltration can be found in Bergsma et al. (1996).

9.3.3. Influence of antecedent moisture on test results

Antecedent moisture content has a definite but complex influence on erosion. The torvane test provides readings that correlate with the soil surface microrelief. Convex areas, expected to dry faster than concave parts, show higher torsion resistance. It is hypothesized that the moisture suction of the topsoil in relation to short wetting and drying periods plays a role.

The antecedent moisture content influences some of the tests. The general moisture condition at a given site can be described by the drainage condition or the soil moisture regime. The local soil moisture regime reflects also the influence of run-on and subsurface flow. However, this generalization is not helpful in the case of the tests, the results of which depend on the moisture status at the moment of testing.

The crumb test has to be performed on air-dry soil. If air-dry soil is not available in the field, samples may be taken. For the infiltration test, it is assumed that the initial infiltration velocities reflect air-dry soil. This is usually the case in fieldwork seasons. The result of the infiltration test is given as the amount of applied rain that infiltrates between 2 and 30 minutes. Therefore, a dry initial moisture status is important.

9.3.4. Infiltration and sensitivity to sealing in loess soils

(1) Process of sealing

(a) Influence of rainfall intensity

Sealing increases with higher rainfall intensity. There is not only the effect of wetting on soil structure, but also the effect of splash. However, it is also known that heavy rain causes alternate phases of sealing and removal of the sealing crust (Luk, 1977, 1979; Cai et al., 1986). Soil surface areas in the study region have been observed after prolonged rain where a smooth sealed appearance alternates in places with a scoured, a little lower, surface affected by concentrated flow such as occurs in braids. In general, crusts protect against splash and scour, but also promote overland flow because of their reduced permeability.

Sumner (1994), quoted by Hoogmoed (1999), recognizes different types of sealing and crusting in relation to tillage. The types of crust are: (1) chemical crust, composed of salt encrustations, commonly found in arid environments; (2) structural crust, formed by raindrop impact and clay dispersion, occurring in a wide range of soils; (3) depositional crust, formed by deposition of suspended soil material after transport; and (4) cryptogamic or biogenetic crust, formed by algae, mosses and lichens growing on the soil surface. Though some efflorescence was observed in our study area, real crusting by salts did not occur, if not more eastward. The second and third types of crust were of common occurrence. An example of the third type, present in our area, are the laminar seals formed by deposition of clay-rich material from suspension. The seal dries to an upward-curled crust.

Imeson and Kwaad (1990) describe the processes involved in or leading to sealing and crusting, including compaction, shrinking and swelling, mellowing, slaking and dispersion, and emphasize the importance of the "response to wetting". These processes are very important in the loess soils of our study area.

Hydraulic properties influenced by sealing and crusting are: saturated and unsaturated hydraulic conductivity, water retention characteristics, sorptivity, time to ponding at a given rainfall intensity, and infiltration capacity. As a consequence of the primary effects, influenced are also: bulk density, surface roughness, resistance to penetration, and mechanical resistance of the soil surface to detachment by drop impact and overland flow.

The above-mentioned processes have an effect on soil properties and thus on soil erodibility according to the seasonal distribution of rainfall over the year. Periods can be distinguished in the evolution of the structural elements of a freshly tilled topsoil, including: (1) a short period with freshly tilled soil; (2) a period in which rainfall-induced processes lead to stepwise degradation of soil structure and stepwise decline of various soil physical processes; and (3) a period in which a continuous crust is present at the soil surface and in which no further change in soil physical properties takes place, except by biological activity.

(b) Antecedent moisture and infiltration

Rain infiltration in loess soils from Canada, USA, China and Belgium was studied by Romkens et al. (1995) under simulated rain. Pre-ponding infiltration was described by a linear function, while the infiltration velocity remained rather constant. After this phase, a power function described the rapid decline that wore off to a low, constant infiltration rate.

It follows from this discussion on periods of variable influence of the rain on a freshly ploughed topsoil, that soil surface properties can vary much during the seasons of the year. Consequently, soil erodibility varies with them, and erodibility tests performed at a given moment in the development of the soil surface structural state may give a result that is not representing the situation some months later. This has to be taken into account when interpreting the results of our field tests.

The soil characteristics influencing infiltration behaviour in the loess soils, studied by Romkens et al. (1995), were organic matter, particle size distribution, swelling clay content, Fe-oxihydroxides and carbonates. Clay content (19% and 24 %), with a large proportion of swelling clay, had a stronger influence on infiltration than organic matter. Subsoils with carbonates or iron-compounds had higher and more sustained infiltration rates. This observation may be of interest for the soils in the eastern part of the study area, where more carbonate is found in the subsoils (INTA, 1985).

Other research of loess soils focussed on the antecedent moisture content (Le Bissonnais et al., 1995). Ten loess soil samples from northwestern Europe, with silt loam texture, 12-35% clay and 1-2% organic carbon, were packed in 0.5 m^2 microplots with 5% slope and subjected to simulated rainfall of 30 mm h^{-1}. Rain amounts of 120 mm were applied on field-moist soil, dried soil and re-wetted soil, to investigate the effect of soil moisture content prior to the rain. Runoff and sediment yield were measured at five-minute intervals. All soils formed seals. On field-moist soils, the runoff rates at the end of the rain were 70-90 %. Apparently, a wet field period caused the soil structure to deteriorate. Air-dried soils and re-wetted soils showed large differences in runoff rates at the end of the rain. Sediment concentration in runoff readily reached a steady state. Runoff and erosion were lower on air-dried plots than on field-moist plots.

One may ask here if the initial infiltration is dominating the result. This is unlikely. Air-drying probably produces more stable and compact soil aggregates that will then better resist erosion. Soils with high organic matter content had the lowest erosion rate in air-dry conditions. It looks logical that high and stable macroporosity was related to organic matter content. For re-wetted plots, the runoff and soil loss were either intermediate or lower. Soils with high clay content had the lowest erosion rate when re-wetted. These results indicate the complexity of the effect of initial moisture and the interactions between soil properties and rainfall.

Much research has been done on the sealing of soils developed on loess. For example, Mermut et al. (1995) investigated loess soils from Canada, USA, China and Belgium. The soils were subjected to artificial rain and the resulting sealing and crusting were observed. Higher rain intensities caused quicker destruction of the soil surface structure and seals formed earlier, denser and thicker. Inter-aggregate pores disappeared. Later surface outwash layers of sand and silt did form. Suspended clay settled in depressions and formed lamellar seals. Smectite caused a drastic reduction of infiltration under high intensity showers. Soils with low clay and high carbonate contents or with stable clay and iron oxide coatings showed no sealing.

(2) Sealing of loess soils and sealing sensitivity indicator

Most loess soils are sensitive to sealing because of rapid loss of surface porosity under the influence of splash and wetting. Infiltration velocity on initially dry soil decreases from the start of rain with the disappearance of adhesive, capillary and osmotic forces during the penetration of rainwater into the soil. This results in lowering the gradient of suction forces.

An indicator of sealing sensitivity can be calculated from the reduction of the infiltration velocity between 2 and 10 minutes into the rain (v2 and v10, respectively), relative to the infiltration velocity at 10 minutes into the rain, with the sealing indicator = (v2-v10)/v10. The infiltration value at 2 minutes allows avoiding the high variability of initial infiltration velocities, even though it includes the beginning of the sealing process. The value at 10 minutes into the rain is based on the assumption that, in this period, a large part of the reduction in infiltration velocity takes place due to high rates of sealing. This assumption is supported by curves shown in the literature (Carson & Kirkby, 1972, p. 48; Baver et al., 1972, p. 374; Gregory & Walling, 1973, p. 105; Kirkby, 1978, pp. 63 and 233). Implementation of the sealing indicator to establish sensitivity classes is shown in Table 9.5.

Table 9.5. Sealing indicator and sensitivity classes.

Infiltration velocity (mm min^{-1})		v2-v10	Indicator	
at 2 minutes into the rain	at 10 minutes into the rain		v2-v10 / v10	Sealing sensitivity
5	2	3	1.5	High
13	4	9	2.3	High
15	10	5	0.5	Moderate
15	5	10	2	High
50	10	40	4	High
50	30	20	0.7	Moderate
50	40	10	0.3	Low

Indicator values of <0.5, +/-1.0 and >1.5 signal, respectively, low, moderate and strong sealing sensitivity. In cases where the observation time was too short to determine infiltration velocities at 20 or 30 minutes into the rain, estimates were used when needed for a more complete comparison of infiltration behaviour.

The results of our observations using the sealing indicator are shown in Table 9.6. The indicator of sealing intensity gives a general indication. With low values of infiltration velocity, there was great variation of the indicator for similar conditions. Conclusion should be based on the range of obtained data, not the average. Some unexpected values lead to the following comments.

- Salim farm. Unexpected is the strong decrease of infiltration in the subsoil on the second test. The first infiltration test better reflects the character of the B horizon.
- Chaco forest in the west (Lobo). The forest has moderate sealing; all other Chaco soils have strong sealing. As the rainfall is higher in the west, more abundant vegetation may have caused a more coherent soil structure.
- Blasco farm. The Chaco forest shows places of high and low infiltration. By comparison with other Chaco sites, the occurrence of cattle trails and footpaths may explain this variation.

Table 9.6. Sealing indicator values at selected rainfall infiltration test sites.

v2min	v10min	v(2-10)	Indicator	Class	Spot location and features
40	3	37	12.3	SS	Lobo farm, arable land reclaimed before 1970, smooth wheel-track surface
34	10	24	2.4	SS	Lobo farm, arable land reclaimed before 1970, rough convex inter-track surface
50	6	44	7.3	SS	Lobo farm, arable land reclaimed before 1970, smooth wheel-track surface
20	23	-3	-0.1	L	Lobo farm, Chaco forest, near a footpath
14	3	11	3.7	SS	Lobo farm, between trees, nearly flat terrain
19	12	7	0.6	M	Lobo farm, off trails and paths
25	12	13	1.1	M	Salim farm, rainfall infiltration in topsoil on arable field, spot 1
30	10	20	2	SS	Salim farm, rainfall infiltration in topsoil on old cultivated field, spot 2
30	12	18	1.5	S	Salim farm, rainfall infiltrationin topsoil on old cultivated field, spot 3
11	8	3	0.4	L	First rainfall infiltration test in subsoil, spot 4
18	5	13	2.6	SS	Second rainfall infiltration test in subsoil, spot 5
14	7	7	1	M	Third rainfall infiltration test in subsoil, spot 6
66	38	28	0.7	M	Salim farm, Chaco forest, no footpath, convex surface, spot 1
29	20	9	0.5	M	Salim farm, Chaco forest, no path, convex surface, spot 2
12	7	5	0.7	M	Salim farm, Chaco forest, probably old path, spot 3
30	8	22	2.8	SS	Blasco farm, Chaco forest, site P13, spot 1
9	3	6	2	SS	Blasco farm, Chaco forest, site P13, spot 2
34	5	29	5.8	SS	Blasco farm, arable land reclaimed in 1976-1985, tillage ridge, site M12, spot 3
25	4	21	5.3	SS	Blasco farm, arable land reclaimed in 1985-1991, spot 4
37	11	26	2.4	SS	La Argentina, Chaco forest, spot 1
22	7	15	2.1	SS	La Argentina, Chaco forest, spot 2
70	12	58	4.8	SS	La Argentina, Chaco forest, spot 3
23	3	20	6.7	SS	La Argentina, arable land reclaimed in 1970-1976, site M8, spot 4
140	9	131	14.6	SS	La Argentina, field with maize stubble, reclaimed before 1970, spot 5
130	10	120	12	SS	La Argentina, field with maize stubble, reclaimed before 1970, spot 6
125	9	116	12.9	SS	La Argentina, field with maize stubble, reclaimed before 1970, spot 7
32	10	22	2.2	SS	La Virginia, Chaco forest, on interfluve, site P10, spot 1
70	10	60	6	SS	La Virginia, Chaco forest, on path/trail, site P10, spot 2
50	13	37	2.8	SS	La Virginia, soybean, arable land reclaimed in 1991-1996, site P11, spot 1
28	8	20	2.5	SS	La Virginia, soybean, arable land reclaimed in 1991-1996, site P11, spot 2
32	6	26	4.3	SS	La Virginia, on wheel-track, field reclaimed before 1970, site P12, spot 3
29	9	20	2.2	SS	La Virginia, between wheel-tracks, field reclaimed before 1970, site P12, spot 4
60	7	53	7.6	SS	La Virginia, between wheel-tracks, field reclaimed before 1970, site P12, spot 5
30	6	24	4	SS	Deschamps farm, field reclaimed in 1970-1976, furrow, site M27, spot 1
20	5	15	3	SS	Deschamps farm, field reclaimed in 1970-1976, plough rill, site M27, spot 2
6	3	3	1	M	Deschamps farm, field reclaimed in 1970-1976, site M27, spot 3
8	1	7	7	SS	La Ramada, fine struct. (2-5cm), field reclaimed before 1970, site M17, spot 1
9	3	6	2	SS	La Ramada, coarse struct. (3-7cm), field reclaimed before 1970, site M17, spot2
8	2	6	3	SS	La Ramada, fine struct. (2-3cm), field reclaimed before 1970, site M17, spot 3
4	2	2	1	M	La Ramada, 35cm wide furrow, field reclaimed in 1970-1976, site M18, spot 1
5	3	2	0.7	M	La Ramada, flat top plough ridge, coarse clods, reclaimed <1970, M18, spot 2
8	3	5	1.7	SS	La Ramada, field reclaimed before 1970, site M18, spot 3
1.5	1	0.5	0.5	M	La Ramada, Zavaleta farm, Chaco forest, on a path, site P17, spot 1
6	2	4	2	SS	La Ramada, Zavaleta farm, Chaco forest, on a path, spot 2
2	1.5	0.5	0.3	L	La Ramada, Zavaleta farm, Chaco forest, not disturbed, no path, spot 3
6	2	4	2	SS	La Ramada, plough furrows, stubble mulch, reclaimed in 1976-85, M20, spot 4
7	1	6	6	SS	La Ramada, plough furrows, stubble mulch, reclaimed in 1976-85, M20, spot 5
7	2	5	2.5	SS	La Ramada, in rill, field with maize straw, reclaimed in 1976-85, M20, spot 6
10	4	6	1.5	S	Garmendia farm, field reclaimed in 1991-1996, site P9B, spot 1
7	5	2	0.4	L	Garmendia farm, field reclaimed in 1991-1996, site P9B, spot 2
9	5	4	0.8	M	Garmendia farm, field reclaimed in 1991-1996, site P9B spot 3

v2min = infiltration velocity at 2 minutes into the rain
v10min = infiltration velocity at 10 minutes into the rain
Sealing degree: SS = very strong; S = strong; M = moderate; L = light

- Blasco farm. The soil under Chaco forest shows strong sealing. The explanation we suggest is the presence of a more recent wind-blown cover on top of the older soil. Spot 2 which has a low initial infiltration may be on a cattle trail. This is comparable to spot 3 under Chaco forest at Salim.
- La Virginia. Data show high and very high infiltration, explained by the influence of rooting.
- Deschamps farm. Two observation spots in a recently reclaimed field have high infiltration. A third point without microtopographic information shows a much lower rainfall acceptance. It probably is at the bottom of a furrow.

9.3.5. Error estimation of test results

The maximum expected error in the individual field tests can be estimated as follows:
- Dry crumb test: results can always be allocated to one of the assessment classes.
- Field pinhole test: results can always be allocated to one of the assessment classes.
- Manipulation test: results can always be allocated to one of the assessment classes. In hot weather, drying of the soil to be manipulated is to be avoided. It may otherwise cause an error of one class.
- Rainfall infiltration test: 1-15 mm min^{-1}, but less than 15 % of the calculated infiltration velocity (CLAS, 1998).
- Torvane test: 0.1 reading unit of shear strength. Very small roots to be avoided.
- Rilling test: 0.5 gram per rill
- Soil loss test: 1 gram.

The relative erodibility classes can be crosschecked in several ways by means of comparison, such as follows:
(a) Compare the soil erodibility class resulting from using the detachability and overland flow production with the result of the soil loss test.
(b) Compare the ranking of erodibility found from test results with the ranking of erodibility according to expert opinion.
(c) Compare the result of the erodibility estimation with the erodibility determined from measured soil loss data.
(d) Compare the ranking of approximate soil erodibility with other determinants such as the ones discussed in Wischmeier et al. (1971); Roth et al. (1974); Bryan (1976); Barber et al. (1979); Ambar and Wiersum (1980).

Crosschecks for (a) and (b) agreed within one of five established classes in 45% of the cases. A one-class difference was found in 35% of the cases. Unacceptable difference of two classes was found in less than 20 % of the cases, requiring repetition of the observations.

It is important to be aware that soil erodibility itself varies over the year, related partly to the weather conditions of the seasons, partly to land use and management. It must also be realized that soil erodibility alone cannot predict rain erosion hazard. Topography, plant cover, and rainfall and its distribution are relevant too and often more important than soil erodibility.

9.3.6. How to assess soil erodibility from field test results

In erodibility assessment, a distinction should be made between interrill and rill erodibility (Meyer et al., 1976; Savat & de Ploey, 1984; Elliot & Laflen, 1993). This distinction is related to factors that determine the occurrence of rill erosion, including slope steepness, soil texture and local volume of overland flow (Boon & Savat, 1981).

The potential for rill erosion depends on rainfall, slope gradient and relief form with their influence on concentration of overland flow, and the kind of soil with its permeability distribution over depth and its topsoil properties, while the actual rill erosion depends dominantly on the plant cover and the farmer's soil management practices. The spectrum of data and information obtained from the field tests allows assessing the availability of material for erosion, the overland flow production, and the sensitivity to rill flow.
Conclusions from field investigation can be obtained from evaluating the results for interrill and rill erodibility. For the former, detachability and overland flow production are used; for the latter,

detachability and resistance to scour are used. The availability of erodable material is derived from the structure of the surface horizon (recorded during profile description), the crumb test and the manipulation test. The rainfall infiltration test and the flow volume of the soil loss test give indications about the overland flow production. The soil loss test has not been included in the present study. The shear strength of the soil is derived from the results of the pinhole, shear vane and rilling tests. How to assess soil erodibility from data on erodibility components is described more extensively in Bergsma (2002).

9.4. ESTIMATION OF EROSION RATES

9.4.1. Reconstruction of the original soil profile after truncation by erosion

Reconstruction of soil profiles that existed before erosion took place has been done, for instance, by Kelly et al. (1988). The reconstruction serves studies of landscape development, gives insight into soil erosion hazard and helps planning soil conservation. Not only the physical soil loss, also properties of the new topsoil are indicators for the remaining suitability of the land. The method may be called soil profile reconstruction. It has served the study of organic matter and soil losses in the semi-arid plains of North America.

The authors compared cultivated soils with their unaltered equivalents. An evaluation of the physical, chemical and morphological changes resulting from cultivation practices was made. A discriminant analysis was carried out to establish the degree of homogeneity of the investigated properties at the unaltered and the cultivated sites. Field identification of genetic horizons was corroborated by the soil properties in 86% of all horizons. Soil horizons were A/Ap+A, Bw, BCk and C. Over time, the solum became thinner by loss of the A and Bw horizons. Criteria for identifying soil horizons and thus for assessing the degree of soil loss (in this case, mainly through wind erosion) allowed a profile reconstruction (Table 9.7). Pairs of uncultivated and cultivated soils were compared for their organic carbon and soil mass. The differences showed a relation of erosion with parent material and position in the landscape. This can be understood because transport dynamics is related to slope steepness and shape that relate to position in the landscape. Parent material dominantly acts through its resulting soil texture, fertility, plant growth and organic matter production.

Table 9.7. Criteria for discriminant analysis of soil horizons.

Chemical	Physical	Morphological
Organic C	Bulk density	Colour
Organic P	Soil texture	Structure
Total P		Topsoil horizon thickness
Total N		(A, AB, BA horizons)
pH		
$CaCO_3$		

(from Kelly et al., 1988).

9.4.2. Estimation of erosion rates based on soil texture

After reclamation, there is rapid change in a number of soil characteristics, including hydraulic conductivity, (basic) infiltration rate, apparent density, aggregate stability and organic matter content. Change slows down with time.

(1) Site P1A

Site P1A is on a level II glacis with 2-3% slope, developed on loess cover, deforested 40 years ago, in fallow during 8 years, and cultivated again from 1994 onwards (32 years in arable use). There is a discontinuous plow-pan at 13-15 cm depth. An average thickness of 14 cm for the Ap horizon was used in the following calculations. Observation was made on 30.05.1995.
The Ap (0-13 cm), compared to the Bt (15-35 cm), has 2.6% more sand, 3.3% more silt and 5.6% less clay. The total sand ratio of Ap to Bt (20 cm) and BC (20 cm) is 1.31 and 1.2, respectively. Very coarse,

coarse and medium sand fractions are in percentages smaller than 1%. Fine and very fine sand ratios of Ap to Bt and BC are 1.3 and 1.25. This indicates outwash of fines. It is assumed that the sand fractions serve as indicator of past erosion. This criterion was used to reconstitute the original topsoil thickness and consequent loss of topsoil depth through erosion (Table 9.8).

Table 9.8. Estimated erosion at site P1A.

Particle size fraction	Estimate of reconstituted topsoil depth (cm)	Estimate of consequent erosion depth (cm)
Total sand	18	4
Very fine sand	18	4
Fine sand	18	4

The estimated thickness of soil loss from profile P1A is 4 cm. However, restrictions on the accuracy of this estimation have to be made. The coarse fractions are the ones that are more likely to remain behind during an outwash process. However, their volume is less than one percent of the total soil and thus their relative fluctuation may be strong. For this reason, very coarse and coarse sand fractions were not considered for topsoil reconstruction in this case.

If in total, during erosion periods, 30% of the sand were washed away to drainage ways, the approximation of the thickness of the original topsoil would be (1.31+30%)* 14 cm = 24 cm. Erosion depth would have been about 10 cm. Therefore, the approximation of the erosion degree on the assumption that the entire sand fraction lags behind gives only an indication of the minimum rate of erosion that has occurred.

One has to consider that the coarser soil material that lags behind and serves as indicator for the amount of erosion, may have been subjected itself to local rewash. Local accumulation of sand was observed in the field, showing a pattern of flow paths. The C1 layer has more sand than the underlying 2Btb1 (18% versus 7%) and has somewhat less organic carbon (0.23% versus 0.32%). These data may indicate an old washed surface.

(2) Replicate SW of site P1A

Replicate SW of site P1A is located 80 m southwest from modal profile. The current topsoil is 14 cm deep, similar to the average topsoil depth at site P1A. Total sand, very fine sand and fine sand fractions were used to estimate the original topsoil depth (Table 9.9). Other sand fractions occur in variable but very low amounts.

Table 9.9. Estimated erosion at replicate SW of site P1A.

Particle size fraction	Estimate of reconstituted topsoil depth (cm)	Estimate of consequent erosion depth (cm)
Total sand	18	5
Very fine sand	15	2
Fine sand	20	7

(3) Site P2

Site P2 is under Chaco forest cover. The topsoil (28 cm) has a much higher sand content than that of the underlying Bt horizon (24 cm). The difference suggests an outwash of fines, but local inhabitants report that a sandy cover is occasionally deposited by heavy overland flow events. Thick, very local sandy deposits were indeed observed after recent rainfall events. The forest acts as a depositional area for the coarser material that is being transported from the arable plots. It is unlikely that the forest patches have undergone more erosion than the exposed arable land. The difference in sand content between A and Bt horizons is likely to be due to selective deposition of coarse material in transport by overland flow from arable fields (Table 9.10).Other sand fractions occur in variable but very low amounts.

Table 9.10. Estimated erosion at site P2.

Particle size fraction	A1 (%)	Bt (%)	Unlikely reconstituted topsoil depth (cm)
Total sand	5.5	1.1	140
Very fine sand	2.1	0.4	147
Fine sand	2.2	0.2	308

(4) Site P3B

The area has been reclaimed from Chaco forest in 1995, one year before the test time. The total sand data allowed an estimate of the reconstituted topsoil depth (20 cm) and the consequent erosion depth after one year of arable land use (3 cm). There were no data of the sand subfractions.

(5) Site P4A

The area has been reclaimed from Chaco forest before 1970. Data for the estimation of the topsoil depth before reclamation are given in Table 9.11.

Table 9.11. Estimated erosion at site P4A.

Particle size fraction	Ap (10 cm) (%)	2A1 (20 cm) (%)	Reconstituted topsoil depth (cm)	Estimated depth of erosion (cm)
Total sand	24.9	20.7	12	2
Very fine sand	11.6	7.3	16	6
Fine sand	10.8	9.9	11	1

(6) Site P5A

The area is under Chaco forest cover. There is no soil texture break between the A horizon (13 cm) and the underlying 2A horizon (18 cm). The associated minipits have no data on soil texture.

(7) Conclusion

Soil texture and organic matter data of some profiles serve to estimate the original topsoil depth before reclamation from Chaco forest. The depth of erosion in the first year after reclamation is estimated at 3 cm. After 40 years, it is estimated at 2-7 cm with an average of 4.3 cm. This suggests that perhaps more than half the erosion occurs already in the first year. The reclamation itself accelerates erosion, when after deforestation the soil is exposed to rain during a full rainy season. This may lead to conditions with a much higher erosion hazard than has the plant cover by soybean and weeds during the following years.

The estimate of 3 cm soil loss in the first year equals 300 ton/ha/year on an assumed bulk density of 1 Mg m^{-3} for the loose topsoil. Such an extremely high value of soil loss is not completely impossible, though unlikely. Disposal of this mass of material would cause sedimentation elsewhere. Some forest patches show deposition, and incised drainage ways have a flat, colluvio-alluvial cover. Whether the estimated erosion rates are in agreement with deposition volumes was not further investigated.

Subsequent erosion rate at site P1A would be on average 1.3 cm per 32 years, or 0.4 ton/ha/year. This is a negligible amount, lying within the range of soil loss tolerance. Soil loss tolerance as related to topsoil formation rates is conventionally estimated at 5-12 ton/ha/year (Grant, 1973; Mannering, 1981; McCormack & Young, 1981).

The estimated erosion rates for our study area may be put into classes of accelerated erosion, with quantitative boundaries similar to those used for erosion hazard classes (Bergsma, 1986b). One class is added for extremely high rates (Table 9.12).

Table 9.12. Classes of soil erosion intensity (ton/ha/year).

Class	Range	Practical significance
Very light	0–5	Within range of soil
Light	5–12	loss tolerance
Moderate	12–25	Commonly present
Severe	25–60	Effect on medium term
Very severe	60–150	Effect on short term
Extremely severe	150+	Effect on short term

9.4.3. Estimation of erosion rates based on organic matter data

Estimation was done using the soil profile at site P2 and associated SW, NE, SE and NW replicates. Organic matter contents in the topsoil at the four replicate sites are 4.9, 3.5, 4.1 and 4.5%. The sum of cations for P2 and its four replicates are 33, 21, 23, 30, 20 cmol(+)/kg soil, respectively. It appears that the main soil profile and the SE replicate both have a higher cation exchange capacity than the other sites. SE direction is the general surface drainage direction of the local area.

With respect to topsoil organic matter, there is a decline of content over long periods of arable use. In the first year, it declines 2.5%; in 40 years it declines 4.8%. Thus, the first year causes half of the decline. The burning of the vegetation during reclamation, the subsequent absence of forest litter production and the exposure of the topsoil to the sun might explain the strong decline in organic matter content after reclamation.

Erosion removes fine topsoil particles that are relatively rich in organic matter. Subsequent ploughing to prepare the land would till the soil a little deeper. The new topsoil will have somewhat lower organic matter content, because the topsoil is now a mixture of the remaining topsoil and some subsoil material.

The use of these data to assess erosion depth can give only a rough estimation, as the loss and gain of organic matter depend strongly on land management and plant growth. In case erosion would be the dominant factor influencing changes in organic matter, erosion rate could be approximated as follows. It is assumed that the original topsoil thickness in the Chaco forest was 18 cm from the average of four soil profiles (Gomez et al., 1992) and that the organic matter content in the arable land is 0.8% lower underneath the Ap horizon (from profile data in our study area). Erosion depth in the first year (E^*) is then calculated as:
$18 \text{ cm} \times 8.4\% = 13 \text{ cm} \times 5.9\% + 5 \text{ cm} \times 5.1\% + E^* \text{ cm} \times 5.9\%$, which gives $E^* = 1.2$ cm.

This amount represents a maximum, as burning and natural degradation of organic matter during reclamation will probably account for most of the loss of organic matter in the first year. The tentative estimate of the depth of erosion in the following 32 years (E^{**}) is calculated as: $5.9 \times 13 \text{ cm} = (13+E^{**}) \times 1.3$, which gives $E^{**} = 5.5$ cm in 32 years or 0.14 cm/year. The results are shown in Table 9.13, together with the rates derived from the sand fractions.

Table 9.13. Estimated depth of erosion since reclamation from Chaco forest.

Erosion estimates	Chaco forest	Land reclaimed to arable use since	
		1 year	40 years
Estimated depth of erosion based on particle size (cm)	Deposition	3	4.2*
Organic matter content (%)	7.3*	5.9	4.3*
Estimated depth of erosion based on organic matter distribution in soil profile (cm)	--	1.2	5.5

** = average of 5 values*

9.5. ERODIBILITY TESTS AT THE OBSERVATION SITES

The results of the field tests to assess soil erodibility are grouped and discussed per observation site regarding soil properties, soil detachability, rainfall infiltration and scour resistance (when available). Tests included detachability tests (dry crumb, pinhole and manipulation tests), rainfall infiltration test and shear strength tests (torvane and penetrometer tests).

The location of the observations is indicated by:

- Farm: general location of one or more observation sites where soils and other features were described.
- Site: plot of Chaco forest or arable field of a given age of reclamation from forest, where soils and other features were described. At one farm there are usually several observation sites representing different reclamation periods.
- Point: location of a soil profile and other soil observations. At a site, there may be several points.
- Spot: exact place where field tests were performed. At an observation point, there are usually several spots of tests of soil erodibility and their replications.

9.5.1. Lobo farm (site P1A)

(1) Terrain and soil

Site P1A is on an old cultivated land reclaimed before 1970, located in Lobo farm near Burruyacú, in the northwest of the study area. Soil structure is platy in the lower part of the A horizon (plow-pan) and prismatic in the underlying Bt horizon. This means that, without tillage, rain infiltration is slow in the upper part of the soil and moderately rapid in the subsoil when dry, but slow when moist. Clay skins cover the prismatic structure.

(2) Soil detachability

The general drainage direction in the region is towards the SE, in agreement with a 2-3% slope. The soil detachability tests show the character of the various soil horizons. The tests were performed on truncated surfaces of the subsoil horizons on 12.09.1995. From the results in Table 9.14, the following conclusions can be drawn:

- The upper part of the A horizon has a rather stable structure.
- The prismatic Bt horizon has a very stable structure.
- The subsoil made of reworked loess has a structure that is unstable against wetting, but is otherwise rather coherent.
- The buried Bt has a rather stable structure.

Table 9.14. Soil detachability classes at site P1A.

Soil horizon	dcr	pin	man
A horizon	1	2	2
Bt prismatic	1	1	1+2
Reworked loess	4	2	2
Buried Bt	1-2	1-2	3+1

dcr = dry crumb test - *: intergrade*
pin = pinhole field test + *: repetitions*
man = manipulation test

(3) Rainfall infiltration

Results of the infiltration test are reported in Table 9.15 and point to the following conclusions:

- The impression is that moistening is slow; organic matter could be hydrophobic after prolonged dry conditions.
- In general, smooth surfaces are compacted. Wheel-tracks have rough surface because of the loose earth moulded into the tyre surface pattern. The rougher surfaces have loose structure and are apparently more permeable.
- Infiltration rates are high, even after five minutes. Infiltration in the dry soil is very rapid. If this were representative of the arable surface as a whole, all rain would infiltrate in the soil when dry. However, the rainy season shows extensive flooding, but we could not measure infiltration in wet condition.

Table 9.15. Rainfall infiltration at site P1A.

Site feature	mm rain per observation	Sealing indicator	Infiltration velocity in mm/min. at						Inf.vol. 2-30 min.
			0	5	10	20	30	> 35 min.	
Smooth wheel-track	24	12.3	48	9	3	6	6	-	103 mm
Rough, convex wheel-track	24	2.4	58	19	10	9	4	-	169 mm
Smooth wheel-track	24	7.3	96	8	6	4	4	2	118 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

(4) Shear resistance

The torvane test gave the following average results: 28 kPa cm^{-2} dry, 11 kPa cm^{-2} moist. Moist values are less than half the dry values. This large difference indicates workability restrictions. Timing of land management is to be accurate on loess soils.

9.5.2. Lobo farm (site P2)

(1) Terrain and soil

Site P2 is under Chaco forest, located in Lobo farm near Burruyacú, in the NW of the study area. The A1 horizon is 28 cm thick, has a moderate medium subangular structure and overlies a Bt of 24 cm with a medium to coarse subangular blocky structure. Along cow paths, the surface structure is platy. Vegetation is strongly disturbed.

(2) Soil detachability

Detachability of the A horizon was assessed by means of the pinhole test (class 3) and the manipulation test (class 4), both performed on 15.09.1995. Tests indicate that the soil is moderately coherent and weakly resistant to scour.

(3) Rainfall infiltration

Results of the infiltration test are reported in Table 9.16. There are the following conclusions:
- Infiltration velocity varies strongly with time. Soil (macro)porosity and bulk density have irregular spatial distribution (Flores, 1997). A second factor that contributes to explaining the irregular infiltration velocity is the lateral flow that takes place once the wetting front reaches the soil horizons below the infiltration cylinder.
- Spot 1 has laminar soil structure that breaks into platy elements. At spot 2, litter and organic matter appear to be hydrophobic. The two sites show the effect of soil compaction beneath cow trails.
- Site 3, not affected by animal trampling in trails, shows a sustained rapid infiltration.

Table 9.16. Rainfall infiltration at site P2.

Site feature	mm/obs. Tot. vol.	Sealing indicator	Infiltration velocity in mm/min. at						Inf.vol. 2-30 min.
			0	5	10	20	30	> 35 min.	
Near a cowpath	24 168	0.1	10	11	23	4	3	--	121 mm
Between trees, flat surface	24 144	3.7	18	4	3	3	3	47’:2; 67’:1	75 mm
Off paths and trails	24 144	0.6	19	4	12	14	10	--	172 mm

mm/obs. = mm rain per observation
Tot. vol. = total volume of applied rain
Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

(4) Shear resistance

The torvane test to assess shear resistance was applied to the top one centimeter depth of the soil surface. Descriptive statistics of the data are reported in Table 9.17. When choosing the observation spots, small roots should be avoided as much as possible. The large variation in readings of dry shear resistance probably indicates great variation in bulk density of the surface soil. Local cattle paths and root growth may very well cause this variation in bulk density.

Table 9.17. Statistics of torvane readings (kPa cm^{-2}) in wet and dry topsoils at site P2.

Characteristics	Mean	Median	Mode	Range
Dry shear resistance	22	36	26 and 35	20-86
Wet shear resistance	9	12	13	8-19

The dry shear resistance shows bimodal distribution at the low observation numbers of the test. At higher observation numbers, this may change into a monomodal distribution. The distribution is now strongly skewed, resulting from some hard and a few very hard and compact soil surface spots. A factor that may contribute to skewness, apart from the rooting and the presence of cattle trails and footpaths, is the unequal exposure to sunshine under forest cover. It was observed that places of some 10 m^2 are sunnier and drier than the parts that receive more shadow.

The values of the wet soil penetrometer resistance are much lower and show less variability than those of the dry resistance. Apparently, soil drying compacts some parts of the terrain surface much more than others, while soil moistening strongly lowers the resistance for all parts.

9.5.3. Salim farm (site P4A)

(1) Terrain and soil

Site P4A is on an old cultivated land reclaimed before 1970, located in the Salim farm, in the NE of the study area. The terrain has a general slope of 1% to the south and is crossed by sub-parallel drainage ways running west-east.

A cross-section with 20 m intervals was made (15.09.1995) to record the thickness of friable topsoil, corresponding to a possible, relatively recent thin eolian cover from reactivated soil material. The thickness of this layer is 12/17, 13, 6 and 0 cm from site P4A southwards, and 13, 5, 7, 8, 7, 11, 15 and 3 cm from site P4A eastwards. The microrelief of the deeper parts of the loose surface layer is sometimes convex and sometimes concave. It is not clear whether the deep convex parts were protected by vegetation before the land was used for cultivation of soybean. The conclusion about an eolian cover is not definite, though the texture at the surface is silt loam.

(2) Soil detachability

Detachability of the topsoil (0-10 cm) and the subsoil (30-40 cm) was assessed in the old cultivated field and in path and no-path spots in the Chaco forest near the farm (Table 9.18), leading to the following conclusions:

- Topsoil and subsoil in the arable land are rather unstable against wetting of dry soil, but somewhat stable in wet condition.
- In the Chaco forest, the soil structure is rather stable against wetting, but sensitive to scour.

Table 9.18. Soil detachability classes at site P4A and nearby forest site.

Field tests	Old arable field		Chaco forest	
	Topsoil	Subsoil	No-path	Path
Dry crumb	3	3 (2)	1	--
Field pinhole	2	2-1	3	--
Manipulation	2	2	2	--

(3) Rainfall infiltration

Infiltration tests were applied to topsoil and subsoil in the old cultivated field and in path and no-path spots in the Chaco forest near the farm (Table 9.19), leading to the following conclusions:

- Initial infiltration velocities of the arable topsoil are much higher than those of the subsoil below the plough layer, while infiltration rates at 30 minutes are rather similar. Thus, the topsoil accepts rain easily, but after 30 minutes infiltration equals that of the more stable subsoil.
- The wetted cross-section of the arable topsoil, cut after the infiltration test, indicates stagnation of infiltration at about 4 cm depth and lateral spreading. On the truncated subsoil, infiltration goes deeper. After one hour, it has wetted a cross-section of about 8 cm deep, with 16 cm wide at the top and 10 cm wide at the bottom of the wetted soil. The wetted cross-section reflects the presence of a uniform soil in this deeper part.
- Under Chaco forest, the infiltration test was done at three spots. There is apparently a difference in infiltration between cattle trails and no trails. Spot location in the field is not easy to characterize, because there are trails of different age. The infiltration front in the cut cross-section shows the effect of old and new roots, causing the infiltration front to split into parts.
- Volumes infiltrated in the subsoil are less than in the topsoil, related to variation in porosity with depth. Large macropores occur in irregular distribution in the topsoil. The sealing indicator has similar values.

Table 9.19. Rainfall infiltration at site P4A and nearby forest site.

Infiltration tests (mm per min.)	Old arable field						Chaco forest		
	Topsoil			Subsoil			No-path		Path
Observation spots	1	2	3	4	5	6	7	8	9
Initial infiltration	72	42	33	13	23	17	144	40	10
At 5 min.	19	15	21	8	6	8	31	17	8
At 10 min.	12	10	21	8	5	7	38	20	7
At 20 min.	10	5	3	5	5	5	36	14	5
At 30 min.	5	3	1	4	4	3	30	9	5
Tot. inf. 2-30 min.	174	148	124	110	109	122	710	363	204
Sealing indicator	1.1	2	1.5	0.4	2.6	1	0.7	0.5	0.7

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.4. Salim farm (site P5A)

(1) Terrain and soil

Site P5A is on a Chaco forest plot located in the Salim farm, in the NE of the study area. Field observations were made on 15.09.1995. Slope is less than 1% from west to east.

(2) Soil detachability

The soil is stable against sudden wetting and, once wet, is somewhat stable against detachment.

(3) Rainfall infiltration

There is great variation in infiltration, not only between clear cattle trails and no trails, but also between sites judged to be without trails. Field recognition of trails is not easy, because there are trails of different age, not always indicated by the present vegetation. The size of the wetted cross-section of the soil under the cylinder of the rainfall infiltration test is shown in Table 9.20.

Table 9.20. Rainfall infiltration at site P5A.

Observation spot	No-path, convex	No-path, convex	Probably old path
Rain intensity	21.4 mm/min.	9.2 mm/min.	3.1 mm/min.
Width and depth of wet cross-section below test spot (cm)	17 wide at top 5 wide till 6 deep 4+8 wide till 8 deep	12 wide at top 6+2 wide till 8 deep 4 wide till 13 deep	4 wide at top 4 wide till 36 deep 17 wide till 40 4 wide till 43

A difference between Lobo and Salim farms could be expected based on the climate gradient but not on reclamation age, both sites being in old arable land. In fact, the infiltration data do not show any difference in the topsoil. The subsoil of the old arable land at Salim shows a much lower infiltration than the topsoil. Field observation revealed that a compact structure in the subsoil caused low permeability.

Under Chaco forest, some parts of the terrain surface have high infiltration, many times higher than the infiltration under arable land use. The infiltration in other parts of the Chaco soil surface behaves in a way similar to that of arable land. In the forest plot, infiltration is affected by cattle trampling along roaming paths. Old cow paths show a much lower infiltration than the areas between bushes, where no passage occurred for a period equal to the age of the nearby bushes.

Rainfall application in 4-6 gusts produced strong sealing on all soils except the forest soils. Soil surface sealing led to very low infiltration velocity. After 10 minutes into the rain, only the soils in forest had not yet sealed. But on the old cow paths, low macro-porosity caused also slow infiltration. At both the Lobo and Salim sites, infiltration during the first ten minutes of rain may have been promoted by the extreme dryness of the soils, leading to adsorption in the loose arable layer or forest topsoil.

(4) Shear resistance

Like infiltration, shear strength of the topsoil is strongly influenced by the presence of cattle paths in the degraded Chaco forest. Two locations represent the extreme cases observed on 15.09.1995, one on a cattle and foot path and the other outside the paths, where no animals are expected to pass (Table 9.21).

Table 9.21. Statistics of torvane readings (kPa cm^{-2}) at site P5A under Chaco forest.

Characteristics	Mean	Median	Mode	Range
On cattle trail	37	32	30	20-74
Between trails	32	22	20	20-60

9.5.5. Blasco farm

(1) Terrain and soil

Soil erodibility tests were applied to three sites at Blasco farm, located in the southeast of the study area. Testing was performed on 03.12.1996. The sites were, respectively, in degraded Chaco forest, on old and subrecently reclaimed agricultural parcels.

(2) Soil detachability

The soils at all sites are rather unstable when dry. In moist condition, the forest soil is more stable than soils at reclaimed sites (Table 9.22).

Table 9.22. Soil detachability classes at the Blasco farm sites.

Field tests	Arable field		Chaco forest
	Reclaimed 1976-1985 Spot near M12	Reclaimed 1985-1991	Spot near P13
Dry crumb	3	2	3
Field pinhole	1	3	1
Manipulation	3	3	3

(3) Rainfall infiltration

Field observation of the infiltration velocity was continued after 30 minutes, in some cases even up to three hours (Table 9.23). Generally, sealing occurs already at the beginning of the rain. There is no indication that this is different here. The curve of infiltration velocity versus time is asymptotic.

Table 9.23. Rainfall infiltration at the Blasco farm sites.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at						Inf. vol.
		0	5	10	20	30	> 35 min.	2-30 min.
Chaco forest, site P13								
Spot 1	2.8	96	14	8	4	3	52':3	131 mm
Spot 2	2.0	15	6	3	1	1	64'-146':1	73 mm
Land reclaimed 1976-1985, site M12								
Spot 3 on a tillage ridge in a soybean field	5.8	55	7	5	1	1	47'-113':1 156'-241':<1	76 mm
Land reclaimed 1985-1991								
Spot 4	5.3	55	12	4	2	1	45':2 70'-134':1 176": <1	73 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.6. La Argentina

(1) Terrain and soil

Soil erodibility tests were applied to four sites in La Argentina, located in the centre-north of the study area. Soils of old arable land and Chaco forest have strength of coherence.

(2) Detachability

The soil in the Chaco forest has structural strength against scour, probably promoted by organic matter (Table 9.24).

Table 9.24. Soil detachability classes at La Argentina sites.

Field tests	Arable field		Chaco forest	
	Reclaimed 1970-76 M8 site	Reclaimed 1991-96 P9 site, field with maize stubble	P7 and M6 sites	
	Spot 4	Spots 5-7	Spot 1	Spot 3
Dry crumb	2	-	2	2
Field pinhole	-	-	3	1
Manipulation	2	-	2	3

(3) Rainfall infiltration

Recently reclaimed land had high infiltration, even above that of the (degraded) Chaco forest, while the old arable land had a much lower infiltration (Table 9.25).

Table 9.25. Rainfall infiltration at La Argentina sites.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at 0	5	10	20	30	> 35 min.	Inf. vol. 2-30 min
Chaco forest, sites P7, M6								
Spot 1	2.4	120	17	11	7	4	40':5	138 mm
Spot 2: little disturbed, below creeper vegetation, organic layer about 1.5cm	2.1	96	17	7	4	3	39'-55':2 75'-91':1	107 mm
Spot 3	4.8	76	20	12	6	4	34':4 45':3	150 mm
Land reclaimed 1970-1976, site M8								
Spot 4	6.7	31	4	3	1	1	44':1 55':2 75'-99':1	45 mm
Land reclaimed 1991-1996, site P9, field with maize stubble								
Spot 5	14.6	144	17	9	4	2	44':3 58'-73':2 91':<1	142 mm
Spot 6	12.0	180	24	10	5	3	39':3 50':2	156 mm
Spot 7	12.9	160	26	9	5	4	41':4 51'-63':3 76':2	156 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.7. La Virginia

(1) Terrain and soil

To illustrate the effect of wheel-tracks on infiltration velocity, infiltration tests were performed in an old arable field reclaimed before 1970, near site P12. Spots compacted by wheel-tracks and spots between tracks were compared.

(2) Detachability

In the Chaco forest, the dry structural elements of the topsoil are stable against wetting. Moulded at about field capacity, the soil is rather coherent. Together, this indicates low detachability. However, at saturation, the resistance to scour is low and soil particles easily detached (Table 9.26).

Table 9.26. Soil detachability classes at La Virginia sites.

Field tests	Arable field: Reclaimed <1970 Site P12	Arable field: Reclaimed 1991-1996 Site P11	Chaco forest, Site P10: Spot 1 Interfluve	Chaco forest, Site P10: Spot 2 Path/trail
Dry crumb	-	-	1	1
Field pinhole	-	-	4	4
Manipulation	-	-	3	2

(3) Rainfall infiltration

The observations on spots in the wheel-track pattern do not take into account the periodical management. The effect of present trails may disappear after new land tillage. At spot 3, on a wheel-track, the infiltration velocities are expected to be lower than between tracks (Table 9.27). To explain the data of this spot 3 in comparison with spot 4, one may assume that the upper centimetres soil on the wheel-track are very loose, and the compaction only starts at a depth of several centimetres. At spot 4, during the first few minutes, the infiltration velocity between wheel-tracks is slower than in the spot lying on the wheel-track. After about 100 mm applied rain, infiltrated in about 3 minutes, the infiltration velocities between tracks are higher than on the track.

Table 9.27. Rainfall infiltration at La Virginia sites.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at						Inf.vol. 2-30 min.
		0	5	10	20	30	> 35 min.	
Chaco forest, site P10								
Spot 1 on interfluve	2.2	53	21	10	6	5	35'-51':4	131 mm
Spot 2 path / trail	6.0	103	18	10	6	5	39'-48':4	151 mm
Spot 3	--	45	--	--	--	--		--
Spot 4	--	134	--	--	--	--		--
Spot 5	--	45	--	--	--	--		--
Land reclaimed 1991-1996, site P11								
Spot 1 soybean field	2.8	103	22	13	7	5		153 mm
Spot 2 path / trail	2.5	103	23	8	6	4		130 mm
Land reclaimed <1970, site P12								
Spot 3 on wheel-track	4.3	63	19	6	4	3	47'-64':2 81'-126':1	115 mm
Spot 4 between tracks	2.2	53	18	9	5	4	43'-55':3 68'-83':2 102' :1	129 mm
Spot 5 between tracks	7.6	131	16	7	4	3	57'-101':2 120':1	113 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.8. Deschamps farm (site M27)

(1) Terrain and soil

Infiltration and detachability tests were performed in May 1996, at the beginning of the dry winter, at site M27 on Deschamps farm, located in the northeast of the study region. The land has been reclaimed from forest in the period 1970-1976.

(2) Detachability

The soils show a somewhat weak structural resistance to wetting and scour, but there is some strength of coherence when moulded (Table 9.28).

Table 9.28. Soil detachability classes at Deschamps farm.

Field tests	Arable field		
	Spot 1	Spot 2	Spot 3
Dry crumb	3	3	2
Field pinhole	2	2	3
Manipulation	2	2	3

(3) Rainfall infiltration

Test results lead to the conclusion that all plots have slow infiltration, compared to other sites, and infiltration is slow right from the beginning of the infiltration test (Table 9.29).

Table 9.29. Rainfall infiltration at Deschamps farm.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at						Inf.vol. 2-30 min.
		0	5	10	20	30	> 35 min.	
Spot 1, convex part of a furrow	4	55	10	6	3	2	46’-206’:1	78 mm
Spot 2 , concave part of a plough rill	3	32	9	5	3	2	45’:2 77’-176’:1	76 mm
Spot 3	1	--	7	3	1	1		58 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.9. La Ramada

(1) Terrain and soil

Sites M17, M18, M20 and P17 located near La Ramada, in the southwest corner of the study area, have been studied for erodibility on 07.11.1997. The soil surface state at the sites did not allow performing the torvane and penetrometer tests because of loose soil structure. The soil surface consisted of loosely packed clods produced by recent harrowing, with internal structure of single grain. No erosion features were present.

(2) Detachability

There is no clear change in soil detachability over time between the sites in spite of reclamation time differences. The dry structural elements resist somewhat disintegration on wetting. Soil coherence and shear resistance are moderate (Table 9.30).

Table 9.30. Soil detachability classes in arable fields at La Ramada sites.

Sites	Reclaimed <1970 Site M17			Reclaimed 1970-1976 Site M18			Reclaimed 1976-1985 Site M20		
Test spots	1	2	3	1	2	3	4	5	6
Dry crumb	2	2	-	1	1	-	2	-	-
Field pinhole	2	2	-	3	3	-	-	-	-
Manipulation	3	3	-	3	3	-	3	-	-

(3) Rainfall infiltration

On the test spots at site M17, near La Ramada, there is a correlation between soil structure grade and final infiltration rate. Coarser soil structure has higher final infiltration velocities in the test (Table 9.31).

Table 9.31. Rainfall infiltration at site M17, near La Ramada, on land reclaimed <1970.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at						Inf.vol. 2-30 min.
		0	5	10	20	30	min.	
Spot 1	4	57	2	1	2	1		46 mm
Spot 2	2	67	5	3	2	1		86 mm
Spot 3	3	57	4	2	2	1		47 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

Spot 1 has a flattish, harrowed surface with fine structural elements of 2-5 cm diameter. The cross-section of the wetted soil depth does not show compaction effect up to 10 cm deep, but infiltration was slow because of sealing. Spot 2 has a flattish, harrowed surface with coarse structural elements of 3-7 cm diameter. The wetted area in the cross-section under the infiltration cylinder shows a possible compaction effect at 15 cm depth. Spot 3 shows a flattish, harrowed surface with fine structural elements of 2-3 cm diameter. The cross-section of the wetted soil depth shows a possible compaction effect at 10 cm depth.

Site M18 is located close to the same road as M17, but more to the east. The field has 35 cm wide furrows and both fine and coarser structured lines of the tillage system, with soybean straw incorporated. The initial infiltration rates vary widely, probably influenced by soil structure. The coarsest soil structure does not lead to the highest initial infiltration velocity, but the later infiltration velocities are relatively high in that case (Table 9.32).

Spot 1 is in a furrowed field, with 35 cm wide furrows, on one of the finer structured tillage lines, with soybean straw incorporated. The cross-section of the wetted soil depth does not show compaction effect up to 14 cm deep, but infiltration was slow. Spot 2 is in a furrowed parcel, with 35 cm wide furrows, on a nearly flat-topped plough ridge with coarser clods. The wetted area in the cross-section is 14 cm deep and irregular in shape, laterally as well as downwards. This may indicate discontinuous compaction or a recent deep ploughing. Spot 3 is located two meters from spot 2. The cross-section of the wetted soil is 14 cm deep, with a shape suggesting strong compaction from 9 cm downwards.

Table 9.32. Rainfall infiltration at site M18, near La Ramada, on land reclaimed 1970-1976.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at 0	5	10	20	30 min.	Inf.vol. 2-30 min.
Spot 1	1	101	3	2	2	1	61 mm
Spot 2	0.7	50	4	3	2	1	82 mm
Spot 3	1.7	40	3	3	1	1	55 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

Site M20 is under maize cultivation, with plough furrows and stubble mulch (Table 9.33). There is a very strong decrease of infiltration velocity in the first two minutes. The probable cause is the very dry state of the loose soil surface, which can adsorb much moisture upon initial wetting, but which has no natural large pores for percolation. Sealing is very strong. Spot 6 is on a rill in a field with maize straw that shows a line pattern of vegetative residues. Near site P17, infiltration is low to very low in fallow condition, while sealing is moderate to strong.

Table 9.33. Rainfall infiltration at sites P17 and M20, near La Ramada.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at 0	5	10	20	30 min.	Inf.vol. 2-30 min.
Chaco forest, site P17							
Spot 1, on a path	0.5	--	1	1	1	1	30 mm
Spot 2, on the same path, 3 m from spot 1	2	67	4	2	1	1	55 mm
Spot 3, undisturbed	0.3	2	2	2	2	--	56 mm
Land reclaimed 1976-1985, site M20, maize cultivation, with plough furrows and stubble mulch							
Spot 4	2	80	3	2	1	1	46 mm
Spot 5	6	134	3	1	1	1	34 mm
Spot 6	2.5	80	3	2	1	1	38 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.5.10. Garmendia farm (site P9B)

(1) Terrain and soil

Site P9B is in the Garmendia farm, located in the area of La Argentina, centre-north of the study region. The site is in arable land reclaimed in the period 1991-1996.

(2) Rainfall infiltration

The volume of rain infiltrated between 2 and 30 minutes into the rain of the test is relatively low. Overland flow production will be relatively high. The sealing indicator rates moderate to strong at the three spots (Table 9.34).

Table 9.34. Rainfall infiltration at Garmendia farm.

Test spots	Sealing indicator	Infiltration velocity in mm/min. at 0	5	10	20	30 min.	Inf.vol. 2-30 min.
Spot 1	1.5	31	6	4	3	2	81 mm
Spot 2	0.4	50	5	4	3	2	86 mm
Spot 3	0.8	57	6	5	3	2	100 mm

Inf.vol. 2-30 min. = rain volume infiltrated between 2 and 30 minutes into the rain

9.6. EVALUATION AND DISCUSSION OF ERODIBILITY AND SEALING

Data on soil erodibility gathered at the test sites are summarized in Table 9.35. In general, soil detachability is moderate. In dry condition, it is at times low. Infiltration in the topsoil is usually accompanied by strong sealing and a decline of velocity within 10 minutes. Decline of infiltration velocity remains high even at 30 minutes. In general, tests have not been continued after 30 minutes. Thus, they do not characterize the situation when prolonged rainy periods may semi-saturate the topsoil above relatively impermeable layers or soil horizons. Only in a few cases, the infiltration was measured over periods up to 3 hours.

Outside rainy periods, soil erodibility is very low. Overland flow would be the limiting factor for erosion. In the rainy periods, in case overland flow on saturated topsoil occurs, soil erodibility is moderate. Then detachability may be limiting to some extent the erodibility of the topsoil. Exposed compact subsoil layers would resist detachment, resulting in a moderate to low soil erodibility.

The ranks of the erodibility components of the soils are grouped into five classes as shown in Table 9.36. On basis of the ranking of the erodibility components, the 21 observation spots distribute themselves over the five erodibility classes (Table 9.37). The erodibility classes are relative classes. Their total range may be only a part of the range of soil erodibility worldwide.

The manipulation test results show a limited range: 14 times class 2 and 7 times class 3 (Table 9.35). This indicates a certain uniformity of the soils, as exists also in the corresponding textural classes that are mainly silty clay and clay loam. The parent material of the soils is washed loess sediment. It appears that there is enough binding material in the topsoil to give some cohesion to the soil structure.

Alarm about erosion in the area is strong. From our data, there appears a predominance of the lower erodibility classes and this may be due to the dry season condition in which infiltration was measured. Though infiltration is often high on loose Ap horizons and forest topsoil, in the wet season there is high antecedent moisture that prevents high infiltration velocities to occur. Although the influence of soil erodibility on erosion hazard is in general not dominant, the effect of the rainfall distribution on erosion hazard is expected to be strong.

Table 9.35. Derivation of the soil erodibilities from the test results at the observation sites.

Site features	dcr pin man	Inf. in 2-30 min (mm)	r dcr	r pin	r man	Sr	rSr	DET	r inf	FLO	CLA
Lobo farm, land reclaimed <1970											
Smooth wheel-track	1 2 2	103	5	7.5	7.5	20	3	VL	8	L+	VL
Rough convex intertrack	1 2 2	169	5	7.5	7.5	20	3	VL	18.5	VL	VL
Smooth wheel-track	1 2 2	118	5	7.5	7.5	20	3	VL	10	M	VL
Salim farm, land reclaimed <1970											
Spot 1, topsoil	3 2 2	174	18.5	7.5	7.5	33.5	12.5	M	18.5	VL	VL
Spot 2, topsoil	3 2 2	148	18.5	7.5	7.5	33.5	12.5	M	15	L	L
Spot 3, topsoil	3 2 2	124	18.5	7.5	7.5	33.5	12.5	M	10	M	M
Salim farm, Chaco forest											
Spot 1, no path, convex	1 3 2	547?	5	15	7.5	27.5	6	L	21	VL	VL
Spot 2, no path, convex	1 3 2	217?	5	15	7.5	27.5	6	L	20	VL	VL
Spot 3, old path	1 3 2	117	5	15	7.5	27.5	6	L	10	M	L
Blasco farm, Chaco forest											
Spot 1	1 1 2	131	5	2	7.5	14.5	1	VL	13	M-	VL
Spot 2	3 2 3	73	18.5	7.5	17.5	43.5	18	VH	5	H+	H
Blasco farm, land reclaimed 1976-1985											
Spot 3, tillage ridge	3 1 3	76	18.5	2	17.5	38	16	H	5	H+	H
Blasco farm, land reclaimed 1985-1991											
Spot 4	2 3 3	73	12.5	15	17.5	45	20	VH	5	H+	H
La Argentina, Chaco forest											
Spot 1	2 3 2	138	12.5	15	7.5	35	15	H	13	M-	M
Spot 3	2 1 3	150	12.5	2	17.5	32	9.5	M	16.5	L	L
La Argentina, land reclaimed 1970-1976											
Spot 4	2 2.5* 2	45	12.5	10.5	7.5	30.5	8	L+	1	VH	M
La Virginia, Chaco forest											
Spot 1, interfluve	1 4 3	131	5	19.5	17.5	42	17	H+	13	M-	M
Spot 2, path / trail	1 4 2	151	5	19.5	7.5	32	9.5	M	16.5	L	L
Deschamps farm, land reclaimed 1970-1976											
Spot 1, convex furrow	3 2 2	78	18.5	7.5	7.5	33.5	12.5	M	5	H+	M
Spot 2, concave rill	2 3 3	76	12.5	15	17.5	45	20	VH	5	H+	H
Spot 3, concave plough rill	2 3 3	58	12.5	15	17.5	45	20	VH	2	VH	VH

dcr pin man = dry crumb test, field pinhole test and manipulation test, respectively.
N.B. the antecedent moisture was in some cases not the air-dry state.
Inf. 2-30 = volume infiltrated between 2 and 30 minutes into the applied rain of the infiltration test.
r = rank of data — *DET = class of soil detachability*
Sr = sum of ranks of data — *FLO = class of overland flow production*
rS r = rank of the Sr — ** = missing data replaced by average values*

Table 9.36. Ranking of soil erodibility components.

Test sites	1 2 3 4	5 6 7 8 9	10 11 12 13	14 15 16 17	18 19 20 21
Detachability classes	VL	L	M	H	VH
Flow production classes	VH	H	M	L	VL

VH = very high; H = high; M = moderate; L = low; VL = very low

Table 9.37. Relative soil erodibility.

Classes of soil erodibility	VL	L	M	H	VH
Number of soils classified	7	4	5	4	1

9.7. ERODIBILITY AS PART OF EROSION HAZARD

The areal distribution of the soil erodibility is based on a limited number of investigation points. The number and location of the observations did not allow full characterization of the geopedologic units of the landscape. However, some general tendencies are reported in the conclusion of the chapter.

Assessment of erosion hazard cannot be made from soil erodibility alone and would need the consideration of other factors as well. The present study was not extended to measure basal plant cover density during the seasons, nor has the rain erosivity been determined. A rough estimation of the overall effect of all erosion factors is made below, on the assumption that the concept of the USLE model (Wischmeier & Smith, 1978) is applicable to this area (Table 9.38). However, some factors such as rain-plant cover interactions, the effect of slope length, flow concentration in ephemeral channels and other features may be far from the assumed standard conditions in this area. Chaco forest parcels that remain here and there are likely to have, through their location, an effect on the transport routes and overland flow depth and velocity. Scour and deposition may result in places, depending on the routing of the surface flow paths.

This sketchy and hypothetical approximation of the erosion factors in the USLE model results in the conclusion that erosion hazard on nearly flat arable land in the study area would have a seasonal maximum of 150 x 0.4 x 0.6 x 0.6 x 1 = 22 t/ha/y.

It is suggested to approximate the rain erosivity value somewhat more accurately from the 1 hour and 24 hour maximum (with a 2-year recurrence period) and the annual total in a formula that is calibrated with two meteorological stations of the same climate zone nearby (Bergsma, 1981). The exceedance probability of certain erosivity levels would have to be analyzed from meteorological data.

Table 9.38. Estimated USLE values in four possible situations.

Soil erosion hazard factors in the area	Approximate values			
Approximation of rain erosivity	150	150	150	150
Relief factor for nearly level terrain	0.1		0.1	
Relief factor for very long slopes		0.4		0.4
Soil erodibility, dry periods	0.07	0.07		
Soil erodibility, wet periods			0.56	0.56
Plant cover (rain erosivity-annuals)	0.6	0.6	0.6	0.6
Management practices absent and field boundaries far apart	1	1	1	1
Approximate erosion hazard (t/ha/y)	0.6	2.4	5.0	20

9.8. GREEN AND YELLOW STRIPES IN GROWING SOYBEAN

In September 1995 and November 1996, alternation of yellow and green stripes and patches was observed in growing soybean in fields near the observation site of La Virginia. Analysis of air-photos showed some linear and slightly curved striped patterns, which might be caused by burning residues after reclamation, and more strongly curved stripes of light colour, which could be harvest trails. Patterns observed in the field could not be recognized on the air-photos, probably because of a date difference between them.

Yellow soybean in the field shows often less growth than that of green soybean. Yellow soybean is lower and appears influenced by a limiting factor for growth that we could not identify. Laboratory data suggest that the growth conditions in the green soybean stripes are somewhat better than in the yellow soybean stripes, with slightly more organic matter, higher cation exchange capacity and a little more exchangeable Ca (Table 9.39).

The green-yellow pattern coincides partly with a surface drainage system of very shallow drainage ways across the soybean field. A linear colour pattern on the tillage direction has the green soybean in the furrows and the yellow on the plough ridges. This pattern is probably related to a difference in drainage condition between plough ridge and plough furrow. The very large bands of green soybean may be caused by the practice of burning vegetation residues in lines after reclamation of the Chaco forest.

The soil in the yellow soybean stripes is slightly more sandy (light clay loam, very close to sandy clay loam) than the soil in the green soybean stripes (heavy silt loam, very close to loam). Between the two analyzed samples is a difference of 24 % silt content. The difference in texture may cause a difference in water holding capacity, making the silt loam stripes of the green soybean more favourable.

It would be interesting also to investigate the possibility of local addition of wind-blown material, such as fine sand, loess and possibly particles of organic matter. A deposit of eolian origin could go across the surface drainage pattern and may explain the many small depressions that we have observed.

The question if the colour difference coincides with a difference in yield or a difference in crop quality would be a suitable research topic. Investigating the difference between green and yellow land stripes may lead to new insight in the growth requirements of soybean and suggestions may be derived for improvement of soybean cultivation.

Table 9.39. Topsoil data in soybean stripes of different colours.

Soil characteristics	Yellow soybean	Green soybean
pH H_20	6.4	6.2
pH HCl	5.3	5.3
EC (mS cm^{-1})	0.04	0.04
P-Olsen (mg kg^{-1})	4.5	2.8
Organic carbon (%)	0.81	1.58
N-Kjel (% weight)	0.08	0.12
C/N	10	12
Ca (cmol kg^{-1})	7.8	11.4
Mg (cmol kg^{-1})	2.0	2.3
Na (cmol kg^{-1})	0.1	0.0
K (cmol kg^{-1})	1.4	1.6
CEC (cmol kg^{-1})	11.3	14.6
BS (%)	100	100
Texture	Light clay loam	Silt loam
Clay (%)	29	24
Silt (%)	33	57
Sand (%)	38	19

9.9. CONCLUSIONS

The conclusions deal with the soil properties, mostly physical properties and especially infiltration, related to soil erodibility and their trends in the study area under the effect of soil variability, reclamation period, climate and soil profile horizonation.

(1) Time of deforestation

At the time of deforestation, erosion rates may be temporarily very high. The absence of cover, after clearing the forest and heaping the vegetation debris and part of the topsoil in steep ridges, allows high erosion rates.

(2) Age of reclamation

With greater age of reclamation, infiltration decreases clearly and often strongly. In La Virginia, in the middle south of the study area, this tendency is very weak. In the southwest of the area, a comparable tendency may have been missed because infiltration tests were made there by 6.7 mm rain applications instead of 24 mm as was done elsewhere.

Infiltration is greater and soil sealing is less in Chaco forest soils and recently reclaimed land than in older arable land. At 20 years of arable land use, the infiltrated volumes between 2 and 30 minutes into the artificial rain are much lower and, at 25 years of arable use, infiltration has decreased somewhat more. In general, high production of overland flow is to be expected on arable parcels, particularly on the parcels under long arable use.

(3) Infiltration velocities

In general, infiltration velocities at 30 minutes into the simulated rain, with splash, are about 1 mm/min. Infiltrated volumes during this half-hour are mostly 50-100 mm and higher. This means that the soil can cope with very heavy rainfall when it is dry, as was generally the condition at the time of the field tests. However, strong overland flow and extensive inundation occur in rainy periods. Thus, in wet condition, infiltration must be much lower than rain intensity.

(4) Variation in infiltration

The variability of infiltration in Chaco forest soils is great, probably due to cattle trails, footpaths and shallow roots. On arable land, the rough intertrack topsoil in machine trails is often looser and seals less. The subsoil of old arable land at the Salim site shows little sealing and infiltration is rather low with relative high bulk density.

Test results were obtained by raining times of 30 minutes and, in a few cases, up to 2 hours. These limited rain volumes did not generate saturation above relatively impermeable subsoil horizons. It is expected, however, that layers such as plough-pans and Bt horizons will affect infiltration in a dominant way during the later part of the rainy season, with frequent rains at close intervals. In this condition, the older arable land may produce strong overland flow. Observed sand deposits in Chaco forest parcels indicate strong flow from outside the forest.

(5) Effect of subsoil structure on infiltration

The subsoil of the old arable field at Salim farm shows a much lower infiltration than the topsoil, because of compact soil structure and low permeability caused by plough-pan formation. It is less likely that the use of heavy machines over the last decades could produce such a localized compaction effect. It would have affected the whole Ap horizon and contributed to the formation of coarser and more angular topsoil structure than the soil had earlier. Compact layers at greater depth are B horizons, but in some cases B horizons occur at shallow depth too.

The cross-section of the wetted soil after infiltration at Salim farm shows lateral spreading and thus indicates stagnation of infiltrated water at the depth of a few centimetres. This is caused by the platy structure of the plough-pan. The subsoil cross-section after infiltration shows a wetted area in a vertical cylindrical shape. The soil structure of the subsoil is uniformly angular blocky to prismatic.

The presence of relatively impermeable layers in the soil profile plays an important role in limiting infiltration at the soil surface by causing saturation of a shallow upper part of the soil. The layers responsible for the limited infiltration and the occurrence of topsoil-saturation overland flow are supposedly the plough-pan (at about 20 cm), the Bt horizon at about 50 cm, and possibly the soil horizon with prismatic structure that was found locally below the Bt.

(6) Infiltration in degraded open Chaco forest

In the degraded open Chaco forest plots, infiltration is affected by the presence of cow paths. Old cow paths show a much lower infiltration than the areas between bushes and young trees, where no passage could occur for a time equal to the age of the bush. There is great variation in infiltration, not only between clear cattle trails and no trails, but also between sites judged to be without trails. The distinction is not easy to make in the field, because there are trails of different age. The infiltration front, exposed after performing the infiltration test, splits often into parts due to the effect of roots, old and new.

Another factor influencing the state of the topsoil is the unequal drying of the soil surface in the Chaco forest, where plant cover is sparse in places, allowing irregular insolation of the soil surface.

(7) Rainfall infiltration test procedure

The procedure of using 6.7 mm portions of applied rain for measuring the infiltration velocity is very satisfactory for producing rapid, detailed information. The infiltration test with 6.7 mm applications produces less ponding than when using 24 mm portions. To obtain a good approximation of the infiltration rate during periods comparable with the natural rain shower duration, the test must be continued for 30 minutes at least.

The infiltration velocity shows sometimes a temporary minimum after 20-30 seconds. The rapid initial infiltration may correspond to the filling of macro-pores, while the subsequent minimum may be caused by hydrophobic behaviour of the dry soil and the organic matter, slowing the wetting of the surface by adhesion. Drops of water placed on hydrophobic topsoil stayed unchanged for 10 minutes and longer. The next higher infiltration velocities indicate a more normal pattern of gradually declining infiltration velocity.

(8) Penetrometer resistance

As expected, the values of penetrometer resistance in wet soil are much lower and more variable than those obtained in dry condition. The drying process seems to compact some parts of the soil surface much more than other parts, while the moistening lowers the resistance strongly for all parts.

(9) Detachability test and soil horizons

The erodibility tests reflect soil horizonation. This appears, for instance, from the test data gathered in an arable field reclaimed before 1970 at Lobo farm. The surface part of the A horizon shows a rather stable structure. The prismatic part of the Bt horizon shows a very stable structure. The loess subsoil shows a structure that is unstable when wet, but coherent when dry or moist. The buried Bt shows a rather stable structure.

(10) Relief forms

From the analysis of the denudational and depositional relief forms in the study area, an influence of them can be expected on the composition of the soils and their local moisture regime. In Chapter 4 of this report, Van Zuidam et al. indicate the presence of geomorphic units such as glacis, fluvio-eolian plain, fluvial depression, fluvial terrace, low plain, and fluvial denudational depression. Further research on these relationships would be desirable.

(11) Geographic pattern of infiltration rates

Spatial patterns of infiltrated volumes of 2-30 minutes applied rain during the rain acceptance test are shown in Figure 9.3. Generally, the eastern part of the study area has lower infiltration than the western part. The unexpected low infiltration in the southwest of the area might have resulted from difference in test procedure, as explained under conclusion (2).

North

moderate	high	low
--	moderate	low
low	moderate	--

Figure 9.3. Geographic distribution of infiltration rates.

(12) Geographic pattern of soil detachability

Soil detachability may increase strongly after reclamation. Most often, detachability is moderate in the degraded Chaco forest, at a level similar to that of arable conditions. The spatial pattern of measured stability against detachment is shown in Figure 9.4. Resistance to detachment decreases from northwest to southeast of the area. This trend may be correlated with a similar gradient in annual rainfall and production of biomass, with effect on organic matter content in the topsoil.

North

high	moderate	low
--	moderate	low
moderate	moderate (in forest)	--

Figure 9.4. Geographic distribution of soil detachability.

(13) Geographic pattern of topsoil erodibility

The erodibility of the topsoil is seen as a combination of sensitivity to detachment and capacity of infiltration. It shows the pattern of distribution in Figure 9.5. The classes in the general distribution of soil erodibility are local relative classes, belonging to a set of five. Of course, the erodibility class has not at all the same meaning as the erosion hazard class. Erosion hazard is mostly controlled by land use and slope form and steepness. The erosion hazard under soybean cultivation on a gentle slope with a soil of low erodibility may be higher than the erosion hazard under soybean cultivation on level land with a highly erodable soil.

North

low - moderate	low - moderate	high
--	moderate	high
? --	moderate ?	--

Figure 9.5. Geographic distribution of soil erodibility.

Soil surface properties can vary during the seasons of the year. There are periods with different influence of the rain that modifies the freshly ploughed topsoil. Erodibility tests performed at a given moment in the development of the soil surface structural state may give results that do not represent the situation some months later. This has to be taken into account when interpreting the results of our field tests. When tests are done during the same season of the year, and with similar weather, they are better comparable.

(14) Colour differences in growing soybean

There appears to be a difference in soil characteristics, important for plant growth, between places of green and yellow growing soybean. Analytical data come from on one soil sample pair.

9.10. SUGGESTIONS FOR FURTHER RESEARCH

(1) Causes of subsoil compaction

In the Chaco forest and arable land after one-year cultivation, there is no subsoil compaction. But a pan does occur at depths of 10-20 cm in cultivated fields after 40 years of land use. One explanation is the long-term effect of tillage that produces a plough-pan. Another cause may be compaction by the tire pressure of the machines. A greater exposure to wet and dry conditions after reclamation may also play a role. The causes and origin of the dense soil structure should be investigated more. A reference on subsoil compaction is Horn et al. (2000).

(2) Terminal location of produced sediments

The depth of soil loss is estimated at about 3 cm/year for the first year, or 300 ton/ha/year on an assumed topsoil bulk density of 1 Mg/m^3. Such an extremely high value of soil loss is not completely impossible, though the disposal of this mass of material will probably provoke sedimentation problems elsewhere. Investigation of sedimentation sites may clarify where is the area of sedimentation, what is the volume, and what are the periods when the deposition process was/is most active. By implication, a confirmation or correction of the estimated erosion rates may be found.

(3) Relation between soil erodibility and relief forms

Correlation between relief forms and soil erodibility was not studied in sufficient detail. The geographic location of the observation sites in combination with the position of the relief forms may provide more information. Soil-relief toposequences would show the distribution of soil erodibility, but land use and reclamation history have had an influence too.

(4) Macro-porosity and structural stability

As infiltration depends on macro-porosity and structural stability, additional questions are: is the stability of the macro-porosity related in a dominant way to the organic matter content and the type of organic matter? Has there been a relevant change in the type of organic matter during the period following reclamation?

(5) Field observations during rainfall

Field observations made during prolonged rain would allow monitoring flow paths and their patterns on arable land and inside Chaco forest patches. Study of the sediment load in the overland flow and selective particle-size transport would give information about the origin of observed textural differences between topsoil and subsoil.

It would also allow observation of the erosion slope length, i.e. the length of uninterrupted overland flow, which is important for applying a model of erosion prediction. One may observe concentrations of flow in wide braids and gullies. This would greatly improve the understanding of the erosion impact on the land.

(6) Infiltration test procedure

Measurements should be made to assess the importance of the difference between using 6.7 mm and 24 mm rain applications.

(7) Character of whitish surface sediment

The characterization of the fine whitish sediment, that is left behind on the soil surface inside the cylinder after the infiltration test, could lead to better understanding of the soil reaction to wetting and splash. In the field, this material did not react with acid. It could be very fine eolian quartz sand, part of the loess material, separated by the splash process.

(8) Soil data correlation

Correlation of the soil profile data of Gomez et al. (1992) with the soil and landform data obtained by the present investigations would allow more insight in the landscape formation and this may lead to better understanding of differences in land suitability in support to land use planning.

(9) Colour differences in growing soybean

The question if the colour difference coincides with a difference in yield volume or a difference in quality of the yield would be a suitable research topic. Investigating the difference between green and yellow land stripes may lead to new insight in the growth requirements of soybean and suggestions can be derived for improvement of soybean cultivation.

9.11. REFERENCES

Ambar, S., Wiersum, K.F., 1980. Comparison of different erodibility indices under various soil and land use conditions in west Java. The Indonesian Journal of Geography 10 (39): 1-15.

Barber, R.G., Moore, T.R., Thomas, D.B., 1979. The erodibility of two soils from Kenya. Journal of Soil Science 30: 579-591.

Baver, L.D., Gardner, W.H., Gardner, W.R., 1972. Soil physics. 4th Edition. John Wiley & Sons, London.

Bergsma, E., 1981. Indices of rain erosivity, a review. ITC Journal 1981-4: 460-484.

Bergsma, E., 1986a. Development of soil erodibility evaluation by simple tests. In: Chisci, G., Morgan, R.P.C. (eds.). Soil erosion in the European community, impact of changing agriculture. Proceedings seminar on land degradation due to hydrological phenomena in hilly areas, Cesena-Firenze, 1985. Balkema, Rotterdam, the Netherlands, pp. 213-223.

Bergsma, E., 1986b. Aspects of mapping units in the rain erosion hazard catchment survey. In: Siderius, W. (ed.). Land evaluation for land use planning and conservation in sloping areas. Proceedings International Workshop ITC, 1984. International Institute for Land Reclamation and Improvement (ILRI). Publication 40, Wageningen, the Netherlands, pp.84-105.

Bergsma, E., 1987. Unpublished field report.

Bergsma, E., 2002. Some field tests of soil erodibility (revision July 2002), 17p. To be obtained as hard copy, email attachment or CD from E. Bergsma (bodem@wanadoo.nl), or A. Farshad (farshad@itc.nl) or D. Shrestha (shrestha@itc.nl). International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands.

Bergsma, E., Charman, P., Gibbons, F., Hurni, H., Moldenhauer, W.C., Panichapong, S., 1996. Terminology for soil erosion and conservation; concepts, definitions and multilingual list of terms for soil erosion and conservation in English, Spanish, French and German. International Soil Reference and Information Centre (ISRIC), Wageningen, the Netherlands, 313 p.

Boon, W., Savat, J., 1981. A nomogram for the prediction of rill erosion. In: Morgan, R.P.C. (ed.). Soil conservation. Proceedings Conservation 80, Silsoe, 1980. John Wiley, London, UK, pp.303-320.

Bouwer, H., 1962. Field determination of hydraulic conductivity above a water table with the double-tube method. Soil Science Society Proceedings 26: 330-335.

Brady, N.C., 1996. Alternatives to slash-and-burn agriculture: a global imperative. Agriculture, Ecosystems & Environment 58 (1): 3-11.

Bryan, R.B., 1976. Considerations on soil erodibility indices and sheetwash. Catena 3: 99-111.

Cai, Q.G., Luk, S.H., Shen, H., Chen, Y.Z., 1986. Effect of surface crusting on water erosion: laboratory experiments on loess soils, China. In: Callebaut, F., Gabriels, D., de Boodt, M. (eds.). Assessment of soil surface sealing and crusting. Proceedings symposium, Ghent, Belgium, 1985. Flanders Research Centre for Soil Erosion and Soil Conservation, pp.99-104.

Carson, M.A., Kirkby, M.J., 1972. Hillslope form and process. Cambridge University Press, Cambridge, UK.

Charter, C.F.L., 1949. Methods of soil survey in use in the Gold Coast. Bull. Agric. Congo Belge 40 (1): 109-120.
CLAS, 1998. Student report of fieldwork exercise. Watershed Management Course 1998. Cochabamba, Bolivia.
Collinet, J., Valentin, C., 1984. Evaluation of factors influencing water erosion in West Africa using rainfall simulation. International Association of Hydrological Sciences 144: 451-461.
De Bont, R., Van der Poel, P., 1976. Het verband tussen textuur en aggregaat-stabiliteit. In: Aspekten van struktuurvorming en –stabiliteit. Internal Report, Lab. for Physical Geography and Soil Science, University of Amsterdam, the Netherlands, pp.39-50.
Elliot, W.J., Laflen, J.M., 1993. A process-based rill erosion model. Trans. ASAE 36 (1): 65-72.
Ellis, S., Mellor, A., 1995. Soils and environment. Routledge, London, UK, 364 p.
Flores, E., 1997. Monitoring land use changes and comparing soil physical properties between arable and forest land use in the western Chaco plain, NW-Argentina. MSc Thesis. ITC, Enschede, the Netherlands.
Gifford, G.F., Bushy, F.E., 1974. Intensive infiltrometer studies on a plowed big sagebrush site. Journal of Hydrology 21: 81-90.
Gomez, L.A., Ferrao, R.F., Casen, M.L., 1992. Carta básica de suelos del Departamento Burruyacú, Provincia de Tucumán. Secretaría de Agricultura, Ganadería y Pesca, Instituto Nacional de Tecnología Agropecuaria, Centro de Investigaciones de Recursos Naturales, Instituto de Suelos. Castelar, Argentina.
Grant, K.E., 1973. Soil erodibility and soil loss tolerance factors in the Universal Soil Loss Equation. Advisory Soils 6. United States Department of Agriculture, Soil Conservation Service, Washington DC, USA.
Greenland, D.J., Rimmer, D., Payne, D., 1975. Determination of the structural stability class of English and Welsh soils, using a water coherence test. Journal of Soil Science 26:3-10.
Gregory, K.J., Walling, D.E., 1973. Drainage basin form and process: a geomorphological approach. Edward Arnold, London.
Hachum, A.Y., Alfaro, J.F., 1977. Water infiltration and runoff under rain applications. Soil Science Society of America Journal 41: 960-966.
Hoogmoed, W.B., 1999. Tillage for soil and water conservation in the semi-arid tropics. PhD Thesis, Wageningen University. Tropical Resource Management Papers 24. Wageningen, the Netherlands.
Horn, R., Van den Akker, J.J.H., Arvidsson, J. (eds.), 2000. Subsoil compaction: distribution, processes and consequences. Advances in GeoEcology 32, Catena Verlag, Reiskirchen, Germany.
Imeson, A.C., Kwaad, F.J.P.M., 1990. The response of tilled soils to wetting by rainfall and the dynamic character of soil erodibility. In: Boardman, J., Foster, I.D.I., Dearing, J.A. (eds.). Soil erosion on agricultural land. John Wiley, London, UK, pp.3-14.
INTA, 1985. Atlas de suelos de la República Argentina (escalas 1:500.000 y 1:1.000.000). Provincia de Tucumán y Provincia de Santiago del Estero, Regiones Naturales. Instituto Nacional de Tecnología Agropecuaria, Buenos Aires, Argentina, Tomo II: 563-606.
ITC, 1988-1990. Unpublished field reports.
Jungerius, P.D., 1982. A rapid method for the determination of soil dispersion, and its application to soil erosion problems in the Rif Mountains, Morocco. Studia Geomorphologica Carpatho-Balcanica XV: 31-38.
Kelly, E.F., Aguilar, R., Huhaimeed, A.S., Deutsch, P.C., Heil, R.D., 1988. Profile reconstruction: A method to quantify changes in soil properties resulting from cultivation. Agriculture, Ecosystems and Environment 21:153-162.
Kirkby, M.J. (ed.), 1978. Hillslope hydrology. John Wiley & Sons, Chichester, UK.
Lal, R., 1976. Soil erosion problems on an Alfisol in Western Nigeria and their control. IITA Monograph 1, Ibadan, Nigeria.
Le Bissonnais, Y., Renaux, B., Delouche, H., 1995. Interactions between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils. Catena 25: 33-46.
Loveday, J., Pyle, J., 1973. The Emerson dispersion test and its relationship to hydraulic conductivity. Commonwealth Scientific and Industrial Research Organization, Division of Soils, Technical Paper 15, Melbourne, Australia.
Luk, S.H., 1977. Rainfall erosion of some Alberta soils, a laboratory simulation study. Catena 3: 295-309.
Luk, S.H., 1979. The effect of soil properties on erosion by wash and splash. Earth Surface Processes 4: 241-255.
Mannering, J.V., 1981. The use of soil loss tolerance as a strategy for soil conservation. In: Morgan, R.P.C. (ed.). Soil conservation, problems and prospects. Proceedings Conservation 80, Silsoe, l980. John Wiley, London, UK, pp.337-349.

McCormack, D.E., Young, K.K., 1981. Technical and societal implications of soil loss tolerance. In: Morgan, R.P.C. (ed.). Soil conservation, problems and prospects. Proceedings Conservation 80, Silsoe, 1980. John Wiley, London, UK, pp.365-376.

Mermut, A.R., Luk, S.H., Romkens, M.J.M., Poesen, J.W.A., 1995. Micromorphological and mineralogical components of surface sealing in loess soils from different geographic regions. Geoderma 66: 71-84.

Meyer, L.D., DeCoursey, D.G., Romkens, M.J.M., 1976. Soil erosion concepts and misconceptions. Proceedings Third Federal Interagency Sedimentation Conference, Denver, Colorado, USA.

Munn, J.R., Huntington, G.L., 1976. A portable rainfall simulator for erodibility and infiltration measurement on rugged terrain. Soil Science Society of America Journal 40: 622-624.

Romkens, M.J.M, Luk, S.H., Poesen, J.W.A., Mermut, A.R., 1995. Rain infiltration into loess soils from different geographic regions. Catena 25: 21-32.

Roth, C.H., Meyer, B., Frede, H.G., 1985. A portable rainfall simulator for studying factors affecting runoff, infiltration and soil loss. Catena 12: 79-85.

Roth, C.B., Nelson, D.W., Romkens, M.J.M., 1974. Prediction of subsoil erodibility using chemical, mineralogical and physical parameters. Agricultural Experiment Station, Purdue University, Paper 5460, Project 15030 HIX.

Savat J., de Ploey, J., 1984. Sheetwash and rill development by surface flow. In: Bryan, R., Yair, A. (eds.). Badland geomorphology and piping. Geo-Books, Norwich, England, pp.113-125.

Schwertmann, U., 1986. Soil erosion: extent, prediction and protection in Bavaria. In: Chisci, G., Morgan, R.P.C. (eds.). Soil erosion in the European Community, impact of changing agriculture. Proceedings seminar on land degradation due to hydrological phenomena in hilly areas: impact of land use and management, Cesena-Firenze, Italy, 1985. Balkema, Rotterdam, the Netherlands, pp.185-200.

Scott, H.D., Mauromoustakos, A., Handayani, I.P., Miller, D.M., 1994. Temporal variability of selected properties of loessial soil as affected by cropping. Soil Science Society of America Journal 58:1531-1538.

Sherard, J.L., Dunningan, L.P., Decker, R.S., 1976. Identification and nature of dispersive soils. Journal of the Geotechnical Engineering Division, Vol.102: 287-301.

Shouse, P.J., Russell, W.B., Burden, D.S., Selim, H.M., Sisson, J.B., Van Genuchten, M.Th., 1995. Spatial variability of soil water retention functions in a silt loam soil. Soil Science 159 (1):1-12.

Wischmeier, W.H., Johnson, C.B., Cross, B.V., 1971. A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26: 189-193.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. A guide to conservation planning. USDA Handbook 537. Washington D.C., USA.

CHAPTER 10

SOIL COMPACTION AND FERTILITY DEPLETION

J.A. Zinck, E. Flores, J.M. Sayago

10.1. INTRODUCTION: THE LAND DEGRADATION ISSUE

The study region lies in the ecological zone of the Chaco forest, a two-story seasonal forest common in northern Argentina, southern Paraguay and western Uruguay. During the middle of the 19th century, the Chaco forest was substantially decimated by selective extraction of wood for sleepers used in the construction of a railway that transported mineral ores (tin, lead and silver) from the Bolivian Altiplano to the harbour of Buenos Aires. By the end of the 19th century and beginning of the 20th century, the same forest was additionally depleted through extraction of tannin-bearing trees. Remnants of the original Chaco forest are now often reduced to the lower tree story (5-8 m high), with a few emergent upper story trees (algarrobo, quebracho), and are mainly used for firewood and cattle browsing.

The selected study region, located in the Burruyacú district, northeast of the city of S.M. de Tucumán, was still largely covered by secondary Chaco forest in the early 1950s. By that time, only a few land patches in the western part of the study region, along road 304 linking S.M. de Tucumán to Santiago del Estero, were used for traditional wheat and maize production. A drastic land use change occurred in the early 1970s with the introduction and fast expansion of soybean farming in large production units, related to a variety of factors including the onset of a favourable rainfall cycle, attractive market price for soybean, demographic and social pressure requiring expansion of the agricultural frontier, and arrival of new farming entrepreneurs.

In an area of about 106,000 ha, forest cover decreased from 69% in 1971 to 22% in 1991, representing a conversion of 50,000 ha of forest to arable land, with an average deforestation rate of 2850 ha per year. In general, the forest is cleared with heavy machinery causing truncation and compaction of the topsoil layer. Soybean farming after deforestation is also heavily mechanized, leading to soil compaction. Preliminary field inspection when formulating the research project showed plow-pan formation beneath the arable layer, soil surface sealing, and temporary water stagnation at the terrain surface during the rainy season. Because of their unbalanced particle size distribution, with remarkably high silt content, loess soils are intrinsically fragile and vulnerable to extensive dry-farming ("mining" agriculture) and therefore prone to physical degradation. In contrast, loess soils are usually well provided in nutrient-bearing minerals, but natural fertility may be soon depleted if supplementary fertilization is not provided. In this context, one of the objectives of the study was to assess the nature and level of land degradation, especially in terms of soil compaction and fertility depletion, taking place after 20 years of uninterrupted soybean farming.

10.2. CONCEPTUAL FRAMEWORK

10.2.1. Indicators of physical soil degradation

Soil degradation refers to a diminution of the current and/or potential capability of the soil to produce quantitative or qualitative goods or services (Lal & Stewart, 1990b). Compaction is a major process of soil degradation, leading to variation in soil bulk density. It can be caused by both natural and man-induced processes, including clay illuviation, freezing and thawing, traffic of people, animals and equipment, and plow effect, among others.

(1) Soil compaction and compactness

Soil compaction is a process of densification in which porosity and permeability are reduced, strength is increased and many changes are induced in the soil fabric and in various behavioural characteristics (Soane & Ouwerkerk, 1994).

Compactness is the state that indicates the extent to which compaction processes have influenced the packing of the constituent solid parts of the soil fabric. It can be measured or assessed by a wide range of soil properties, such as bulk density, porosity, void ratio and pore size distribution. It can also be expressed with the value taken by such properties relative to the value of those properties for the same soil when in a specified reference state (Soane & Ouwerkerk, 1994).

(2) Bulk density

Soil bulk density, or more precisely wet soil bulk density, is defined as the mass of soil particles plus the mass of soil water per unit volume of soil. To allow soils at different water contents to be compared, soil compaction is usually described in terms of dry soil bulk density. Dry bulk density of soil is derived from the wet bulk density by subtracting the mass of water present per unit volume. Changes in dry soil bulk density provide a quantitative evaluation of both the loosening effect of tillage and the compacting effect of wheels. Closely associated with bulk density, other properties such as void ratio, total porosity, specific volume and unit weight, are frequently employed to indicate changes in compactness (Campbell, 1994).

Variations in bulk density are accompanied by changes in structural properties, thermal and hydraulic conductivity, and gaseous transfer characteristics. All these affect chemical and biological balances. Thus, through compaction, the soil is changed in such a way as to affect all soil processes to a greater or lesser extent, depending on the degree of compaction (Raghavan et al., 1990).

10.2.2. Factors and processes of physical soil degradation

Structural degradation, caused by a decline in organic matter together with a reduction in biological activity, may lead to compaction and crusting (Lal, 1986). The degree to which soils are sensitive to compaction depends mainly upon texture, although other properties also play a role in the process. Soils with high clay content are prone to compaction, especially when the moisture content is relatively high. Compaction causes the formation of platy aggregates with clay platelets aligned perpendicular to the direction of compression and thus more o less parallel to the land surface, which in some cases results in the formation of pan horizons with platy structure. Usually, the depth to the cultivation pan or plow pan is around 20-30 cm (Ellis & Mellor, 1995).

Socio-economic conditions, in particular increasing food demand, and biophysical factors also play an important role in soil degradation (Lal & Stewart, 1990a). The intensity and scale of mechanization in arable cultivation have increased dramatically, promoting soil compaction and leading to impeded drainage and restricted root growth (Ellis & Mellor, 1995). Even the timing of cultivation is an important factor of soil compaction. Both structural damage and compaction are likely to occur if soils are cultivated when being at moisture levels at or near field capacity or near their plastic limit (Briggs & Courtney, 1989).

10.2.3. Changes in soil properties after forest clearing for farming

García et al. (1993) identified and assessed changes in physical, chemical and biological properties of soils under forest and agriculture in the Chaco-pampean plain east of Tucumán, northwest Argentina. They found that total organic carbon and the light fraction of organic carbon decreased 40 % and 80%, respectively, after 25 years of agricultural land use. After ten years of continuous cropping, the amount of available phosphorus was reduced by 90%. Other soil properties, such as structural stability, hydraulic conductivity and basic infiltration rate, also deteriorated (García et al., 1996).

Casas et al. (1997) monitored the changes affecting the physical and chemical properties of soils cultivated for several years after deforestation in the province of Santiago del Estero, northwest Argentina. From original content of 4.8-5.2% in forest soils, organic matter decreased in farmland at an annual rate of 6.0-6.5% in the first five years of cultivation and 3-4% during the following ten years. Bulk density increased from 1 Mg m^{-3} in forest soils at a rate of 2.4-2.6% in the first five years of cropping. Deterioration of structure, porosity and permeability reduced water infiltration in the topsoil and percolation to the subsoil, resulting in severe limitation for cropping in semiarid environment. Similarly in the Chaco province, Casas and Michelena (1983) observed, after ten years of continuous cropping, strong compaction of the surface layer, crusting and restricted infiltration, together with 21-73% decrease in organic matter.

Domzal et al. (1992) studied the impact of farming practices on soil structure and bulk density, among other properties, of a Haplic Phaeozem and an Orthic Luvisol developed from loess in Holland. A similar study was conducted on a Stagnogleyic Luvisol developed from loam, an Orthic Luvisol developed from sandy loam and a Leptic Podzol developed from sand. Each soil type included forest soils and agricultural soils, the latter on unmechanized farms, mechanized farms and 50-year-old vegetable gardens. Bulk density values were higher in arable-humus layers than in the corresponding horizons under forest. The reclamation of forest soils for agricultural purposes decreased acidification and changed the organic matter distribution in the soil profiles. Soil structure deteriorated due to mechanization of the cropping practices. Humus contents and pH values increased in garden soils, making them more favourable for plant growth than agricultural soils.

In the Amazon basin, Brasil, bulk density of the topsoil increased on new pasture sites after clearing the forest and the amount of available nutrients decreased, particularly phosphorus (Eden et al., 1988). Similary, Ellis and Mellor (1995) reported the effect of forest clearing on bulk density, especially when mechanical methods were used instead of the traditional slash-and-burn.

Undisturbed and degraded forest sites, with eight different agricultural rotation systems, were selected in the Chitwan district, Nepal, to document differences in soil quality due to land use changes (Burton et al., 1989). Soil fertility, expressed by organic carbon, total nitrogen and cation exchange capacity, decreased when forest was reclaimed for agriculture. Forest degradation occurred also because of over-utilization.

The effect of land use change on morphological, physical and chemical properties of red podzolic soils under pasture and forest was reported for four soil catenas northwest of Sydney (Parker & Chartres, 1983). Soils under pasture had lower organic matter contents and porosity, higher bulk density and reduced aggregate stability in the topsoil in comparison to soils under forest.

Taking a forest soil as reference, Martins et al. (1991) studied the chemical, physical and micromorphological changes occurring after sequential burning. Deforestation and tillage caused decrease and qualitative changes in soil organic matter: fulvic acids first increased, then humic acids decreased, leading to the destruction of clay and organic matter complexes in the A horizon. Hence, dispersion and migration of fine particles occurred, causing obstruction of macropores and an increase in bulk density. Crop production decreased after two years and the soil had to be abandoned.

Aweto and Adejumbodi (1991) have analyzed the changes in topsoil properties under grazed plots and ungrazed savanna woodland in the southern Guinean savanna zone of Nigeria. Mean values of all investigated properties, including organic carbon, total nitrogen, exchangeable bases, cation exchange capacity, pH and phosphate content, were significantly lower in the soils of the grazed plots than in those of the ungrazed sites. The lowering of the soil organic matter content and nutrient levels in the grazed sites was controlled by a number of interrelated causal factors. Removal of the protective vegetation cover by grazing livestock and by burning, together with soil compaction caused by animal trampling, resulted in increased soil exposure and enhanced surface runoff. The former in turn resulted in accelerated soil erosion, organic matter decomposition and nutrient loss through leaching. The return of organic matter and nutrients to the soil by grazing livestock was insufficient to compensate for the deterioration of the soil herbage quality.

A comparison of the effects of different ways of clearing the forest was done in a Typic Haplustalf in Bolivia (Barber & Romero, 1994). Four bulldozers and chain methods were used, all of them causing important soil degradation. For instance, bulk density increased by 10-20% and total porosity decreased by 6% to a depth of 20 cm. Deforestation caused also a lowering of the soil surface by about 3 cm because of compaction. Cumulative infiltration rate was 30 minutes longer after deforestation, compared with the forest control site. No important differences in subsequent yields of corn were found among land clearing methods.

10.2.4. Effects of farming practices on soil properties

(1) Penetration resistance and bulk density

Much research has been done on the effects of farming on both soil resistance to penetration and soil bulk density, with emphasis on the effect of heavy machinery on soil stability and compaction (Flores, 1997). For instance, Vázquez et al. (1991) did an experiment on the compaction of a Paleudult after eight years of oat/soybean double-cropping tillage, with four treatments: no-tillage, conventional tillage, no-tillage plus in-row subsoiling, and conventional tillage plus in-row subsoiling. The most notable overall long-term effect of no-tillage compared to conventional tillage occurred at 15 cm depth for soil penetrometer resistance and in the 5-10 cm depth for bulk density. Increases were 19% and 11%, respectively, with maximum values at depths of 25-35 cm. Soil penetrometer resistance increased 35% by wheel traffic in the upper 25 cm, while bulk density increased less than 3%. This means that penetrometer resistance was, in that case, a 10-times better indicator of soil compaction than bulk density. Bulk density of the soils compacted by agricultural machinery could exceed 1.5 Mg m^{-3}. Soils without compaction had bulk densities ranging from 1 to 1.5 Mg m^{-3}.

(2) Other properties affected by farming practices

Raghavan et al. (1990) studied the influence of compaction by vehicles on the root network development. The rooting depth in a clay soil, subjected to variable wheel passes at a constant pressure of 62 kPa, decreased from the original 50-60 cm to less than 30 cm depth after 15 passes.

Different kinds of machinery can affect physical properties in different ways, but also the way of tilling can influence some properties to various degrees. Ellis and Mellor (1995) compared the amount of organic carbon and total nitrogen in topsoils under conventional and no/minimum tillage. Organic carbon was higher in the untilled topsoil, while total nitrogen was higher in the tilled one. Soil characteristics, especially those relating to aggregate stability, improved with reduced tillage.

Differences in land use have influence on soil properties as well. Soils under continuous production usually suffer diminution in organic carbon over time (Garwood et al., 1977).

10.2.5. Effects of trampling on physical soil properties

The effect of animal trampling on soil compaction has been studied by many authors. Colburg (1976) concluded that grazing did not change surface soil compaction to a great extent. According to Van Haveren (1983), the bulk density of soils with coarse texture was not influenced by trampling, but the bulk density of soils with fine texture increased significantly under grazing. Studying the effect of different stocking rates on a Mollisol, Stephenson and Veigel (1987) found that an increase from 10 to 40 heads/ha resulted in a significant increase of soil bulk density. According to Ahmed et al. (1987), a cow exerts a load of 10.9 kg cm^{-2} at rest and 2-4 times that load when it is moving. The magnitude of the trampling effect is infuenced by, among other factors, the number of cattle, the distance to water and the forage availability (Martínez, 1992). Valentin (1985) gives examples of soil degradation around water holes due to grazing and trampling in the Sahelian zone. Trampling led to soil deterioration through sealing and compaction, while grazing resulted in wind and water erosion, with deterioration spreading at least 2 km from the water holes.

In Colombian Amazonia (Martínez & Zinck, 2004), evidence of soil compaction through cattle trampling, after clearing the primary forest, included the formation of an Ap horizon with platy structure and dominant greyish or olive colours, reflecting impaired surface drainage, the increase of bulk density and penetration resistance, and the decrease of porosity and infiltration rate. From primary forest to pastures older than 9 years, bulk density increase of the 5-10 cm layer was 42% in fine-textured soils and 30% in coarse-textured soils. Penetration resistance ranged from 0.45 MPa under forest to 4.25 MPa in old pastures, with maximum values occurring at 3-12 cm depth in pastures older than 9 years. Crude protein content and dry matter yield of the forage grass steadily decreased over time, reflecting the effect of soil compaction on pasture performance. After about 9-10 years of use, established grass did no longer compete successfully with invading weeds and grazing plots were abandoned. The spatial distribution pattern of soil compaction was found to be related to soil type, landscape position, pasture management and animal load (Martínez & Zinck, 1994).

Usman (1994) found that cattle trampling increased soil bulk density and cone penetrometer resistance in a northeastern Nigerian sandy loam soil. Infiltration was reduced due to soil compaction, most significantly at 7.5 cm depth. There was an 11-fold difference in hydraulic conductivity and infiltration rate between the heavily and lightly trampled soils, while compaction decreased by 19%. Bezkorowajnyj et al. (1993) and Mulholland et al. (1991) report similar behaviour of soil properties under trampling. Mulholland and Fullen (1991) found zones of very dense compaction at 7-10.5 cm depth in loamy sand soils, leading to severe drainage restriction.

10.2.6. Spatial variability of land degradation

(1) Spatial variability of soil properties and geostatistics

According to Wilding and Drees (1978), spatial variations of soils have both systematic and random components. At a given scale, the systematic component can be explained by soil-forming processes (e.g. climate, lithology, etc), while the random components concern those soil properties which cannot be associated to a known cause. As spatial heterogeneity of the soil mantle increases, conclusions accuracy about soil properties and soil behaviour decreases. The precision of extrapolations is strongly linked to the magnitude of soil variations. Spatial and temporal variability of soils has also a strong influence on the successful transfer of knowledge about a particular land use from one site to another (Trangmar et al., 1985). The classical statistical approach does not account for the geographic distribution of differences within sampling areas. In contrast, geostatistics take into account both the structured and random characteristics of spatially distributed variables, thus providing tools for their description and optimal estimation (Trangmar et al., 1985; Stein, 1996).

Conventional statistics approaches are based on random, independent variables that assume zero continuity, meaning no reference to locations, and do not allow for extrapolation of data values (Trangmar et al., 1985; Davis, 1986; Aranof, 1989; Ingram, 1996). In contrast, geostatistics assume that close points are spatially correlated to each other. During interpolation, this continuity is measured and is then used for point, cell or block estimates. The particular relationship expressing the extent of the continuity, or correlation, is reflected in the variogram function (Ingram, 1996).

Geostatistical analysis is based on a two-step procedure: (1) the calculation of the experimental variogram and fitting a model to it; the variogram merely describes the spatial relationship between the data points; (2) the actual interpolation through kriging, a moving average technique that uses the variogram parameters to assess the relationship between the data points (Ingram, 1996).

(2) Use of geostatistics in penetration resistance and bulk density studies

Ley and Laryea (1994) studied the spatial variation of penetration resistance in a hardsetting tropical Alfisol. They found different models for describing the semivariograms at two soil-water conditions. An isotropic linear model showed the best fit for the dry soil, while an isotropic spherical model was the best fit for the wet soil. In a complementary study on the spatial structure of water contents, a similar trend was found.

Martínez and Zinck (1994) compared penetration resistance and bulk density between two grid sample areas, one under forest and another under pasture, in the Colombian Amazonia. Both penetration resistance and bulk density strongly incremented in the upper 10 cm of the soil under pasture compared to the forest site. Compaction under pasture was related to landscape position and differences in pasture management. Large nugget effects were obtained, indicating that penetration resistance and bulk density values varied at distances smaller than the selected sampling intervals, particularly in the pasture plot.

Meshalkina et al. (1995) studied spatial variability of two plots in Russia under forest and cultivated land, respectively. They observed a normal distribution of the data collected from the agricultural plot, so that spatial variability could be modelled by means of semivariograms, allowing the use of ordinary kriging for mapping. In contrast, the data from the forest plot were lognormally distributed and showed a quadratic trend, requiring the application of generalized covariance functions to model the spatial structure and of universal kriging for mapping. It was concluded that the farming plots had less spatial variability than the forest plots due to the homogenizing effect of different land uses.

Bono et al. (1993) determined correlations between water content and soil penetration resistance in three soils of Argentina, including Ustipsamment, Typic Haplustoll and Entic Haplustoll soils with variable organic matter and sand contents. Correlation between water content and penetration resistance was mainly associated to texture and, in the case of the Haplustolls, to the amount of organic matter. The lower the organic matter content, the higher the penetration resistance.

Penetration resistance varies also with time. Spain et al. (1990) reported temporal variations in three tropical soils under rainforest in Queensland, with up to six-fold ranges according to the period of the year. Because of these temporal variations, Lal suggested to monitor bulk density and penetration resistance every season of the year (Lal, 1994).

10.3. STUDY METHOD AND SAMPLING SCHEME

10.3.1. Selection of study transects, areas, plots and sites

To identify spatial variations and temporal changes in land degradation, two west-east study transects, 25 km apart, were selected, one 20 km long in the north (Burruyacú-La Argentina-Gobernador Garmendia) and another 30 km long in the south (La Ramada-La Virginia-Gobernador Piedrabuena) (Figure 10.1).

In west-east direction, both transects cross two main landscape types: (1) to the west, an undulating piedmont of mixed origin, with alluvial fans locally covered by eolian deposits, at 500-900 m elevation, lying at the foot of the lower pre-Andean mountain ranges (Sierra de La Ramada, Sierra del Campo y Sierra del Nogalito, with elevation of 900-2000 m); and (2) to the east, a flat eolian plain at 400-500 m elevation, covered by a Holocene loess mantle and locally incised by temporary creeks coming from the lower Andean slopes. By far, the largest part of the study region corresponds to the plain landscape. Climate and soils gradually vary from west to east. Average annual rainfall ranges from 900 mm in the west to 600 mm in the east. Rainfall variation has contributed to soil differentiation, with mainly Argiustolls in the west, Haplustolls in the center, and Ustropepts in the east of the region.

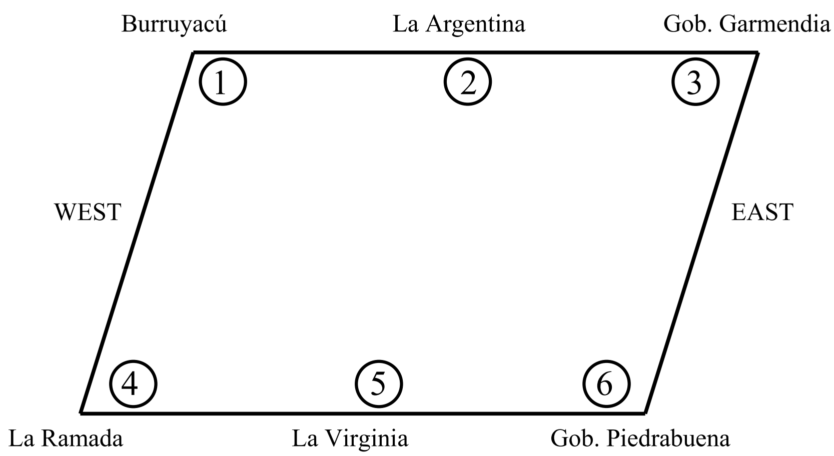


Figure 10.1. Location of the study transects and study areas.

The two transects cross a large agricultural frontier region deforested from the early 1970s onwards. Deforestation started along the established road network and later penetrated into less accessible areas, leading to the opening of new roads. Using the results from the land use changes analysis (Chapter 7), land plots deforested over the last three decades were identified and clustered in five reclamation classes according to available time series of remote sensing data: <1970, 1970-76, 1976-85, 1985-91 and 1991-96.

Along each transect, three study areas were located in the west, center and east of the region, respectively, to take into account the soil-climate spatial gradient. In each study area, agricultural fields belonging to the five deforestation classes were identified from the consecutive land use maps (Chapter 7). This procedure allowed thus to combine spatial soil-climate variability with temporal land use changes in one sampling scheme (Figure 10.2). In each study area, forest plots were included as reference areas for comparison with agricultural fields. This has resulted in the selection of 46 basic study sites, distributed over the six study areas and supplemented with 43 replication sites (Table 10.1).

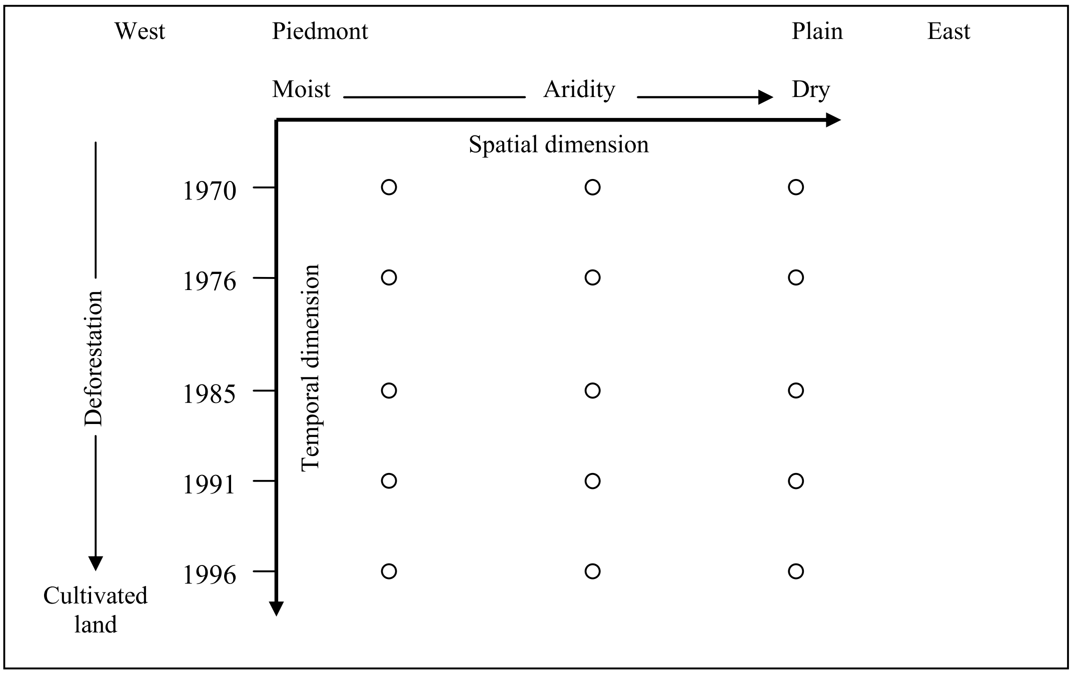


Figure 10.2. Methodological approach.

10.3.2. Field data collection and laboratory determinations

In each selected agricultural or forest plot, a study site was located for data collection, including vegetation survey, characterization of the soil surface features resulting from farming or erosion/deposition, soil description and soil sampling. In specific places, corresponding to forest sites (situation in 1996-97), old reclaimed sites (deforested before 1970) and recently incorporated sites (deforested in 1991-1996), full-pit (2 m deep) soil description and sampling were carried out. In the other places, smaller pits (<1 m deep) were used for soil description and sampling. In many places, data gathered in pits and minipits were supplemented by means of observation replicates. In each site, specific data, additional to the data recorded in the conventional soil descriptions (Chapter 13), were collected to assess soil degradation. Soil surface description and test data are presented and discussed in Chapter 9. The present chapter concentrates on data collected for assessing soil compaction and fertility depletion.

To assess soil compaction, two parameters, namely penetration resistance and bulk density, were systematically determined, in addition to the description of qualitative features such as the presence of plow-pan and surface crusting. Soil penetration resistance of the topsoil and subsoil, to a maximum depth of 80 cm, was measured using a Stiboka penetrograph. The standard apparatus consists of a measuring device with a compressing spring of 500 N and sounding rods terminated by adjustable cones of different basal areas (Eijkelkamp, 1989). For this research, a cone of 1 cm^2 basal area was used. The instrument graphically recorded the measured resistance values into penetrograms. Five repetitions were made at each observation site. Recorded resistance penetration curves were digitized cm per cm and averaged for each site. For being a time-consuming field test, determination of soil penetration resistance was limited to (1) two local grid experiments in the Burruyacú area and (2) point tests at all study sites of the northern transect. The total number of point measurements generated 900 possible comparison pairs in agricultural fields and 105 pairs under forest cover for geostatistical treatment. Bulk density was determined in laboratory from undisturbed soil samples taken with a Uhland equipment. To assess fertility depletion over time, three parameters were used, including organic carbon content, soluble phosphorus and exchangeable calcium.

Results were analysed at three spatial levels: (1) the regional level, covering the whole study region (approximately 100,000 ha); (2) the local level, corresponding to the six study areas distributed over the two transects; and (3) the plot level in one specific area (Burruyacú) for geostatistical treatment of detailed grid surveys.

Table 10.1. Sampling scheme.

Western strip (Burruyacú + La Ramada)

	Forest	< 1970	1970-76	1976-85	1985-91	1991-96
North - Burruyacú						
Pit	P2	P1A				P3A P3B
Minipit	M4	M3	M28	M9	M15	M2
Replicate	P2W	M3N		M9N	M15E	P3N
	P2E	M3E		M9W	M15W	P3E
	M4N					M2W
	M4S					M2SW
South - La Ramada						
Pit	P17					
Minipit		M17	M18	M20	M19	

Central strip (La Argentina + La Virginia)

	Forest	< 1970	1970-76	1976-85	1985-91	1991-96
North - La Argentina						
Pit	P7B	P6B				P9B
Minipit	M6	M1	M8	M5	M7	M16
Replicate	P7E	P6S	M8E	M5E	M7S1	P9S
	P7N	P6W	M8W	M5W	M7S2	P9W
	M6S	M1W				M16N
	M6N	M1E				M16S
South - La Virginia						
Pit	P10	P12				P11
Minipit			M23	M21	M22	

Eastern strip (Gobernador Garmendia + Gobernador Piedrabuena)

	Forest	< 1970	1970-76	1976-85	1985-91	1991-96
North - Garmendia						
Pit	P5A	P4A				P8B
Minipit	M11	M10	M27	M12	M13	M14 M29
Replicate	P5E	P4W		M12W	M13S	P8SW
	P5W	M10W		M12E	M13E	P8E
	M11E	M10E				M14N
	M11W					M14S
South - Piedrabuena						
Pit	P13	P15 P16				P14 (16)
Minipit			M24	M25	M26	

Total						
Pits+Minipits	9	10	6	6	6	9
Replicates	12	9	2	6	6	8

10.4. RESULTS AT REGIONAL SCALE (STUDY REGION)

10.4.1. Spatial variations

To explore the existence of spatial trends throughout the study region as a whole, which might reflect regional differences in farming practices and/or in soil vulnerability, all data belonging to the six study areas were lumped together and averaged for selected topsoil parameters, including bulk density (BD), organic carbon (OC), exchangeable calcium (Ca^+) and soluble phosphorus (Ps), regardless of the reclamation dates and thus regardless of the different time spans over which land has been under use (Tables 10.2 and 10.3). This provides background information allowing us to contrast intra-regional differences (Tables 10.4 and 10.5).

(1) Bulk density

The regional mean value of bulk density in the topsoil is 1.09 Mg m^{-3} in the first horizon and 1.23 Mg m^{-3} in the second one, corresponding to an increase of 13%. Such data bear relatively low meaning as they mask intra-regional spatial trends, as well as temporal variations according to land reclamation dates and differences between forest and arable land. In the first horizon (Ap1), BD values are in the range of 1.01-1.22 Mg m^{-3}, with slightly higher values in La Argentina and Gobernador Garmendia than elsewhere, indicating that the physical conditions of the arable layer are in general good. In the second horizon (Ap2 or Apd), average BD values are higher than in the first one in all study areas, with values ranging from 1.17 to 1.31 Mg m^{-3} (Figure 10.3). This reveals a general tendency to compaction in the second horizon, with plow-pan formation. A regional trend is visible in the northern transect, where bulk density values seem to parallel the displacement of the agricultural frontier from west to east, with the highest values in the oldest reclamation areas (Burruyacú and La Argentina) (Figure 10.4b).

(2) Organic carbon

The regional mean value of organic carbon in the topsoil is 2.55% in the first horizon and 1.53% in the second one, corresponding to a decrease of 40%. In all study areas, the OC content is higher in the first horizon (1.94-3.15%) than in the second (1.19-2%) (Figure 10.5). When compared to conventional standards, these OC contents can be considered medium to high in the upper part of the topsoil and low in its lower part. Organic carbon clearly decreases from west to east in both horizons (Figure 10.6). This parallels a decrease in annual rainfall and might reflect the influence of the climate gradient on biomass production and organic matter incorporation into the soil.

(3) Exchangeable calcium

Exchangeable calcium is high throughout the topsoil, with average values slightly higher in the first horizon (12.4-25.6 cmol(+) kg^{-1} soil) than in the second one (12-17 cmol(+) kg^{-1} soil) (Figure 10.7). In the southern transect (La Ramada-Piedrabuena), there is a trend of decreasing Ca^+ from west to east in both topsoil horizons (Figure 10.8).

(4) Soluble phosphorus

On average, in all study areas except La Virginia, there is about two times more soluble phosphorus in the first horizon than in the second one (26.2 mg kg^{-1} and 13.4 mg kg^{-1}, respectively) (Figure 10.9). When compared to the other selected topsoil parameters, Ps shows a different spatial pattern, with values increasing at the same time from west to east and from south to north, to let alone the area of Garmendia as an outlier case (Figure 10.10). According to conventional standards, these Ps contents can be considered low to very low everywhere, with values of 7-56 mg kg^{-1} in the first horizon and 4-30 mg kg^{-1} in the second horizon. Piedrabuena is the study area with the highest Ps content, while La Ramada and La Virginia are particularly poor in Ps.

Table 10.2. Degradation indicators in the upper topsoil.

Study area	Landuse	Site	Horiz.	Depth	BD	OC	pH	Ca^+	P sol.
Burruyacú	Forest	P2	A	0-28	1.22	4.87	7.4	26.50	35.0
	Forest	M4	A	0-12/18	0.91	5.67		27.22	53.2
	<1970	P1A	Ap	0-13	1.09	2.07	7.5	10.81	2.5
	<1970	M3	Ap	0-23	1.03	2.91		15.34	3.5
	1970-76	M28	Ap1	0-9/12	1.23	1.60	6.3		15.1
	1976-85	M9	Ap	0-8/11	1.19	2.71		15.55	27.7
	1985-91	M15	Ap	0-10/12	1.13	2.88		24.19	21.7
	1991-96	P3A	Ap	0-17	0.94	3.43	6.6	18.23	15.1
	1991-96	P3B	Ap	0-9	1.15	2.39	7.2	13.18	23.1
	1991-96	M2	Ap	0-13/15	0.94	2.99		15.34	33.6
	Mean of total area				1.08	3.15	7.0	18.48	23.1
	Mean of cultivated area				1.09	2.62	6.9	16.09	17.8
Argentina	Forest	P7B	A1(Ad)	0-21	1.41	2.55	7.2	15.30	52.2
	Forest	M6	A1	0-10	1.22	4.63		24.95	35.0
	<1970	P6B	Ap	0-10	1.13	1.57	7.0	13.61	24.7
	<1970	M1	Ap	0-4	1.19	1.40		11.34	25.6
	1970-76	M8	Ap	0-12	1.37	1.56		13.07	4.6
	1976-85	M5	Ap	0-12		1.96		28.18	10.5
	1985-91	M7	Ap	0-18	1.31	1.12		19.01	2.1
	1991-96	P9B	Ap	0-11	0.99	3.03	6.4	15.88	18.8
	1991-96	M16	Ap	0-12	1.17	2.71		15.77	27.3
	Mean of total area				1.22	2.28	6.9	17.46	22.3
	Mean of cultivated area				1.19	1.91	6.7	16.69	16.2
Garmendia	Forest	P5A	A	0-13	1.06	2.75	6.5	17.77	42.6
	Forest	M11	A1	0-3/7	1.27	1.60		11.56	46.2
	<1970	P4A	Ap	0-8/12	1.29	0.96	8.0	13.45	30.8
	<1970	M10	Ap	0-5/8	1.12	2.00		15.44	44.1
	1970-76	M27	Ap1	0-9	1.18	1.76	6.8		42.0
	1976-85	M12	Ap	0-9/12	1.02	1.96		15.55	35.0
	1985-91	M13	Ap	0-16	1.17	1.88		14.69	20.0
	1991-96	P8B	Ap	0-11	1.07	2.43	7.7	19.55	44.0
	1991-96	M14	Ap	0-14	1.10	1.92		19.22	24.9
	1991-96	M29	Ap	0-10/13	1.00	2.15	6.6		70.0
	Mean of total area				1.13	1.94	7.1	15.90	40.0
	Mean of cultivated area				1.14	1.88	7.3	16.32	38.9
Ramada	Forest	P17	A1	0-19	0.96	4.71	6.9	25.55	7.4
	<1970	M17	Ap	0-10	1.03	1.72	5.7		3.5
	1970-76	M18	Ap1	0-11	1.16	2.00	6.2		6.0
	1976-85	M20	Ap	0-18	1.16	3.19	7.1		22.4
	1985-91	M19	Ap1	0-17	0.91	4.07	7.6		5.6
	Mean of total area				1.04	3.14	6.7		9.0
	Mean of cultivated area				1.07	2.75	6.7		9.4
Virginia	Forest	P10	A1	0-6	1.09	4.23	5.8	15.90	10.5
	<1970	P12	Ap1	0-8	1.04	2.15	6.6	12.06	9.8
	1970-76	M23	Ap1	0-11	0.92	2.15	6.2		4.6
	1976-85	M21	Ap	0-18	1.09	2.07	6.6		3.2
	1985-91	M22	Ap	0-12/15	0.93	1.76	6.0		2.8
	1991-96	P11	Ap	0-12	0.99	2.71	6.9	16.33	9.8
	Mean of total area				1.01	2.51	6.4	14.76	6.8
	Mean of cultivated area				0.99	2.17	6.6	14.20	6.0
Piedrabuena	Forest	P13	A1	0-8	0.89	5.11	5.5	14.66	108.5
	<1970	P15	Ap	1-9	1.13	1.12	6.5	7.90	9.8
	<1970	P16	Ap1	0-14	1.11	1.84	6.3	15.08	29.8
	1970-76	M24	Ap	0-8	1.18	2.79	7.5		65.1
	1976-85	M25	Ap	0-8/12	1.10	1.80	7.1		66.5
	1985-91	M26	Ap	0-15	1.02	1.60	6.9		73.5
	1991-96	P14	Ap1	0-7	0.94	1.60	6.1	12.06	38.5
	Mean of total area				1.05	2.27	6.6	12.43	56.0
	Mean of cultivated area				1.08	1.79	6.7	11.68	47.2

Landuse: arable land according to deforestation periods; Depth (cm); BD: bulk density (Mg m^{-3}); OC: organic carbon (%); pH (water 1:1); Ca^+: exchangeable calcium (cmol kg^{-1}); P sol.: soluble phosphorus (mg kg^{-1}).

Table 10.3. Degradation indicators in the lower topsoil.

Study area	Landuse	Site	Horiz.	Depth	BD	OC	pH	Ca^+	P sol.
Burruyacú	Forest	P2	Bt	28-52	1.42	1.02	7.6	10.40	7.4
	Forest	M4	Bt	12/18-40/44	1.07	3.03		25.16	39.2
	<1970	P1A	Ad	13-15	1.36	1.56	6.7	13.93	0.1
	<1970	M3	AB	23-35	1.24	2.11		16.42	0.1
	1970-76	M28	Ap2	9/12-22	1.40	1.52	6.6		2.1
	1976-85	M9	A2	8/11-28	1.32	1.48		14.90	5.6
	1985-91	M15	Bt1	10/12-38	0.93	2.07		21.06	18.6
	1991-96	P3A	A2	17-28	1.27	1.92	7.0	16.54	2.5
	1991-96	P3B	Bt	9-50	1.38	0.88	6.8	11.54	0.1
	1991-96	M2	AB	13/15-48	1.72	2.07		14.26	21.0
	Mean of total area				1.31	1.77	6.9	16.02	9.7
	Mean of cultivated area				1.33	1.70	6.8	15.52	6.3
Argentina	Forest	P7B	A2	21-39	1.15	1.04	8.1	14.26	49.4
	Forest	M6	A2	10-16	1.05	1.24		23.65	6.0
	<1970	P6B	A2	10-28	1.36	1.04	7.4	14.69	13.5
	<1970	M1	Ad	4-30/35	1.43	1.04		12.64	4.9
	1970-76	M8	A2	12-37	1.28	1.00		14.36	0.1
	1976-85	M5	Ad	12-23		1.16		26.89	1.4
	1985-91	M7	AB	18-32	1.32	1.16		18.04	3.5
	1991-96	P9B	Ad	11-29	1.04	1.48	6.4	12.96	12.3
	1991-96	M16	A2	12-32	1.52	1.56		15.23	2.1
	Mean of total area				1.27	1.19	7.3	16.97	10.4
	Mean of cultivated area				1.33	1.21	6.9	16.40	5.4
Garmendia	Forest	P5A	2A	13-31	1.05	1.52	7.7	16.42	29.4
	Forest	M11	A2	3/7-22	1.12	0.96		14.15	20.0
	<1970	P4A	2A1	8/12-30	1.20	0.78	8.2	16.80	4.2
	<1970	M10	A2	5/8-18	1.21	1.64		16.20	50.4
	1970-76	M27	A3	20-30	1.55	0.80	7.0		17.2
	1976-85	M12	Bw1	15/19-25/28	1.18	1.24		15.55	9.5
	1985-91	M13	A2	16-23/26	1.28	1.16		15.01	7.7
	1991-96	P8B	Bw1	11-28	1.08	1.52	6.6	16.96	17.4
	1991-96	M14	A2	14-25	1.09	1.32		14.26	9.1
	1991-96	M29	A2	10/13-30	1.13	1.56	6.9		45.5
	Mean of total area				1.19	1.25	7.3	15.67	21.0
	Mean of cultivated area				1.22	1.25	7.2	15.80	20.1
Ramada	Forest	P17	A2	19-32	1.13	1.68	7.4	16.46	4.6
	<1970	M17	Ad	10-26	1.37	1.44	5.9		1.8
	1970-76	M18	Ap2	11-31	1.27	1.52	6.5		3.5
	1976-85	M20	A2	18-37	1.16	2.47	7.5		7.0
	1985-91	M19	2Ap2	17-36	1.17	2.87	7.6		2.8
	Mean of total area				1.22	2.00	7.0		3.9
	Mean of cultivated area				1.24	2.08	6.9		3.8
Virginia	Forest	P10	A2	6-21	1.15	1.66	5.4	10.92	4.6
	<1970	P12	Ap2	8-20	1.22	1.92	6.3	12.38	6.0
	1970-76	M23	Ap2	11-21	1.13	1.84	6.5		15.4
	1976-85	M21	Ad	13-18	1.22	1.84	6.9		3.2
	1985-91	M22	A2	12/15-33	1.14	0.52	8.0		1.4
	1991-96	P11	A2	12-32/36	1.15	1.40	6.9	12.69	2.5
	Mean of total area				1.17	1.53	6.7	12.00	5.5
	Mean of cultivated area				1.17	1.50	6.9	12.54	5.7
Piedrabuena	Forest	P13	A2	8-28	0.99	1.88	6.1	13.42	38.5
	<1970	P15	Ad	9-20/30	1.33	1.12	6.4	10.09	5.6
	<1970	P16	Ap2	14-30/40	1.41	0.80	6.6	11.02	6.0
	1970-76	M24	A2	8-23	1.22	2.19	7.3		59.5
	1976-85	M25	Bw	8/12-25	1.23	1.56	7.1		53.2
	1985-91	M26	A2	15-23	1.04	1.20	6.9		29.8
	1991-96	P14	Ap2	7-20	1.21	1.40	6.2	13.31	17.5
	Mean of total area				1.20	1.45	6.7	11.96	30.0
	Mean of cultivated area				1.24	1.38	6.8	11.47	28.6

Landuse: arable land according to deforestation periods; Depth (cm); BD: bulk density (Mg m^{-3}); OC: organic carbon (%); pH (water 1:1); Ca^+: exchangeable calcium (cmol kg^{-1}); P sol.: soluble phosphorus (mg kg^{-1}).

Table 10.4. Spatial distribution of degradation indicators in the upper topsoil (means).

Study area	BD	OC	pH	Ca^+	P sol.
Burruyacú	1.08	3.15	7.0	18.5	23.1
Argentina	1.22	2.28	6.9	17.5	22.3
Garmendia	1.13	1.94	7.1	15.9	40.0
Ramada	1.04	3.14	6.7	25.6	9.0
Virginia	1.01	2.51	6.4	14.8	6.8
Piedrabuena	1.05	2.27	6.6	12.4	56.0
Mean	1.09	2.55	6.8	17.5	26.2
Standard deviation	0.08	0.50	0.3	4.5	18.8
Confidence interval 0.05	0.06	0.40	0.2	3.6	15.1
Maximum	1.22	3.15	7.1	25.6	56.0
Minimum	1.01	1.94	6.4	12.4	6.8
Number of samples	46	47	31	34	47

BD: bulk density (Mg m^{-3}); OC: organic carbon (%); pH (water 1:1);
Ca^+: exchangeable calcium (cmol kg^{-1}); P sol.: soluble phosphorus (mg kg^{-1}).

Table 10.5. Spatial distribution of degradation indicators in the lower topsoil (means).

Study area	BD	OC	pH	Ca^+	P sol.
Burruyacú	1.31	1.77	6.9	16.0	9.7
Argentina	1.27	1.19	7.3	17.0	10.4
Garmendia	1.19	1.25	7.3	15.7	21.0
Ramada	1.22	2.00	7.0	16.5	3.9
Virginia	1.17	1.53	6.7	12.0	5.5
Piedrabuena	1.20	1.45	6.7	12.0	30.0
Mean	1.23	1.53	7.0	14.9	13.4
Standard deviation	0.05	0.31	0.3	2.3	10.1
Confidence interval 0.05	0.04	0.25	0.2	1.8	8.1
Maximum	1.31	2.00	7.3	17.0	30.0
Minimum	1.17	1.19	6.7	12.0	3.9
Number of samples	46	47	31	34	47

BD: bulk density (Mg m^{-3}); OC: organic carbon (%); pH (water 1:1);
Ca^+: exchangeable calcium (cmol kg^{-1}); P sol.: soluble phosphorus (mg kg^{-1}).

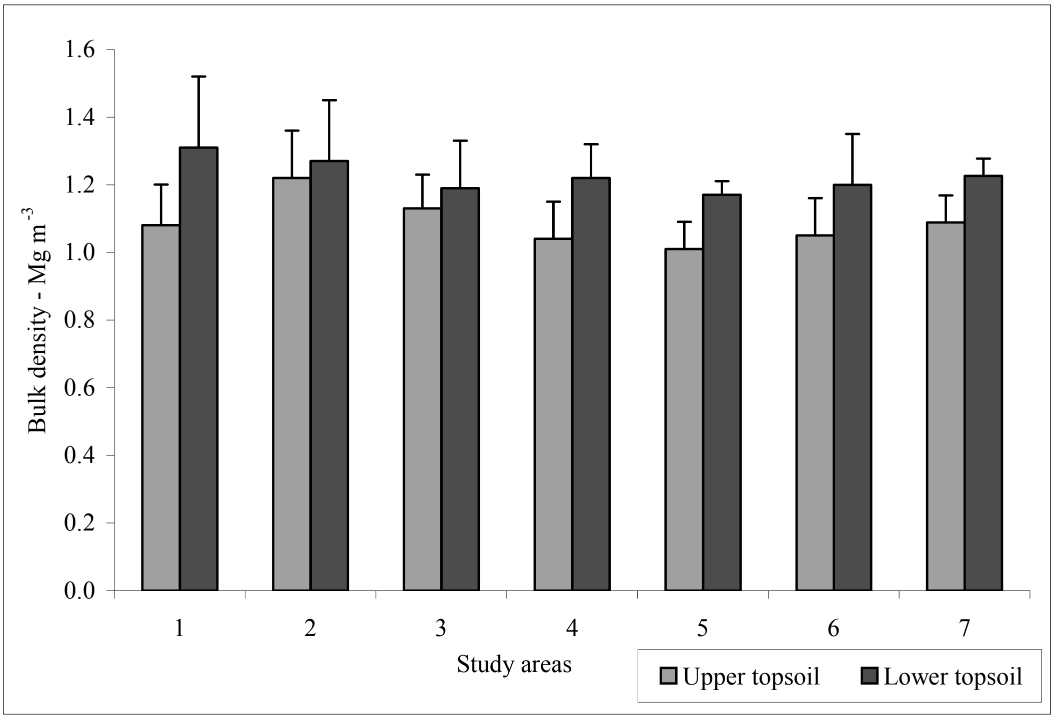


Figure 10.3. Spatial distribution of bulk density values in the upper and lower topsoils (mean values per study area and regional mean):
1: Burruyacú; 2: Argentina; 3: Garmendia; 4: Ramada;
5: Virginia; 6: Piedrabuena; 7: Regional mean;
Bars represent standard deviations of the means.

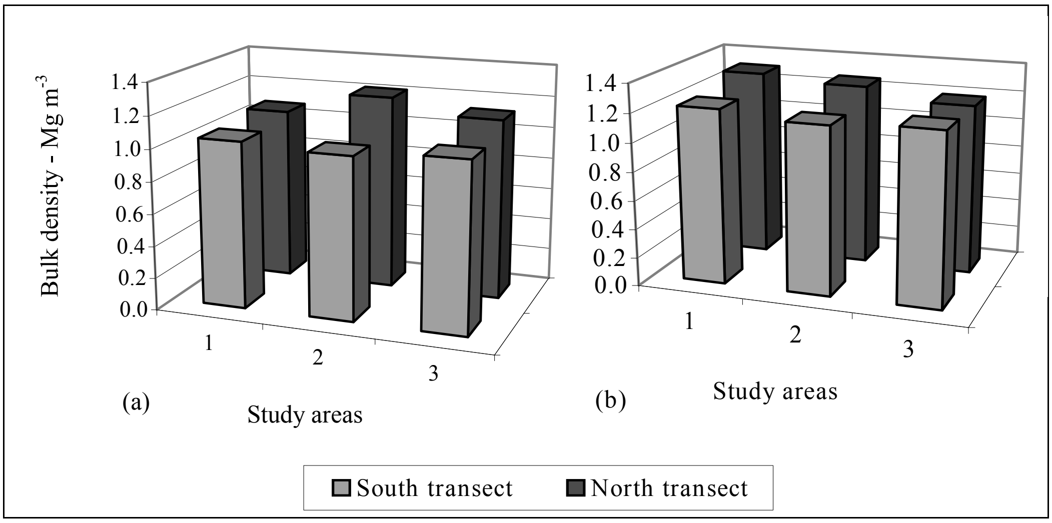


Figure 10.4. Spatial distribution of bulk density values (study area means)
(a) upper topsoil; (b) lower topsoil
South transect: 1: Ramada; 2: Virginia; 3: Piedrabuena;
North transect: 1: Burruyacú; 2: Argentina; 3: Garmendia.

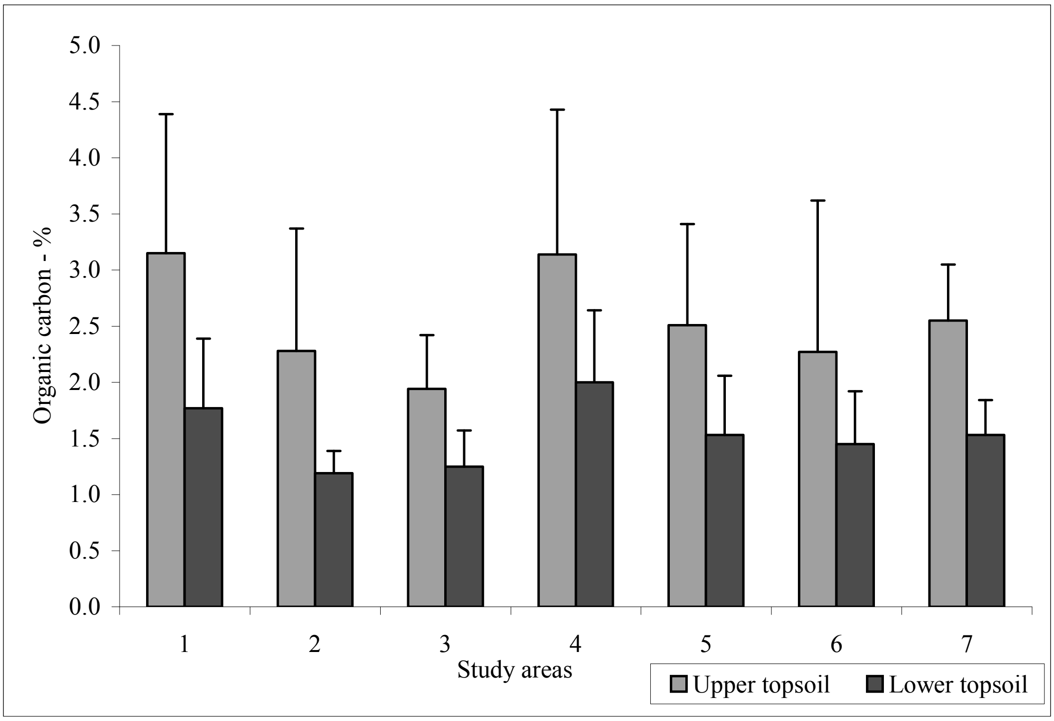


Figure 10.5. Spatial distribution of organic carbon content in the upper and lower topsoils (mean values per study area and regional mean):
1: Burruyacú; 2: Argentina; 3: Garmendia; 4: Ramada;
5: Virginia; 6: Piedrabuena; 7: Regional mean;
Bars represent standard deviations of the means.

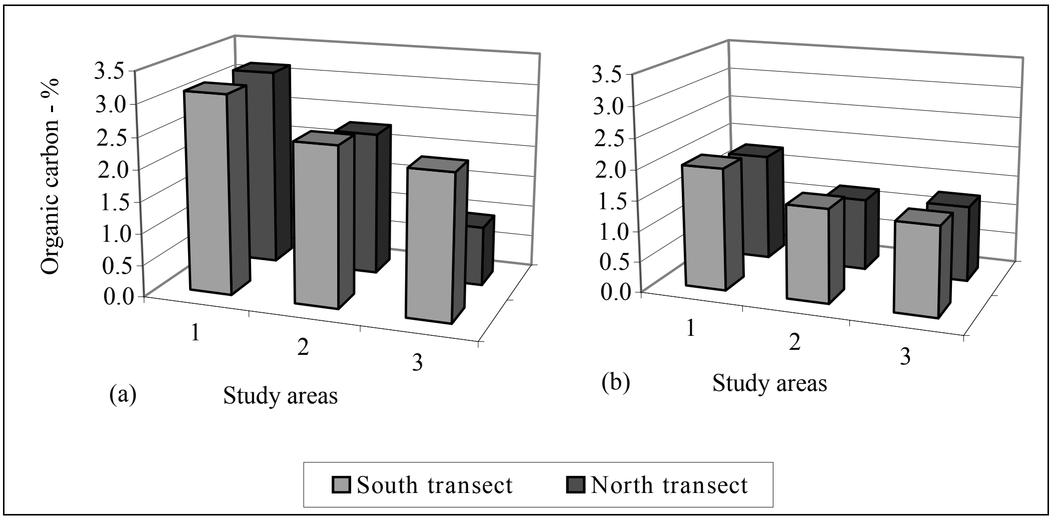


Figure 10.6. Spatial distribution of organic carbon content (study area means)
(a) upper topsoil; (b) lower topsoil
South transect: 1: Ramada; 2: Virginia; 3: Piedrabuena;
North transect: 1: Burruyacú; 2: Argentina; 3: Garmendia.

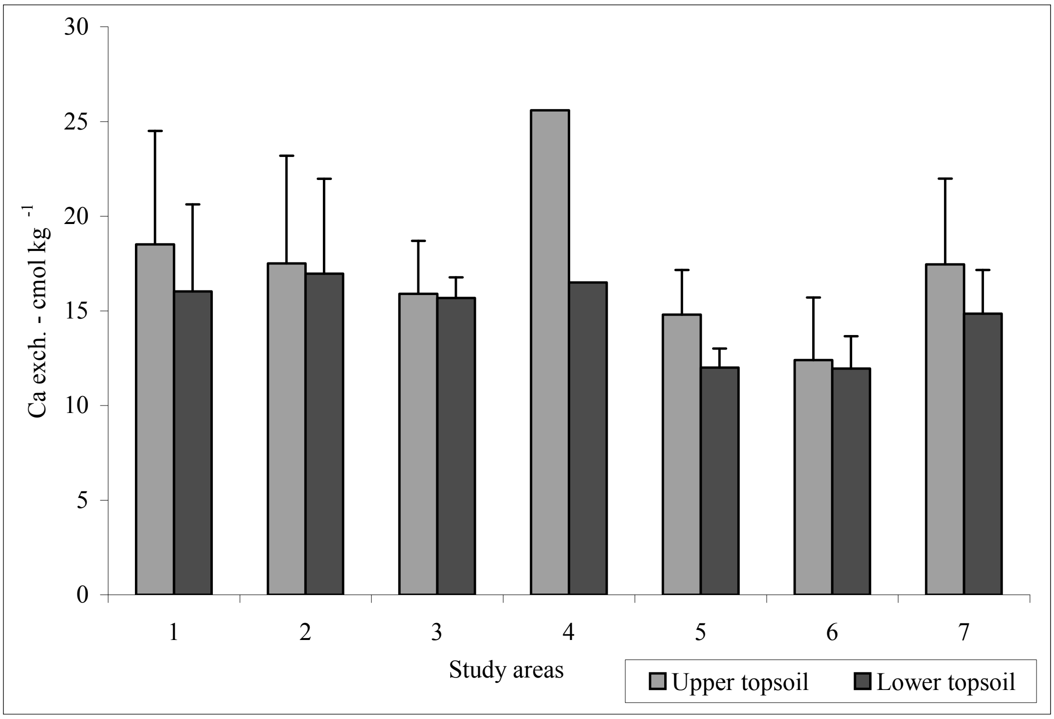


Figure 10.7. Spatial distribution of exchangeable calcium in the upper and lower topsoils (mean values per study area and regional mean):
1: Burruyacú; 2: Argentina; 3: Garmendia; 4: Ramada;
5: Virginia; 6: Piedrabuena; 7: Regional mean;
Bars represent standard deviations of the means.

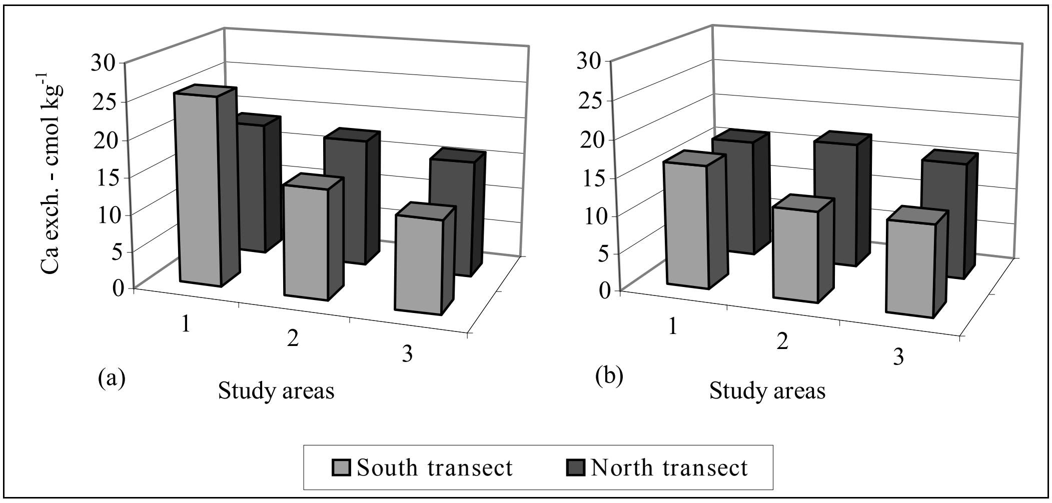


Figure 10.8. Spatial distribution of exchangeable calcium (study area means)
(a) upper topsoil; (b) lower topsoil
South transect: 1: Ramada; 2: Virginia; 3: Piedrabuena;
North transect: 1: Burruyacú; 2: Argentina; 3: Garmendia.

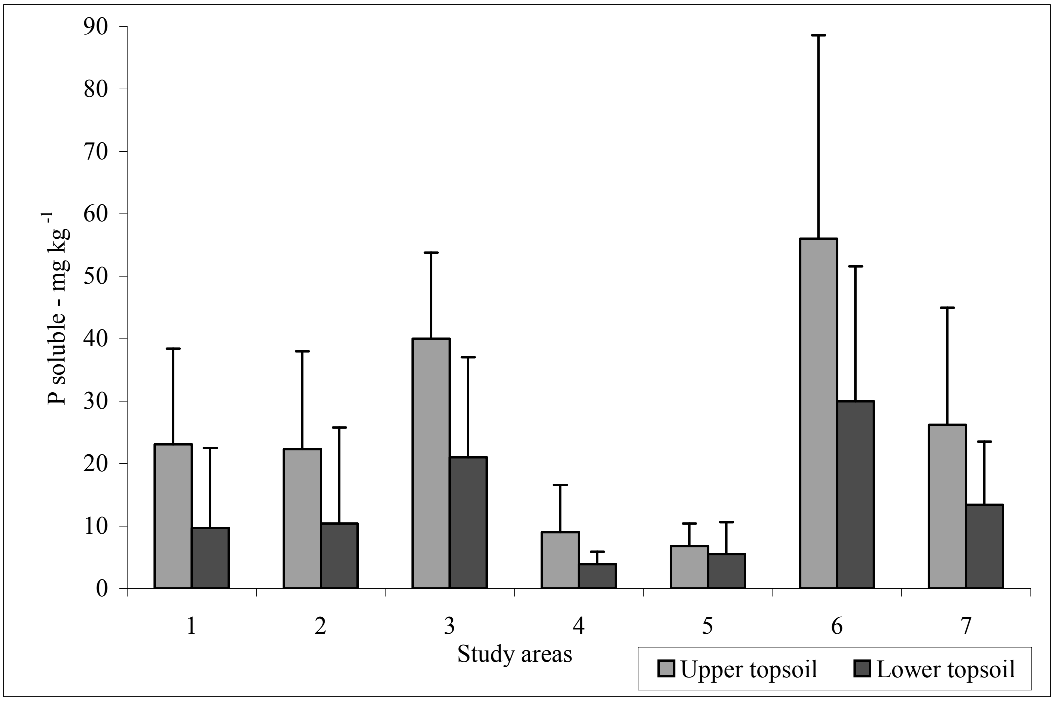


Figure 10.9. Spatial distribution of soluble phosphorus in the upper and lower topsoils (mean values per study area and regional mean):
1: Burruyacú; 2: Argentina; 3: Garmendia; 4: Ramada;
5: Virginia; 6: Piedrabuena; 7: Regional mean;
Bars represent standard deviations of the means.

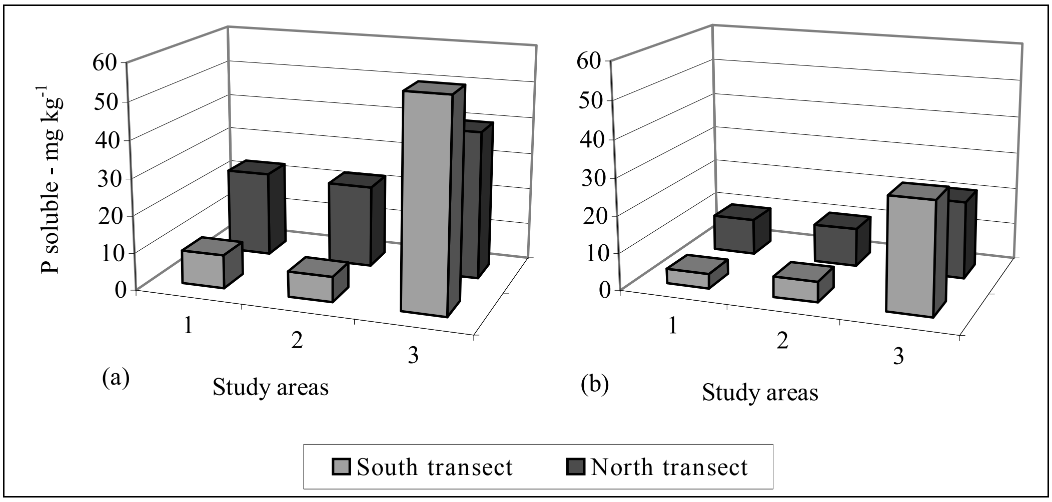


Figure 10.10. Spatial distribution of soluble phosphorus (study area means)
(a) upper topsoil; (b) lower topsoil
South transect: 1: Ramada; 2: Virginia; 3: Piedrabuena;
North transect: 1: Burruyacú; 2: Argentina; 3: Garmendia.

10.4.2. Temporal variations

The same four above-mentioned parameters, including bulk density (BD), organic carbon (OC), exchangeable calcium (Ca^+) and soluble phosphorus (Ps), were used to detect temporal changes in the topsoil throughout the research region. Data belonging to the six study areas were lumped and averaged according to reclamation dates, reflecting thus different time spans over which land has been under use, regardless of spatial distribution.

(1) Bulk density

In general, there is a slight increase in bulk density in both topsoil horizons from the younger to the older fields. Upon reclamation, it seems that the physical conditions of the upper topsoil might be even improved, probably because annual tillage removes the earlier trampling effect of cattle browsing under Chaco forest. In all land reclamation ranges considered, BD is higher in the lower topsoil than in the upper one, reflecting compaction beneath the arable layer through plow-pan formation (Tables 10.6 and 10.7; Figure 10.11). Surprisingly, the strongest gap between upper and lower topsoil layers concerns the most recent period of deforestation (1991-96), with considerable variations in BD values (1.04-1.72 Mg m^{-3}) that reflect differences in land management among farms. In contrast, under forest, there are no differences in BD throughout the topsoil.

Table 10.6. Temporal changes in bulk density (Mg m^{-3}) in the upper topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	1.11	1.03	1.08	1.11	1.17	1.12
Change in BD agric/forest (%)		-7	-3	0	5	1
Standard deviation	0.18	0.09	0.15	0.07	0.15	0.08
Confidence interval 0.05	0.12	0.05	0.12	0.06	0.12	0.05
Maximum	1.41	1.17	1.31	1.19	1.37	1.29
Minimum	0.89	0.94	0.91	1.02	0.92	1.03
Number of samples	9	10	6	5	6	10

Table 10.7. Temporal changes in bulk density (Mg m^{-3}) in the lower topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	1.13	1.26	1.15	1.22	1.31	1.31
Change in BD agric/forest (%)		12	2	8	16	16
Standard deviation	0.12	0.22	0.15	0.06	0.15	0.09
Confidence interval 0.05	0.08	0.14	0.12	0.05	0.12	0.05
Maximum	1.42	1.72	1.32	1.32	1.55	1.43
Minimum	0.99	1.04	0.93	1.16	1.13	1.20
Number of samples	9	10	6	5	6	10

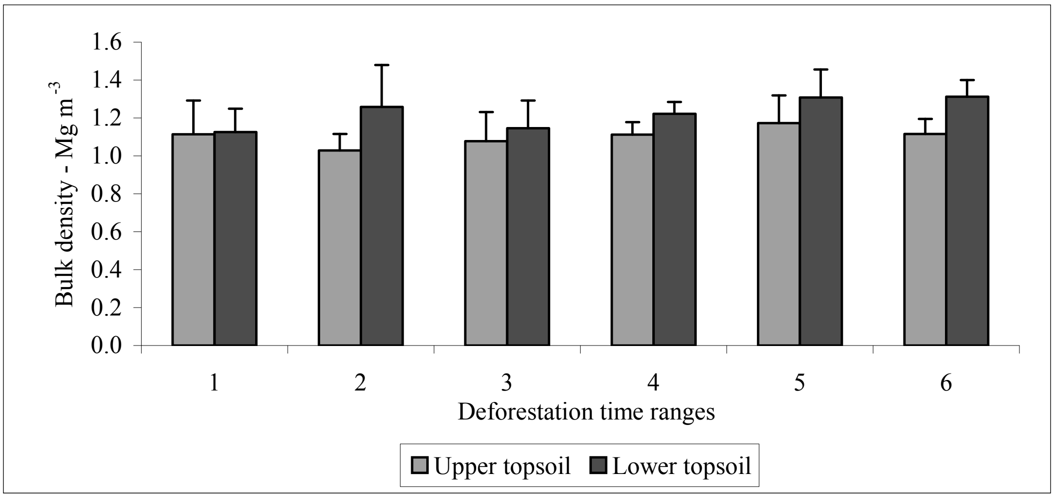


Figure 10.11. Bulk density mean values in the upper and lower topsoils under forest and in cultivated fields of increasing time of deforestation:
1: forest; 2: 1991-96; 3: 1985-91; 4: 1976-85; 5: 1970-76; 6: <1970;
Bars represent standard deviations of the means.

(2) Organic carbon

Overall, there is more organic carbon in the upper topsoil than in the lower, although the difference between both horizons becomes tiny in the oldest fields. Taking the most recent reclamation period (1991-96) as a reference, OC in the upper topsoil drops soon after deforestation to less than two thirds of the original content under forest (Tables 10.8 and 10.9; Figure 10.12). After this accelerated initial depletion, OC decreases slowly over time to about 60% of the original content in the oldest fields (from 2.54% to 1.77% over the period <1970-1996). Thus, the OC status at regional level is not yet limiting for agriculture, in spite of continuous depletion. The lower topsoil layer does not show significant variations in OC content over time (1.41-1.77%).

Table 10.8. Temporal changes in organic carbon (%) in the upper topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	4.01	2.54	2.22	2.38	1.98	1.77
Change in OC agric/forest (%)		-37	-45	-41	-51	-59
Standard deviation	1.38	0.55	1.08	0.55	0.46	0.56
Confidence interval 0.05	0.90	0.34	0.86	0.95	0.37	0.35
Maximum	5.67	3.43	4.07	3.19	2.79	2.91
Minimum	1.60	1.60	1.12	1.80	1.56	0.96
Number of samples	9	10	6	6	6	10

Table 10.9. Temporal changes in organic carbon (%) in the lower topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	1.56	1.54	1.56	1.63	1.77	1.41
Change in OC agric/forest (%)		-1	0	4	13	-10
Standard deviation	0.64	0.36	0.92	0.48	0.32	0.44
Confidence interval 0.05	0.42	0.22	0.74	0.38	0.26	0.28
Maximum	3.03	2.07	2.87	2.47	2.19	2.11
Minimum	0.96	0.88	0.52	1.16	0.80	0.78
Number of samples	9	10	6	6	6	10

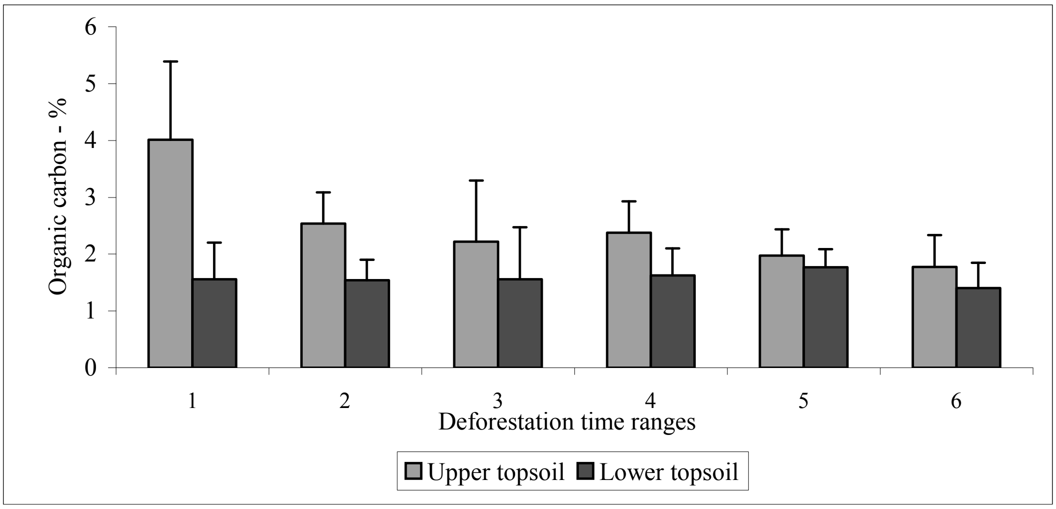


Figure 10.12. Organic carbon mean contents in the upper and lower topsoils under forest and in cultivated fields of increasing time of deforestation:
1: forest; 2: 1991-96; 3: 1985-91; 4: 1976-85; 5: 1970-76; 6: <1970;
Bars represent standard deviations of the means.

(3) Exchangeable calcium

The exchangeable calcium data set lacks consistency, as the time series is incomplete for three of the five time ranges (Tables 10.10 and 10.11). In spite of that, some general conclusions can be drawn from Figure 10.13. Overall, Ca^+ is slightly higher in the upper topsoil than in the lower one. However, the reverse occurs in the two oldest time ranges, reflecting stronger depletion of Ca^+ in the arable layer. Although the time series continuity is interrupted by the higher values shown by the two intermediate time ranges (1976-85 and 1985-91), the long-term tendency is one of decreasing Ca^+ in both topsoil horizons, with some kind of stabilization in the old fields at around one third of the original Ca^+ content under forest conditions.

Table 10.10. Temporal changes in exchangeable calcium (cmol kg^{-1}) in the upper topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	19.93	16.17	19.30	19.76	13.07	12.78
Change in Ca^+ agric/forest (%)		-19	-3	-1	-34	-36
Standard deviation	6.05	2.54	4.76	7.29		2.51
Confidence interval 0.05	3.96	1.66	5.38	8.25		1.64
Maximum	27.22	19.55	24.19	28.18		15.44
Minimum	11.56	12.06	14.69	15.55		7.90
Number of samples	9	9	3	3	1	9

Table 10.11. Temporal changes in exchangeable calcium (cmol kg^{-1}) in the lower topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	16.09	14.19	18.04	19.11	14.36	13.80
Change in Ca^+ agric/forest (%)		-12	12	19	-11	-14
Standard deviation	5.16	1.80	3.03	6.74		2.43
Confidence interval 0.05	3.37	1.17	3.42	7.63		1.59
Maximum	25.16	16.96	21.06	26.89		16.80
Minimum	10.40	11.54	15.01	14.90		10.09
Number of samples	9	9	3	3	1	9

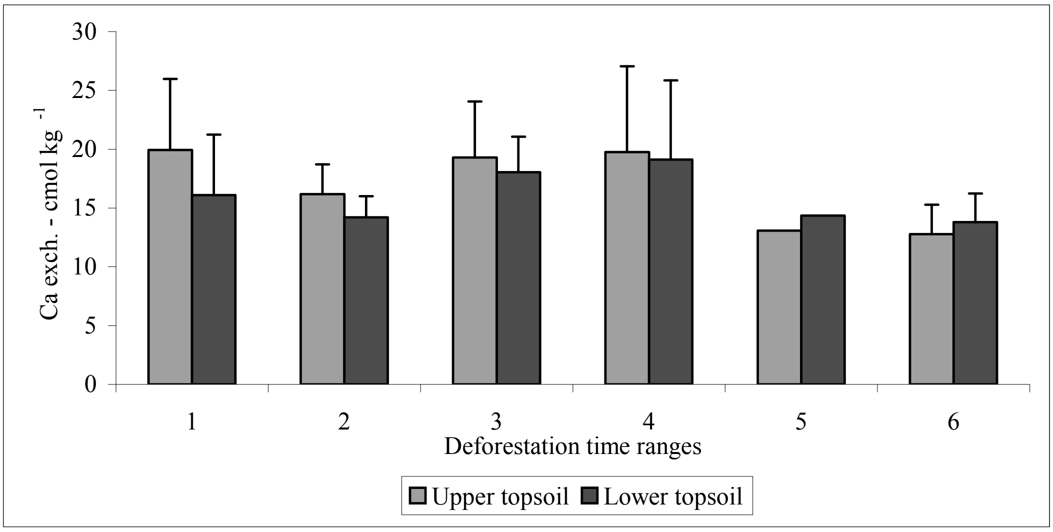


Figure 10.13. Exchangeable calcium mean values in the upper and lower topsoils under forest and in cultivated fields of increasing time of deforestation:
1: forest; 2: 1991-96; 3: 1985-91; 4: 1976-85; 5: 1970-76; 6: <1970;
Bars represent standard deviations of the means.

(4) Soluble phosphorus

The soluble phosphorus data set lacks consistency because of large data variability within each time range, with standard deviation values frequently outweighing the mean values (Tables 10.12 and 10.13). However, there is clearly an overall trend of decreasing Ps content in the upper topsoil with time. After 10-15 years of agricultural use, the Ps content in cultivated land is 40-60% lower than that in soils under forest. In the lower topsoil, the Ps content is in general half that of the upper topsoil, also under forest (Figure 10.14). The temporal pattern of the Ps content is similar to that shown by organic carbon.

Table 10.12. Temporal changes in soluble phosphorus (mg kg^{-1}) in the upper topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	44.45	30.51	20.95	27.55	22.90	18.41
Change in Ps agric/forest (%)		-31	-53	-38	-48	-59
Standard deviation	31.31	17.37	27.14	22.28	25.15	14.45
Confidence interval 0.05	20.45	10.76	21.72	17.83	20.12	8.96
Maximum	108.5	70.0	73.5	66.5	65.1	44.1
Minimum	7.4	9.8	2.1	3.2	4.6	2.5
Number of samples	9	10	6	6	6	10

Table 10.13. Temporal changes in soluble phosphorus (mg kg^{-1}) in the lower topsoil.

Deforestation ranges	Forest	1991-96	1985-91	1976-85	1970-76	<1970
Mean	22.12	13.00	10.63	13.32	16.30	9.26
Change in Ps agric/forest (%)		-41	-52	-40	-26	-58
Standard deviation	17.51	13.67	11.29	19.74	22.34	14.96
Confidence interval 0.05	11.44	8.47	9.03	15.80	17.88	9.27
Maximum	49.4	45.5	29.8	53.2	59.5	50.4
Minimum	4.6	0.1	1.4	1.4	0.1	0.1
Number of samples	9	10	6	6	6	10

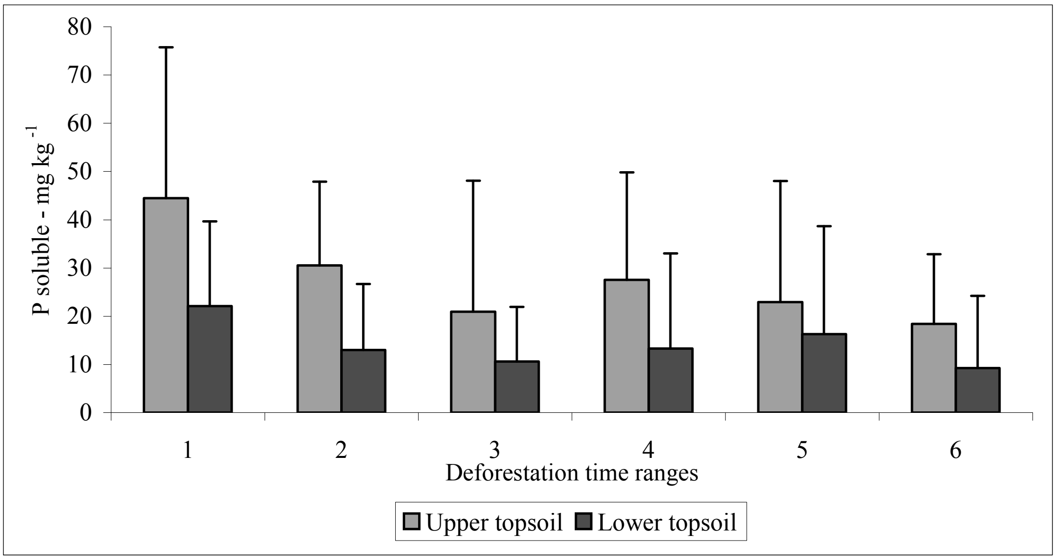


Figure 10.14. Soluble phosphorus mean values in the upper and lower topsoils under forest and in cultivated fields of increasing time of deforestation:
1: forest; 2: 1991-96; 3: 1985-91; 4: 1976-85; 5: 1970-76; 6: <1970;
Bars represent standard deviations of the means.

10.4.3. Temporal analysis of soil compaction

From field observations, soil compaction was identified as the main land degradation feature in the region. In general, subsurface horizons show morphological evidence of plow-pan formation, including heavy soil material, platy to laminar structure, low porosity, obstructed root penetration patterns, and sometimes mottles. To quantify this morphological evidence and identify temporal changes in soil compaction at regional level, bulk density values determined at the 46 basic study sites were used. Soil compaction was assessed by contrasting affected horizons with not affected ones within profiles and between profiles. For this purpose, the topsoil was divided into two layers: (1) the upper topsoil corresponding to the arable layer, cultivated and mixed every year by plowing or disking; and (2) the lower topsoil corresponding to the layer with morphological evidence of compaction, lying beneath the arable layer and receiving the compression effect of the tillage instruments; this is in general the second horizon, but in some cases it might be the third horizon. The upper limit of the lower topsoil is usually not deeper than 25-30 cm from the soil surface and the horizon showing compaction lies usually between 10 and 30 cm depth.

Instead of comparing absolute BD values, ratios were used to highlight changes in relative terms (relative increases or decreases). In agricultural fields, the percent change was determined from the difference in BD between the lower and upper topsoils, normalized by the BD of the upper topsoil at each study site. A second ratio was derived from the percent difference in BD in the lower topsoil in each agricultural field and the BD in the lower topsoil at the forest reference site in each study area.

(1) Within-profile comparison

To assess the magnitude of soil compaction within individual profiles, the percent increase in bulk density from upper to lower topsoil was calculated by means of the ratio: (BD lower topsoil - BD upper topsoil / BD upper topsoil) x 100. It was assumed that this ratio would increase from younger to older agricultural fields, reflecting increasing soil compaction in the lower topsoil with time and, thus, general worsening of the physical soil conditions. From the ratio calculation, the following conclusions can be drawn (Table 10.14; Figures 10.15 and 10.16).

- In each of the time ranges considered, data show large dispersion. More observation sites should be included to improve data distribution.

- In general, BD increases from upper to lower topsoil in agricultural fields. At the majority of the sites, increases are less than 30%, with an average median of 14% when considering all reclaimed sites together (forest sites excluded).
- Data variation is highest for the fields most recently reclaimed (1991-96), with ratio values ranging from 0% to 35% and with an outlier at 83%. This might reflect increasing diversity in management practices and also increasing use of heavy machinery.
- At a few sites, BD decreased from upper to lower topsoil, with compaction taking place in the surface horizon.
- In forest soils, there are as many sites with BD increase as sites with BD decrease from upper to lower topsoil. In the pathways where trampling takes place because of cattle browsing, the surface horizon is compacted, while the subsurface one is not, resulting in BD decrease. The opposite occurs in the proximity of tree stems and in areas with dense bushes, where roaming cattle less penetrate for browsing. In these conditions, the surface horizon is not compacted by trampling and is also more porous because biological activity concentrates therein.
- Data dispersion did not allow satisfactory regression analysis. A regression curve, with limited "indicative" meaning, was fit to the data of four deforestation time ranges, excluding the most recent one (1991-96) and the forest sites. BD ratio values slightly increase with time. The median of the ratios ranges from 5.7% for the sites reclaimed in 1985-91 to 20.2% for the sites reclaimed before 1970, with values of 11.7% and 11.8% for the intermediate periods.
- In conclusion, soil compaction takes place in all time ranges considered, mainly in the lower topsoil, and increases with time in proportions not yet dramatic.

Table 10.14. Comparison of bulk density (Mg m^{-3}) between upper (1) and lower(2) topsoils.

Study area	Landuse	Site	Horiz.1	Depth1	BD1	Horiz.2	Depth2	BD2	Change%
Burruyacú	Forest	P2	A1	0-28	1.22	Bt	28-52	1.42	16.4
	Forest	M4	A1	0-12/18	0.91	Bt	12/18-40	1.07	17.6
	<1970	P1A	Ap	0-13	1.09	Ad	13-15	1.36	24.8
	<1970	M3	Ap	0-23	1.03	AB	23-35	1.24	20.4
	1970-76	M28	Ap1	0-9/12	1.23	Ap2	9/12-22	1.40	13.8
	1976-85	M9	Ap	0-8/11	1.19	A2	8/11-28	1.32	10.9
	1985-91	M15	Ap	0-10/12	1.13	Bt1	10/12-38	0.93	-17.7
	1991-96	P3A	Ap	0-17	0.94	A2	17-28	1.27	35.1
	1991-96	P3B	Ap	0-9	1.15	Bt	9-50	1.38	20.0
	1991-96	M2	Ap	0-13/15	0.94	AB	13/15-48	1.72	83.0
Argentina	Forest	P7B	A1(Ad)	0-21	1.41	A2	21-39	1.15	-18.4
	Forest	M6	A1	0-10	1.22	A2	10-16	1.05	-13.9
	<1970	P6B	Ap	0-10	1.13	A2	10-28	1.36	20.4
	<1970	M1	Ap	0-4	1.19	Ad	4-30/35	1.43	20.2
	1970-76	M8	Ap	0-12	1.37	A2	12-37	1.28	-6.6
	1976-85	M5	Ap	0-12		Ad	12-23		
	1985-91	M7	Ap	0-18	1.31	AB	18-32	1.32	0.8
	1991-96	P9B	Ap	0-11	0.99	Ad	11-29	1.04	5.1
	1991-96	M16	Ap	0-12	1.17	A2	12-32	1.52	29.9
Garmendia	Forest	P5A	A	0-13	1.06	2A	13-31	1.05	-0.9
	Forest	M11	A1	0-3/7	1.27	A2	3/7-22	1.12	-11.8
	<1970	P4A	Ap	0-8/12	1.29	2A1	8/12-30	1.20	-7.0
	<1970	M10	Ap	0-5/8	1.12	A2	5/8-18	1.21	8.0
	1970-76	M27	Ap1	0-9	1.18	A3	20-30	1.55	31.4
	1976-85	M12	Ap	0-9/12	1.02	Bw1	15/19-25/28	1.18	15.7
	1985-91	M13	Ap	0-16	1.17	A2	16-23/26	1.28	9.4
	1991-96	P8B	Ap	0-11	1.07	Bw1	11-28	1.08	0.9
	1991-96	M14	Ap	0-14	1.10	A2	14-25	1.09	-0.9
	1991-96	M29	Ap	0-10/13	1.00	A2	10/13-30	1.13	13.0
Ramada	Forest	P17	A1	0-19	0.96	A2	19-32	1.13	17.7
	<1970	M17	Ap	0-10	1.03	Ad	10-26	1.37	33.0
	1970-76	M18	Ap1	0-11	1.16	Ap2	11-31	1.27	9.5
	1976-85	M20	Ap	0-18	1.16	A2	18-37	1.16	0.0
	1985-91	M19	Ap1	0-17	0.91	2Ap2	17-36	1.17	28.6
Virginia	Forest	P10	A1	0-6	1.09	A2	6-21	1.15	5.5
	<1970	P12	Ap1	0-8	1.04	Ap2	9-20	1.22	17.3
	1970-76	M23	Ap1	0-11	0.92	Ap2	11-21	1.13	22.8
	1976-85	M21	Ap	0-18	1.09	Ad	13-18	1.22	11.9
	1985-91	M22	Ap	0-12/15	0.93	A2	12/15-33	1.14	22.6
	1991-96	P11	Ap	0-12	0.99	A2	12-32/36	1.15	16.2
Piedrabuen	Forest	P13	A1	0-8	0.89	A2	8-28	0.99	11.2
	<1970	P15	Ap	1-9	1.13	Ad	9-20/30	1.33	17.7
	<1970	P16	Ap1	0-14	1.11	Ap2	14-30/40	1.41	27.0
	1970-76	M24	Ap	0-8	1.18	A2	8-23	1.22	3.4
	1976-85	M25	Ap	0-8/12	1.10	Bw	8/12-25	1.23	11.8
	1985-91	M26	Ap	0-15	1.02	A2	15-23	1.04	2.0
	1991-96	P14	Ap1	0-7	0.94	Ap2	7-20	1.21	28.7

Landuse: arable land according to deforestation periods.

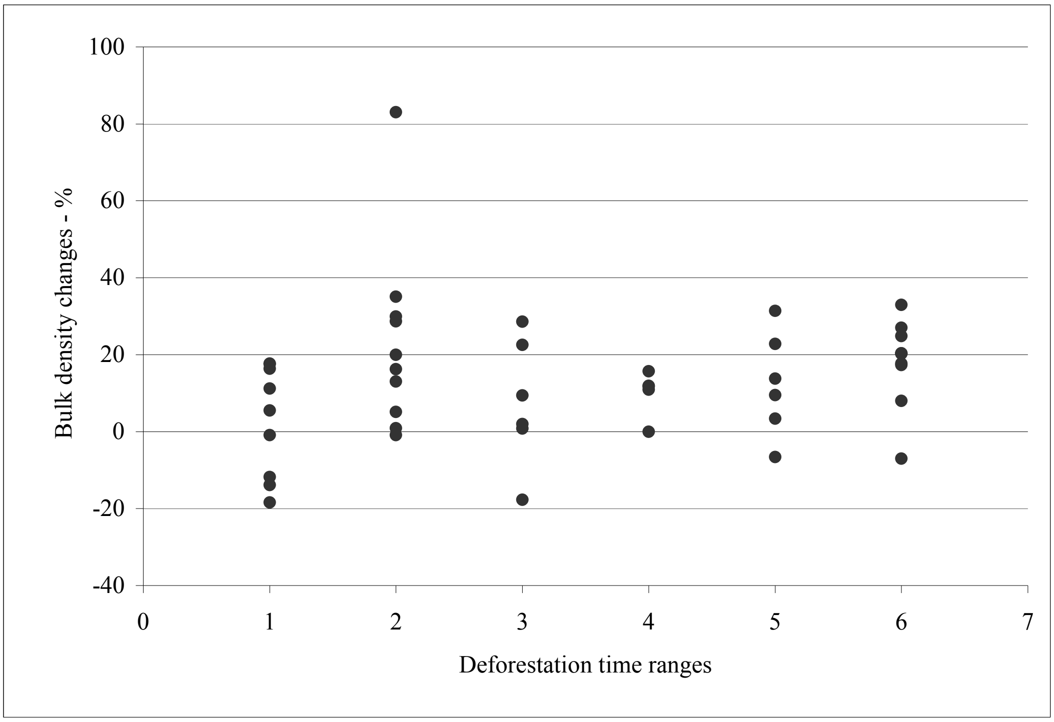


Figure 10.15. Bulk density changes (in %) between the upper and lower topsoils under forest and in cultivated fields of increasing time of deforestation:
1: forest; 2: 1991-96; 3: 1985-91; 4: 1976-85; 5: 1970-76; 6: <1970.

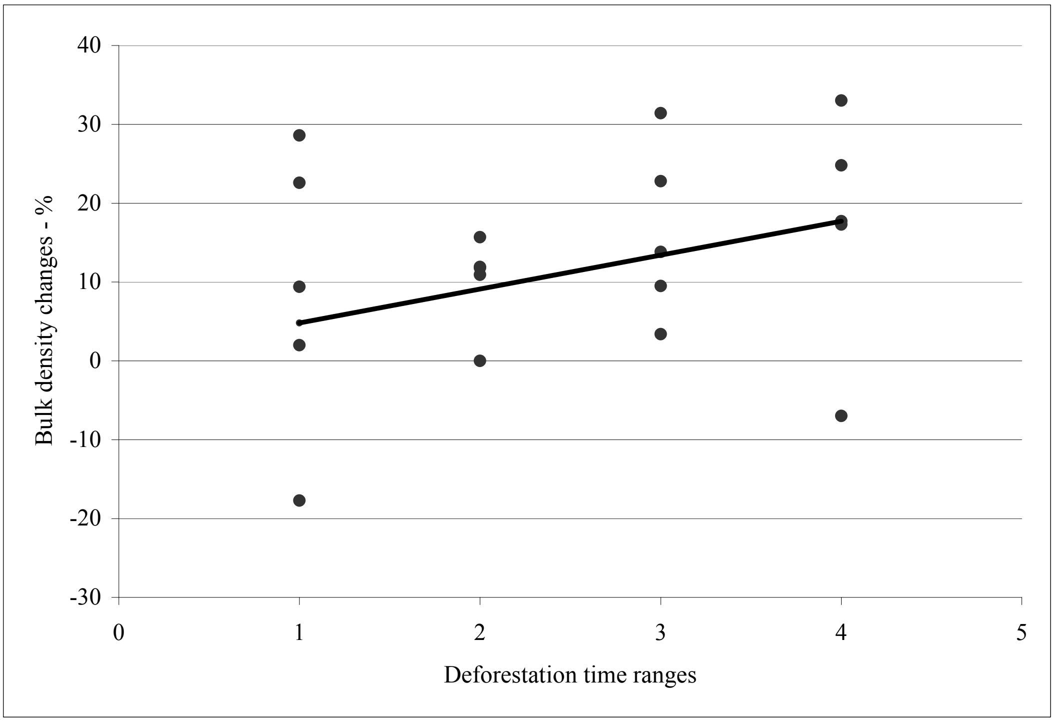


Figure 10.16. Regression of bulk density changes (in %) between upper and lower topsoils against increasing time of deforestation:
1: 1985-91; 2: 1976-85; 3: 1970-76; 4: <1970.

(2) Between-profile comparison

The Chaco forest is frequently used by roaming cattle for browsing. Cattle move through the forest along pathways where compaction takes place at the soil surface and in the upper topsoil (0-5/10 cm). In general, the subsurface horizon is not affected. In agricultural areas, on the contrary, the arable topsoil is regularly plowed and thus loosened, while the subsurface horizon is usually compacted by the passage of the tillage instruments. To assess the magnitude of soil compaction in agricultural soils in relation to their condition before reclamation, the BD values of the subsurface horizon (lower topsoil) were compared between cultivated soils and the corresponding forest reference soil in each study area by means of a simple ratio such as: (BD agricultural field – BD forest / BD forest) x 100. From the ratio calculation, the following conclusions can be drawn (Table 10.15; Figures 10.17 and 10.18).

- After conversion from forest condition to agricultural land use, BD increases except at two sites with negative values.
- There is a large dispersion of the ratios, ranging from 3% to 61% increase.
- Maximum ratio dispersion occurs for the deforestation time range 1991-96 (from -1% to 61%), which reflects increasing diversity in land management practices and differences in tillage mechanization in recent times.
- Overall, BD ratios increment with reclamation age. From the youngest to the oldest fields, the ratio medians increase from 10% in 1985-91, to 15% in 1976-1985, to 23% in 1970-76, to 28% in <1970. Thus, in the oldest agricultural fields, BD is on average almost one third higher than in forest soils.
- In spite of the large data variation, a regression analysis was performed on a selected data set, excluding the period 1991-96, too variable, and incomplete temporal data series. Thus, the regression line is based on five complete data series spanning from <1970 to 1991. Differences in BD between forest and agricultural land augment from recent to old reclamation fields, when compared to the original soil conditions under forest.

10.4.4. Conclusion

In all study areas and for all reclamation time ranges considered, BD values are on average 13% higher in the lower topsoil than in the upper one, reflecting compaction beneath the arable layer through plow-pan formation. Soil compaction decreases from earlier deforested west to later deforested east in the study region. With increasing reclamation time, BD ratios between upper and lower topsoil horizons increase, with ratio medians ranging from about 6% for the period 1985-91 to 20% for the period <1970. When comparing lower topsoil horizons between forest and farming sites, BD is on average one third higher in the oldest agricultural fields than in the corresponding forest reference soils.

In contrast to bulk density, the contents of organic carbon, exchangeable calcium and soluble phosphorus are higher in the upper topsoil than in the lower one. OC decreases from west to east, reflecting decreasing annual rainfall, while calcium and phosphorus do not show conspicuous spatial trends. Soon after deforestation, OC in the upper topsoil drops to less than two thirds of the original content under forest and then decreases slowly over time to about 60% in the oldest agricultural fields.

Table 10.15. Comparison of bulk density (Mg m^{-3}) in the lower topsoil between a reference forest site and cultivated fields of increasing reclamation time spans in each study area.

Study area	Landuse	Site	Horizon	Depth	BD	Change %
Burruyacú	Forest	M4	Bt	12/18-40	1.07	
	<1970	P1A	Ad	13-15	1.36	27.1
	<1970	M3	AB	23-35	1.24	15.9
	1970-76	M28	Ap2	9/12-22	1.40	30.8
	1976-85	M9	A2	9/11-28	1.32	23.4
	1985-91	M15	Bt1	10/12-38	0.93	-13.1
	1991-96	P3A	A2	17-28	1.27	18.7
	1991-96	P3B	Bt	9-50	1.38	29.0
	1991-96	M2	AB	13/15-48	1.72	60.7
Argentina	Forest	M6	A2	10-16	1.05	
	<1970	P6B	A2	10-28	1.36	29.5
	<1970	M1	Ad	4-30/35	1.43	36.2
	1970-76	M8	A2	12-37	1.28	21.9
	1976-85	M5	Ad	12-23		
	1985-91	M7	AB	18-32	1.32	25.7
	1991-96	P9B	Ad	11-29	1.04	-1.0
	1991-96	M16	A2	12-32	1.52	44.8
Garmendia	Forest	P5A	2A	13-31	1.05	
	<1970	P4A	2A1	8/12-30	1.20	14.3
	<1970	M10	A2	5/8-18	1.21	15.2
	1970-76	M27	A3	20-30	1.55	47.6
	1976-85	M12	Bw1	15/19-25	1.18	12.4
	1985-91	M13	A2	16-23/26	1.28	21.9
	1991-96	P8B	Bw1	11-28	1.08	2.9
	1991-96	M14	A2	14-25	1.09	3.8
	1991-96	M29	A2	10/13-30	1.13	7.6
Ramada	Forest	P17	A2	19-32	1.04	
	<1970	M17	Ad	10-26	1.37	31.7
	1970-76	M18	Ap2	11-31	1.27	22.1
	1976-85	M20	A2	18-37	1.16	11.5
	1985-91	M19	2Ap2	17-36	1.17	12.5
Virginia	Forest	P10	A3	21-38	1.06	
	<1970	P12	Ad	20-35/40	1.24	17.0
	1970-76	M23	Ap2	11-21	1.13	6.6
	1976-85	M21	Ap2	13-18	1.22	15.1
	1985-91	M22	A2	12/15-33	1.14	7.5
	1991-96	P11	A2	12-32/36	1.15	8.5
Piedrabuena	Forest	P13	A2	8-28	0.99	
	<1970	P15	Ad	9-20/30	1.33	34.3
	<1970	P16	Ap2	14-30/40	1.41	42.4
	1970-76	M24	A2	8-23	1.22	23.2
	1976-85	M25	Bw	8/12-25	1.23	24.2
	1985-91	M26	A2	15-23	1.04	5.1
	1991-96	P14	Ap2	7-20	1.21	22.2

Landuse: arable land according to deforestation periods.

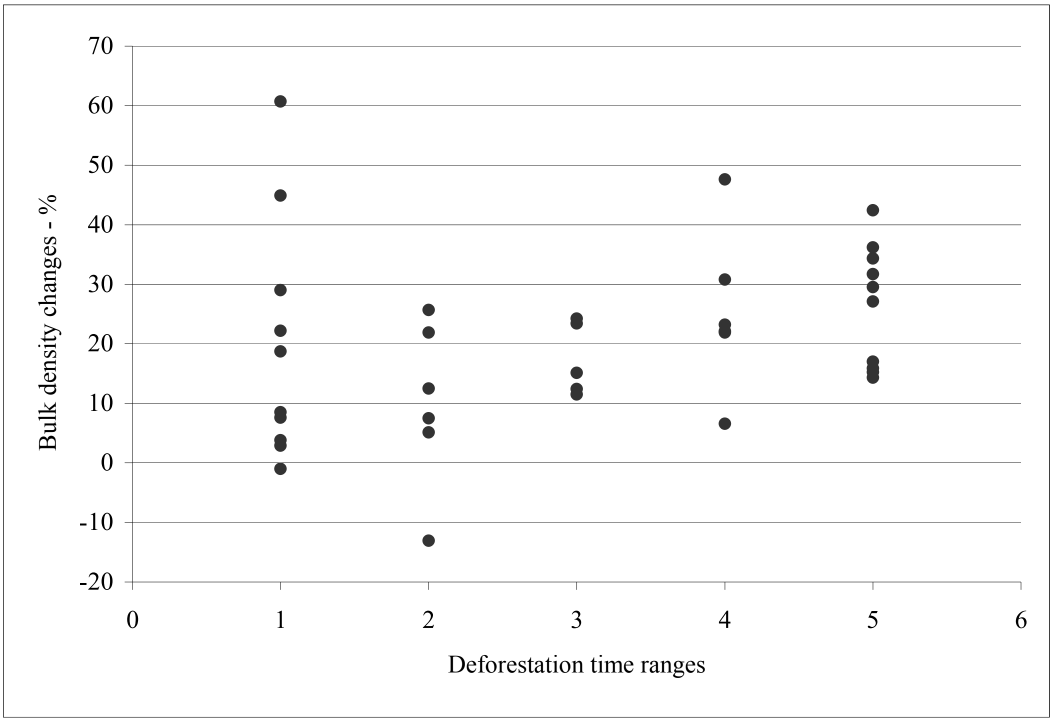


Figure 10.17. Bulk density changes (in %) in the lower topsoil between forest sites and cultivated fields of increasing time of deforestation:
1: 1991-96; 2: 1985-91; 3: 1976-85; 4: 1970-76; 5: <1970.

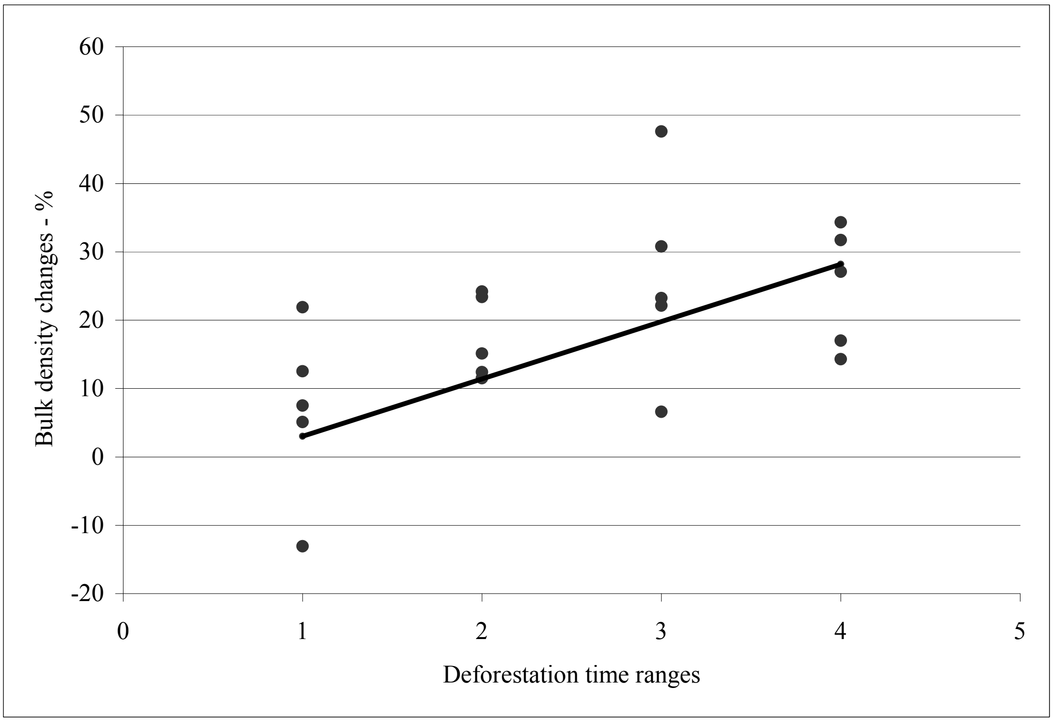


Figure 10.18. Regression of bulk density changes (in %) in the lower topsoil between forest sites and cultivated fields against increasing time of deforestation:
1: 1985-91; 2: 1976-85; 3: 1970-76; 4: <1970.

10.5. RESULTS AT LOCAL SCALE (STUDY AREAS)

In each of the six study areas selected along the northern transect (Burruyacú-Argentina-Garmendia) and the southern transect (Ramada-Virginia-Piedrabuena), study plots were identified according to five land deforestation ranges, as shown in Figure 10.1, Figure 10.2 and Table 10.1, to assess land degradation at local scale. In each study plot, detailed field investigation was conducted, including the description of land use types and management practices under cropping and forest conditions, the description of relevant soil surface features, and the description of soil profiles in pits (2m deep) and minipits (1m deep), with replicates at selected sites. In addition to the former, penetration resistance was measured in the three study areas of the northern transect (Flores, 1997). Since penetration resistance strongly depends upon soil moisture, field determinations were carried out over a three-week period with similar moisture conditions. Bulk density (BD) and penetration resistance (PR) data were used to assess soil compaction, while organic carbon (OC) data were used to assess fertility depletion.

To secure data comparability between land reclamation periods, study plots should be preferably located within the same farm, applying given soil management practices. This was not always possible, as not all farms covered the whole range of deforestation periods. Also, management practices have changed over time, with increasing farming mechanization in recent times.

10.5.1. Burruyacú

The area of Burruyacú occupies the northwest corner of the study region. Deforestation started already in the early 1960s, promoted by easy access along road 304 that connects S.M. de Tucumán with Santiago del Estero. Wheat and maize are still the dominant crops in this area and some farmers continue using traditional farming practices and horsepower for traction. Soybean cultivation started after 1990, somewhat later than in the other areas of the region. Observation sites are concentrated in Lobo farm, with some additional sites in Soria and Ro farms, which apply different management systems.

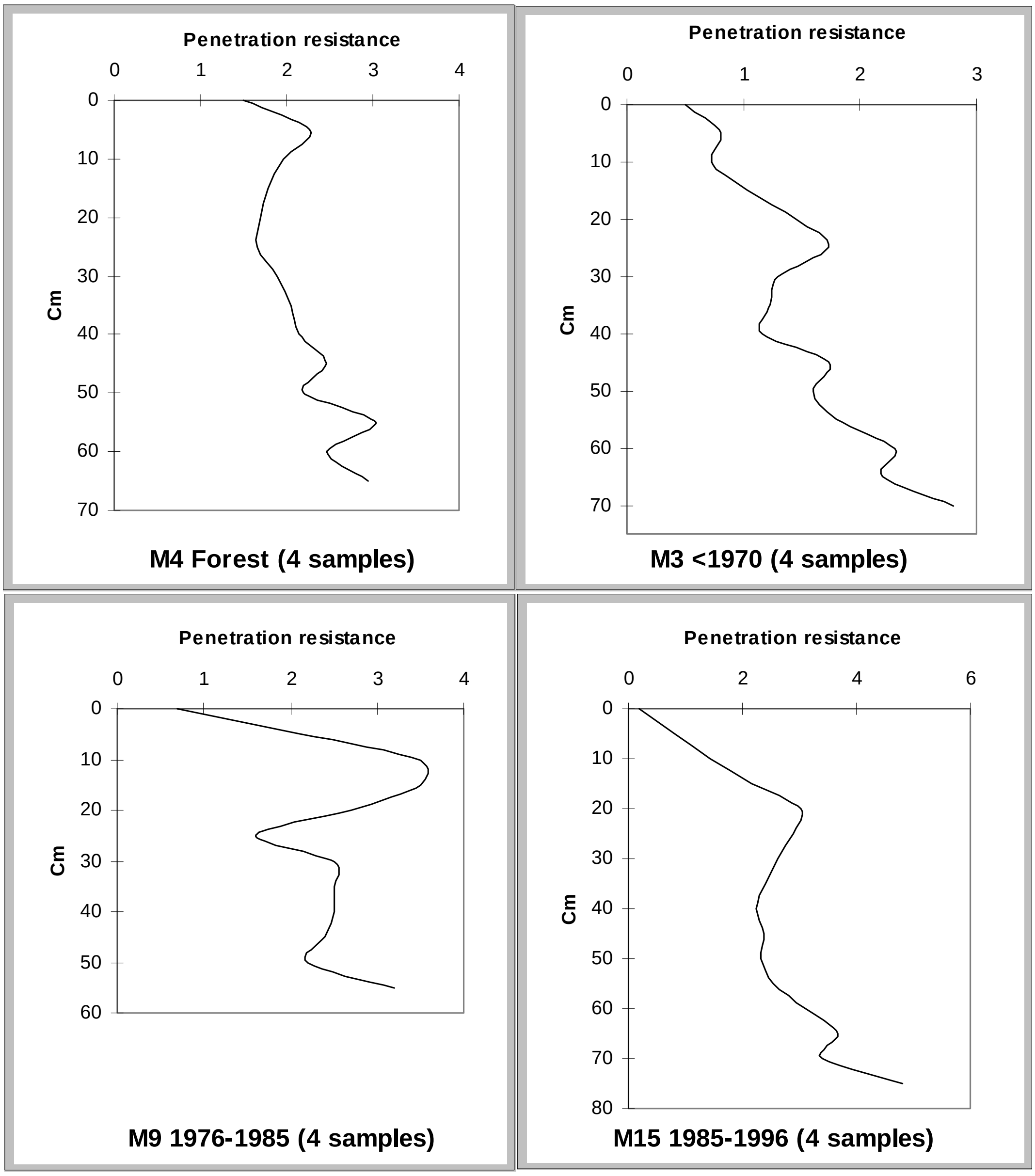
In general, bulk density values of the topsoil are lowest in forest conditions, but high BD values were found under forest along compacted cow paths, such as at observation site P2 (Table 10.16). At Lobo's place, cropping was done all the time without heavy machinery, mainly for family consumption and local market supply, until 1996 when the owner started leasing the field for commercial maize production. The sites located at Soria's place and Ro's place were cropped for commercial purposes. The use of machinery for plowing and sowing affects soil properties in a way different from the traditional plowing, as practiced at the Lobo farm. The cropping system has influenced bulk density and organic carbon. The Lobo sites have lower bulk density and higher organic carbon values than the other sites. Deforestation time has also influenced soil properties. The older the reclamation date, the higher the bulk density and the lower the organic carbon content.

The penetration resistance data are shown in Figure 10.19 and in Table 10.27 (in Appendix). The forest site shows the highest PR values in the topsoil due to the density of the rooting system. In the topsoil of the crop sites, penetration resistance was mainly related to the land management practices. At the Ro farm, wheat was sowed just days before the observations were done. Thus, the topsoil offered less resistance to penetration. But penetration resistance increased with depth because of a plow-pan and, further down, because of a Bt horizon. Surprisingly, the oldest reclamation site (M3) shows the lowest values of penetration resistance in the topsoil. The crop site grid surveyed at the same location shows higher penetration resistance than the M3 site (see section 10.6 in this chapter).

To assess fertility depletion, organic carbon and soluble phosphorus contents in the topsoil were compared between forest, one-year cropping and 40-year cropping sites, all on Fluventic Argiustolls developed from loess material. OC decreased from 4.2% under forest to 3.4% after one year cropping, representing 80% of the original content, to 2.5% after 40 years cropping, representing 60% of the original content. Likewise, soluble phosphorus decreased from 30 to 15 to 5 mg kg^{-1} during the same time sequence, with the two latter values representing 50% and 17% of the original content, respectively.

Table 10.16. Main characteristics of the observation sites in Burruyacú.

Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P2	Burruyacú	-	Forest	0-28	1.22	4.87
	Lobo			28-52	1.42	1.02
				52-74	1.42	0.66
				74-91	1.46	0.43
				91-97	1.27	0.64
				97-117	1.49	0.50
				117-140	1.28	0.31
M4	Burruyacú	-	Forest	0-12/18	0.71	5.67
	Lobo			12/18-40	1.07	3.03
				40-50	1.40	0.78
				50-60	1.43	0.72
P1A	Burruyacú	<1970	Maize	0-13	1.09	2.07
	Lobo			13-13/23	1.36	1.56
				13/23-35	1.35	1.08
				35-53	1.26	0.50
				53-90	1.09	0.23
				90-140	1.17	0.32
M3	Burruyacú	<1970	Maize	0-23	1.03	2.91
	Lobo			23-35	1.24	2.11
				35-60	1.38	0.84
M28	Burruyacú	1970-76	Wheat	0-9/12	1.23	1.60
				9/12-22	1.40	1.52
				22-33	1.26	0.92
				33-55		0.42
				55-70		0.36
M9	Burruyacú	1976-85	Blackbean	0-8/11	1.19	2.71
	Soria			8/11-28	1.32	1.48
				28-45	1.27	1.00
				45-52	1.30	0.78
				52-60		0.62
M15	Burruyacú	1985-91	Wheat	0-10/12	1.13	2.88
	Ro			10/12-38	0.93	2.07
				38-50	1.03	1.37
				50-60		1.17
P3B	Burruyacú	1991-96	Maize	0-9	1.15	2.39
	Lobo			9-50	1.38	0.88
				50-75	1.43	0.58
				75-95	1.44	0.35
				95-118	1.23	0.31
M2	Burruyacú	1991-96	Maize	0-13/15	0.94	2.99
	Lobo			13/15-48	1.72	2.07
				48-73	1.36	0.72



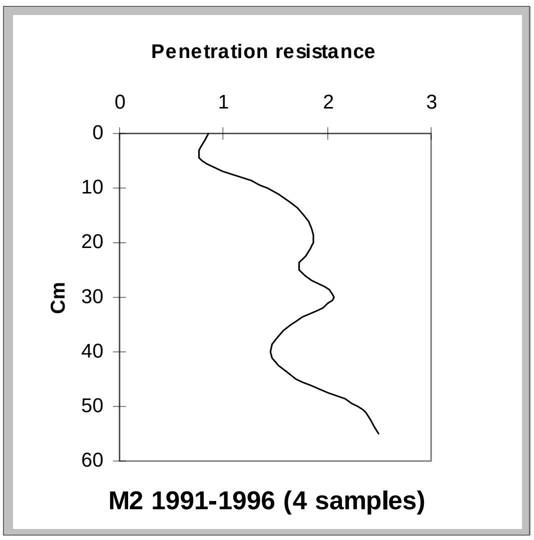


Figure 10.19.
Variation of penetration resistance (N cm^{-2}) with depth in Burruyacú (mean values of several replicates at each site per 5-cm-deep intervals from data in Table 10.27 in Appendix).
From Flores, 1997.

10.5.2. La Argentina

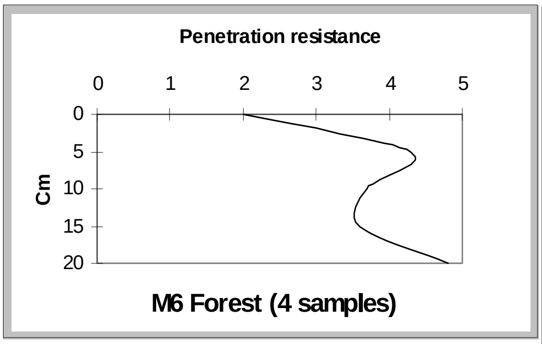
The area of La Argentina lies along road 336 on the northern transect, between Burruyacú to the west and Gobernador Garmendia to the east. Deforestation started in the early 1970s and expanded rapidly so that the area was almost totally reclaimed by 1985. In the 1970s, cattle grazing was the most important activity. In the 1980s, the livestock decreased and, finally by 1995, the remaining cows were removed from the area to the south of the country. Cattle grazing and traffic have caused heavy soil compaction in La Argentina farm. Nowadays, the commercial activity is agriculture, mainly soybean, maize and wheat. In contrast to the Burruyacú area, the sites selected in La Argentina are all but one located on the same farm and have thus similar soil management history.

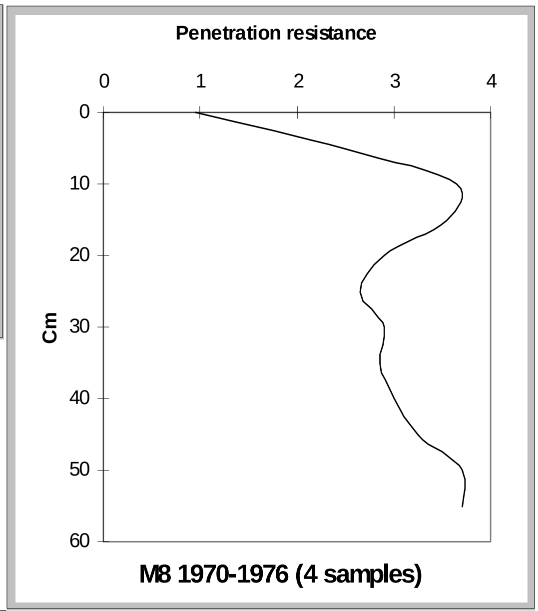
Bulk density values and organic carbon contents of the topsoil reveal severe land degradation (Table 10.17). Some plots cultivated with soybean have higher BD values in the second horizon, with plow-pan formation in the lower topsoil (e.g. sites M1 and M16). Other sites, cultivated with wheat or maize, show BD values equally high in the upper and lower topsoils, a situation which might still reflect soil compaction by earlier cattle grazing (e.g. sites M7 and M8). Organic carbon has been substantially depleted at all sites except the most recently reclaimed (site M16), when comparing the crop sites with the forest reference site.

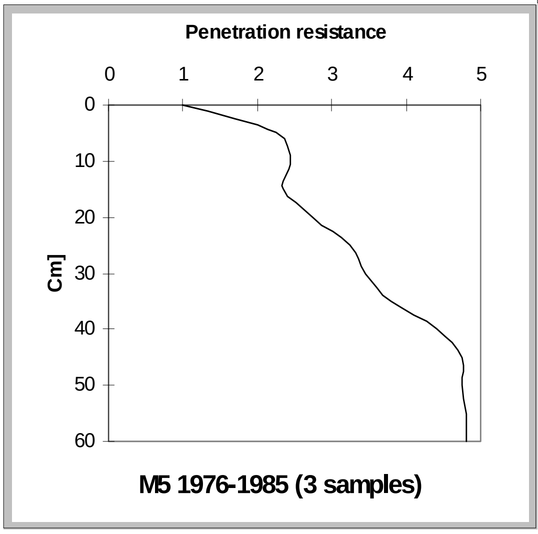
In general, soil penetration resistance is high in the area of La Argentina (Figure 10.20 and Table 10.28 in Appendix). At the forest site, PR values are substantially higher than in agricultural fields at similar depths, reflecting probably the lasting effect of intensive, long-term cattle browsing on this farm. While site M8 reveals the presence of a plow-pan at 10-20 cm depth, sites M5, M7 and M8 show the presence of Bt horizons from 40-50 cm downwards. At site M16, PR is low in the upper topsoil because the field was sown just before making the determinations. In the Heguy farm, PR data strongly reflect the history of land use and management over the past decades. The absence of plow-pan formation except at the earliest reclaimed site indicates recent conversion from cattle raising to agriculture.

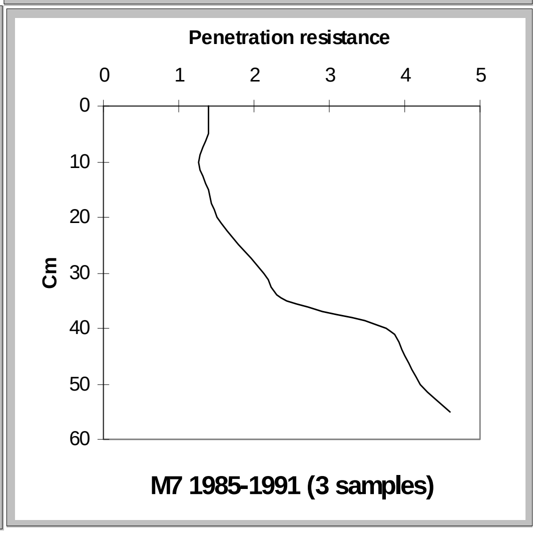
Table 10.17. Main characteristics of the observation sites in La Argentina.

Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P7B	La Argentina Heguy	-	Forest	0-21	1.41	2.55
				21-39	1.15	1.04
				39-68	1.21	0.52
				68-90	1.45	0.35
				90-118	1.43	0.20
M6	La Argentina Heguy	-	Forest	0-10	1.22	4.63
				10-16	1.05	1.24
				16-40	1.07	1.21
				59-65	1.00	0.94
				59-60		0.66
P6B	La Argentina Heguy	<1970	Maize	0-10	1.13	1.57
				10-28	1.36	1.04
				28-51	1.23	0.42
				51-70	1.23	0.22
				70-106	1.27	0.23
M1	La Argentina Heguy	<1970	Soybean	0-4	1.19	1.40
				4-30/35	1.43	1.04
				30/35-49	1.23	0.50
				49-60	1.31	0.32
M8	La Argentina Heguy	1970-76	Wheat	0-12	1.37	1.56
				12-37	1.28	1.00
				37-49	1.11	0.64
				49-60		0.56
M5	La Argentina Giordano	1976-85	Soybean	0-12		1.96
				12-23		1.16
				23-36/40		0.82
				36/40-60		1.21
M7	La Argentina Heguy	1985-91	Maize	0-18	1.31	1.12
				18-32	1.32	1.16
				32-50	1.21	0.80
				50-60		0.54
P9	La Argentina Garmendia	1991-96	Vegetables	0-11	0.99	3.03
				11-29	1.04	1.48
				29-50	1.09	0.88
				50-72	1.18	0.66
				72-110	1.29	0.32
				110-135	1.29	0.04
				135-150	1.33	0.10
M16	La Argentina Heguy	1991-96	Cárcamo	0-12	1.17	2.71
				12-32	1.52	1.56
				32-42	1.28	0.70
				42-59	1.25	0.58
				59-65		0.42









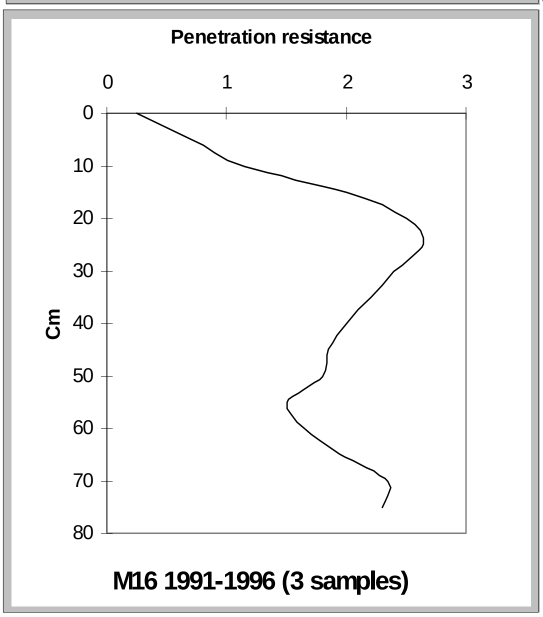


Figure 10.20.
Variation of penetration resistance (N cm^{-2}) with depth in La Argentina (mean values of several replicates at each site per 5-cm-deep intervals from data in Table 10.28 in Appendix). From Flores, 1997.

10.5.3. Gobernador Garmendia

The area of Gobernador Garmendia occupies the northeast corner of the study region. Here, deforestation started in the late 1980s, thus later than in the rest of the region. In contrast to the other study areas, traditional wheat and maize cropping was never important here and, from the beginning on, land was reclaimed in large fields for mechanized soybean production.

As it was impossible to locate all the observation sites in one single place, three farms were selected: the Salim, Deschamps and Rodriguez farms (Table 10.18). Bulk density values at the Gobernador Garmendia sites vary less with depth than in the other areas, as clay illuviation and Bt horizon formation decrease towards the drier east of the study region. Under forest, BD is often high in the surface horizon, reflecting the trampling effect of browsing cattle on the upper topsoil. In contrast, at crop sites, higher BD values occur mainly in the lower topsoil, resulting from plow-pan formation (e.g. sites M10, M12 and M13), while the upper topsoil is loosened through plowing. The most recently reclaimed plots (1991-1996) are clearly less affected by surface soil compaction (sites P8 and M14). There are no significant differences in organic carbon contents between agricultural and forest sites, neither between old and recent reclamation sites.

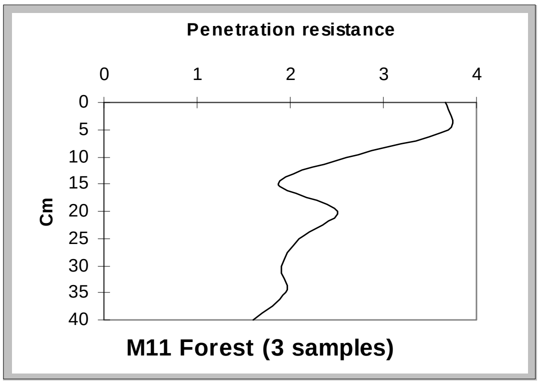
The soils were dry when penetration resistance was determined, generating thus high values (Figure 10.21 and Table 10.29 in Appendix). Even at the forest sites where PR decreased with depth, it was impossible to penetrate deeper than 40-50 cm. The penetrograms clearly show: (1) terrain surface compaction under forest by cattle trampling; (2) the presence of less permeable subsurface horizons from 50-70 cm downwards; and (3) plow-pan formation at crop sites at variable depths (in general, 10-30 cm), even at the most recently reclaimed sites.

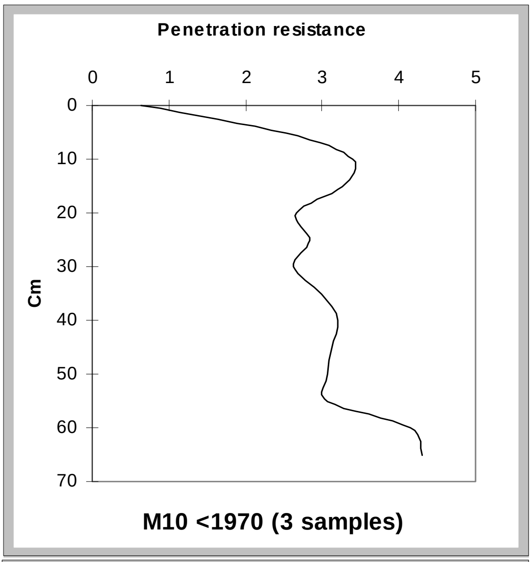
Table 10.18. Main characteristics of the observation sites in Gobernador Garmendia.

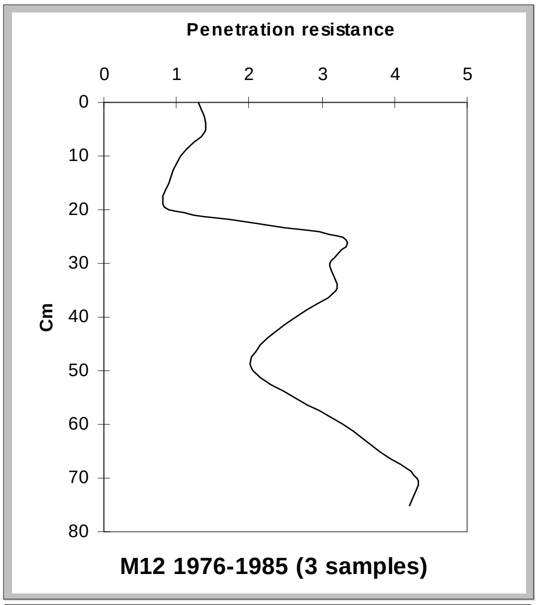
Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P5A	Garmendia	-	Forest	0-13	1.06	2.75
	Salim			13-31	1.05	1.52
				31-64	1.14	0.64
				64-110	1.21	0.37
M11	Garmendia	-	Forest	0-3/7	1.27	1.60
	Salim			3/7-22	1.12	0.96
				22-37	1.04	0.78
				37-64	1.14	0.72
				64-79		0.38
P4A	Garmendia	<1970	Soybean	0-8/12	1.29	0.96
	Salim			8/12-30	1.20	0.72
				30-41	1.14	0.70
				41-67	1.21	0.50
				67-90	1.24	0.29
				90-117	1.26	0.22
M10	Garmendia	<1970	Soybean	0-5/8	1.12	2.00
	Salim			5/8-18	1.21	1.64
				18-32	1.21	1.00
				32-59	1.15	0.52
				59-70		0.38

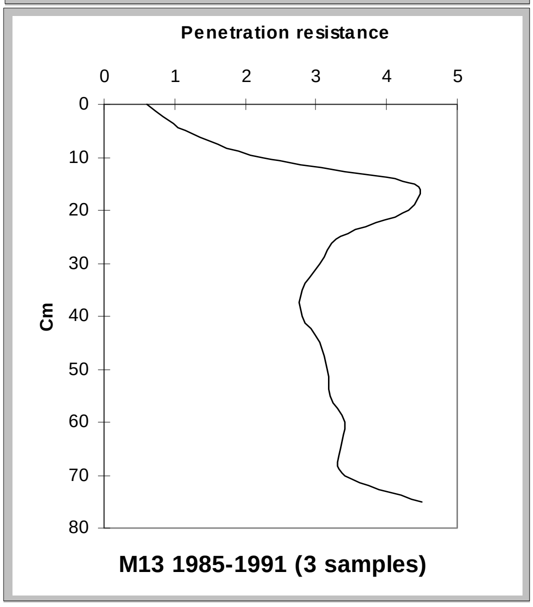
Table 10.18. Main characteristics of the observation sites in Gobernador Garmendia (cont.).

Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
M27	Garmendia	1970-76	Soybean	0-9	1.18	1.76
	Deschamps			9-20	1.24	1.36
				20-30	1.55	0.80
				30-56		0.50
				56-80		0.52
M12	Garmendia	1976-85	Soybean	0-9/12	1.02	1.96
	Deschamps			9/12-19	1.03	1.99
				19-25/28	1.18	1.24
				25/28-42	1.21	0.96
				42-60	1.16	0.64
M13	Garmendia	1985-91	Maize	0-16	1.17	1.88
	Deschamps			16-23/26	1.28	1.16
				23/26-38/40	1.22	1.68
				38/40-51/57	1.18	0.54
				51/57-70		0.28
P8B	Garmendia	1991-96	Soybean	0-11	1.07	2.43
	Salim			11-28	1.08	1.52
				28-40	1.13	0.66
				40-52	1.21	0.46
				52-90	1.34	0.34
				90-107	1.33	0.16
M14	Garmendia	1991-96	Soybean	0-14	1.10	1.92
	Rodríguez			14-25	1.09	1.32
				25-33	1.08	1.00
				33-47	1.12	0.70
				47-60		0.42
M29	Garmendia	1991-96	Soybean	0-10/13	1.00	2.15
	Rodríguez			10/13-30	1.13	1.56
				30-49	1.14	0.74
				49-68		0.32









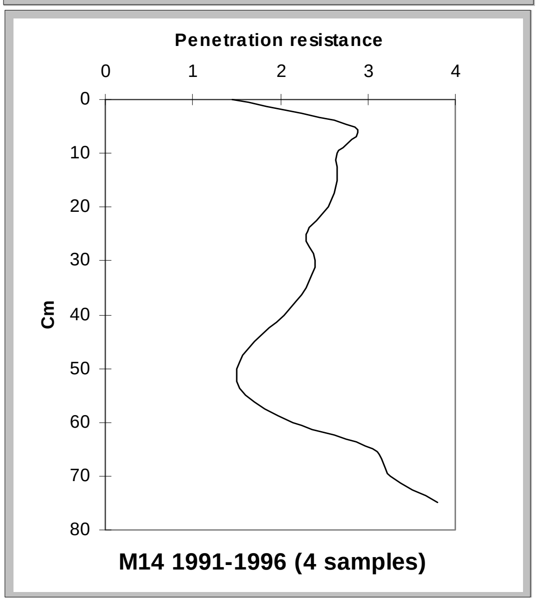


Figure 10.21.
Variation of penetration resistance (N cm^{-2}) with depth in Gobernador Garmendia (mean values of several replicates at each site per 5-cm-deep intervals from data in Table 10.29 in Appendix). From Flores, 1997.

10.5.4. La Ramada

The area of La Ramada occupies the southwest corner of the study region. It is crossed by road 304, the main access way from S.M. de Tucumán along the sub-Andean piedmont towards the north, being thus a penetration axis along which deforestation started and propagated already before 1971. Together with Burruyacú, the area of La Ramada was one of the most active and largest deforestation nuclei in the early 1960s, when maize and soybean cropping initiated in this region of Chaco forest. By the end of the 1990s, soybean was the dominant crop, cultivated in large commercial fields. Observation sites are distributed over two farms with similar soil management practices. Bulk density values of the upper topsoil are clearly higher in cropped fields than under forest, while they also increase in the lower topsoil reflecting the presence of plow-pan layers (Table 10.19). Organic carbon content remains high in the most recently deforested fields (1985-91), close to the values found under forest, but decreases steadily with increasing reclamation time.

Table 10.19. Main characteristics of the observation sites in La Ramada.

Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P17	La Ramada	-	Forest	0-19	0.96	4.71
	Zavaleta			19-32	1.13	1.68
				32-50	1.04	0.98
				50-80		0.66
				80-113		0.60
				113-125		0.29
M17	La Ramada	<1970	Soybean	0-10	1.03	1.72
	Argüello			10-26	1.37	1.44
				37-51/54	1.16	0.50
				51/54-80		0.36
M18	La Ramada	1970-76	Soybean	0-11	1.16	2.00
	Argüello			11-31	1.27	1.52
				31-57	1.18	0.62
				57-80		0.40
M20	La Ramada	1976-85	Maize	0-18	1.16	3.19
	Zavaleta			18-37	1.16	2.47
				37-50	1.09	1.07
				50-75		0.78
				75-85		0.40
M19	La Ramada	1985-91	Soybean	0-17	0.91	4.07
	Zavaleta			17-36	1.17	2.87
				36-53/56	1.22	1.37
				53/56-70		0.94

10.5.5. La Virginia

The area of La Virginia lies along road 317 on the southern transect, between La Ramada to the west and Gobernador Piedrabuena to the east. Early deforestation started in the 1960s, mainly along the road, but considerably expanded in the 1980s. Observation sites are distributed over several farms, with soybean as major crop and with similar soil management practices. There is no significant difference in topsoil bulk density between forest conditions and cultivated areas, neither between reclamation times. However, at all observation sites, bulk density in the lower topsoil is higher than in the upper one, reflecting compaction from plowing in cultivated fields and from trampling by browsing cattle under forest. In contrast, organic carbon dropped in crop fields by as much as about half its values under forest, but without significant differences between reclamation periods (Table 10.20).

Table 10.20. Main characteristics of the observation sites in La Virginia.

Observation Site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P10	La Virginia	-	Forest	1-6	1.09	4.23
				6-21	1.15	1.66
				21-38	1.06	1.00
				38-57	1.12	0.35
				57-88	1.55	0.31
				88-128	1.24	0.17
				128-150		0.07
P12	La Virginia	<1970	Soybean	0-8	1.04	2.15
				8-20	1.22	1.92
				20-35/40	1.24	1.28
				35/40-62	1.15	0.37
				62-99	1.44	0.30
				99-134/140	1.49	0.18
				134/140-155	1.50	0.09
M23	La Virginia Zavaleta	1970-76	Soybean	0-11	0.92	2.15
				11-21	1.13	1.84
				21-34	1.11	1.49
				34-63	1.13	1.13
				63-73		0.28
M21	La Virginia	1976-85	Soybean	0-18	1.09	2.07
				13-18	1.22	
				18-42	1.21	1.84
				42-60	1.13	0.94
M22	La Virginia	1985-91	Soybean	0-12/15	0.93	1.76
				12/15-33	1.14	0.52
				33-60	1.44	0.58
P11	La Virginia	1991-96	Soybean	0-12	0.99	2.71
				12-32/36	1.15	1.40
				32/36-52	1.15	0.44
				52-77	1.33	0.31
				77-100	1.36	0.26
				100-130	1.35	0.16
				130-150	1.35	0.11

10.5.6. Gobernador Piedrabuena

The area of Gobernador Piedrabuena occupies the southeast corner of the study region. Here, deforestation started in the early 1980s, in the same period as for the rest of the eastern fringe of the region, thus about 20 years later than in the west. By the mid 1990s, soybean was not yet the overwhelming crop in this area where a variety of other land uses was still practiced by that time, including pastures. Observation sites are distributed over several farms with different land use histories. However short the period of agricultural use, mechanized cultivation caused a clear differentiation in bulk density between the upper and lower topsoils, with the formation of plow-pan layers at about 10-25 cm depth, together with a temporal trend of increasing bulk density values with increasing reclamation times. Organic carbon is also clearly depleted in cultivated fields, when compared to forest conditions (Table 10.21).

10.5.7. Conclusion

At forest sites, bulk density values increase from west to east, while organic carbon content decreases in the same direction. At crop sites, bulk density values are in general higher in the lower topsoil than in the upper, reflecting the formation of plow-pan layers. Intensive farming for commercial crop production and the use of heavy machinery cause soil compaction.

The original amount of organic carbon, under forest conditions, is related to the rainfall gradient, being thus higher in the moister west than in the drier east. In general, organic carbon contents decrease with increasing reclamation times.

Penetration resistance is highly related to soil moisture and the density of the rooting system. For instance, in Burruyacú, soils were wet when PR was determined, but not so in Gobernador Garmendia. As a consequence, PR values were higher in the drier east than in the wetter west. Thus, comparison of penetration resistance values between the different areas does not make sense. The homogenization of the upper topsoil by plowing makes penetration resistance less variable than in the lower topsoil. Plow-pans were identified at almost all crop sites.

Table 10.21. Main characteristics of the observation sites in Gobernador Piedrabuena.

Observation site	Location Owner	Reclamation period	Land use	Horizon cm	Bulk density Mg m^{-3}	Organic carbon %
P13	Piedrabuena	-	Forest	2-8	0.89	5.11
	Blasco			8-28	0.99	1.88
				28-60	1.09	0.76
				60-80	1.13	0.25
				80-106	1.29	0.22
				106-128	1.31	0.20
				128-153	1.33	0.16
P15	Piedrabuena	<1970	Soybean	1-9	1.13	1.12
	Blasco			9-20/30	1.33	1.12
				20/30-42	1.25	0.32
				42-61	1.30	0.21
				61-85	1.34	0.20
				85-130	1.29	0.14
				130-160	1.34	0.06
P16	Piedrabuena	<1970	Soybean	0-14	1.11	1.84
	Blasco			14-30/40	1.41	0.80
				30/40-50/55	1.51	0.24
				50/55-82		0.23
				82-138		0.17
				138-150		0.09
M24	Piedrabuena	1970-76	Pasture	0-8	1.18	2.79
	Vece			8-23	1.22	2.19
				23-40	0.99	1.28
				40-60		0.46
M25	Piedrabuena	1976-85	Beans	0-8/12	1.10	1.80
	Vece			8/12-25	1.23	1.56
				25-42		0.68
				42-60	1.05	0.56
M26	Piedrabuena	1985-91	Soybean	0-15	1.02	1.60
				15-23	1.04	1.20
				23-47	1.04	0.88
				47-75		0.44
P14	Piedrabuena	1991-96	Soybean	0-7	0.94	1.60
				7-20	1.21	1.40
				20-38	1.09	0.74
				38-57	1.18	0.41
				57-82	1.32	0.25
				82-131	1.37	0.18
				131-152	1.36	0.10

10.6. RESULTS AT PLOT SCALE (STUDY SITES)

The area of Burruyacú was selected to go further in the study of soil compaction, in particular for assessing the difference between forest sites and crop sites. Two local grids, one in a forest plot and another in an old agricultural field, were surveyed, complemented with observation sites at study area level. Penetration resistance and bulk density were determined (Flores, 1997).

10.6.1. Penetration resistance

Penetration resistance was measured in two grids of 400 m^2 each, located on Lobo farm in El Puestito, north of Burruyacú. A forest site and an agricultural site used for cropping over more than 25 years, both with soil pit descriptions, were selected. Observation points were 3 m apart in the crop grid (49 points) and 2 m apart in the forest grid (100 points).

(1) Descriptive statistics

Classical statistics were calculated from the data sets of both grids (Tables 10.22 and 10.23; additional data in Tables 10.30 and 10.31 in Appendix). Most of the data are slightly skewed, negatively at some depths and positively at others. However, in general, the median and mean values of PR are close to each other, with a slight asymmetrical trend of the variable. Mean values of PR are relatively similar between 10 and 20 cm depth and below 60 cm depth. At the other depths, the PR means are higher at the forest site than at the crop site. In the first 5 cm depth, variance is higher at the forest site than in the crop field.

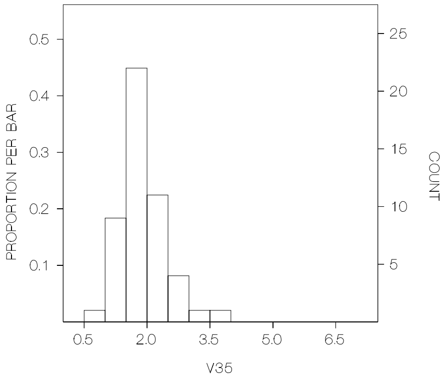
Table 10.22. Statistical parameters of penetration resistance (N cm^{-2}) at the forest site in Lobo farm.

Measurement depth cm	0	5	10	15	20
Number of cases	100	100	100	100	100
Minimum	0.100	0.100	0.600	0.400	0.900
Maximum	3.600	3.700	3.400	4.450	4.100
Range	3.500	3.600	2.800	4.050	3.200
Mean	1.377	1.958	1.985	2.060	2.199
Variance	0.582	0.551	0.376	0.418	0.346
Standard deviation	0.763	0.742	0.613	0.647	0.588
Skewness (G1)	0.455	-0.112	0.045	0.740	0.529
Median	1.300	2.000	2.000	1.950	2.200

Table 10.23. Statistical parameters of penetration resistance (N cm^{-2}) at the crop site in Lobo farm.

Measurement depth cm	0	5	10	15	20
Number of cases	49	49	49	49	49
Minimum	0.200	0.800	0.750	0.900	1.050
Maximum	1.450	2.900	3.900	4.300	3.650
Range	1.250	2.100	3.150	3.400	2.600
Mean	0.981	1.412	1.870	2.097	1.935
Variance	0.089	0.278	0.472	0.524	0.275
Standard deviation	0.299	0.527	0.687	0.724	0.524
Skewness (G1)	-0.493	0.908	0.491	1.146	1.217
Median	1.000	1.300	1.950	2.000	1.900

Histograms were established for all data sets. Two examples are shown in Figure 10.22, one for each grid. The other histograms are grouped in the appendix to this chapter (Figures 10.35 and 10.36). The majority of the histograms shows that data are slightly asymmetrically distributed.



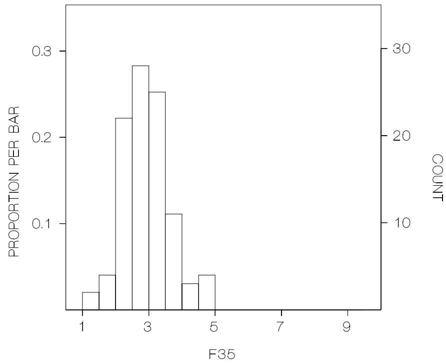


Figure 10.22. Histograms of penetration resistance at crop site (V35) and forest site (F35) at 35 cm depth (from Flores, 1997).

(2) Spatial modeling

The semivariograms, established for the forest and crop data sets, show a strict nugget effect indicating that penetration resistance in both cases has no spatial dependence (Figures 10.23 and 10.24). This could be because the sampling distance was larger than the spatial dependence dimension of the property measured. Since there was no spatial dependence in the penetration resistance data, it was not appropriate to apply kriging for interpolation and, instead, the minimun curvature technique was chosen to establish interpolation maps of PR.

To compare penetration resistance between crop and forest sites, both data sets were reduced to a common size: four rows/columns with four points each, at 6 m lag between points. The minimum curvature technique was applied to the reduced data set to create interpolation maps showing the spatial distribution of the penetration resistance values at the forest and crop sites (Figures 10.25 and 10.26).

There is a clear difference of penetration resistance between forest and crop sites. The topsoil is more homogeneous in the cropland than under forest, because yearly plowing over two to three decades caused homogenization of the surface soil. The presence of a plow-pan is reflected by increased penetration resistance between 10 cm and 20 cm depth, especially at 15 cm depth. In contrast, the dense rooting system in the forest topsoil makes penetration resistance more variable (Figure 10.27).

Also, the pattern of the penetration resistance isolines varies between forest and crop sites. In the crop field, PR isolines tend to be concentrical. In the forest, the isolines are elongated between 0 cm and 35 cm depth, corresponding to soil compaction along the pathways repeatedly used by roaming cattle when browsing the Chaco forest. At both the forest and crop sites, PR increased from 35-40 cm downwards, indicating the presence of Bt horizons in the subsurface soil.

The minimum curvature interpolation technique was also applied to the original complete data sets collected from 2m x 2m forest site grid and from 3m x 3m crop site grid (Figures 10.28 and 10.29). Conclusions are similar to those drawn from the generalized 6m x 6m grids. Some differences in the isoline patterns are probably due to the differential size of the two data sets used for interpolation. Although the elongated isoline pattern shown by the forest model at sampling distance of 6m x 6m is not easy to recognize at shorter sampling distances, the cow paths can be identified especially at 0 cm and 10 cm depth. Three-dimensional models were established at three selected depths (0 cm, 15 cm and 40 cm) to show the difference in PR variation with depth at forest and crop sites (Figures 10.30, 10.31 and 10.32). At similar depths, PR is less variable at the crop site than at the forest site. Under the long-lasting effect of plowing, the arable soil has become more uniform, especially between 15 cm and 40 cm depth. In contrast, the upper forest soil mantle shows short-distance variability thanks to its dense rooting system and intense biological activity, and the effect of these properties on soil structure and aeration. Thus, the original short-distance pedodiversity, typical of the forest environment, has been significantly impoverished through monocultural farming.

Kriging is a moving average technique that uses the semivariogram parameters for interpolation. In spite of the nugget effect shown by the semivariogram in Figure 10.33, the kriging procedure was applied to one selected depth, i.e. the 15-cm forest data set, for comparing kriging interpolation results with the minimum curvature interpolation results (Figure 10.34). In this particular example, the nugget effect did not significantly influence the interpolation procedure and the spatial pattern of penetration resistance. Even when fitting the spherical model of Figure 10.33 to the variogram, the two interpolation patterns remain very similar.

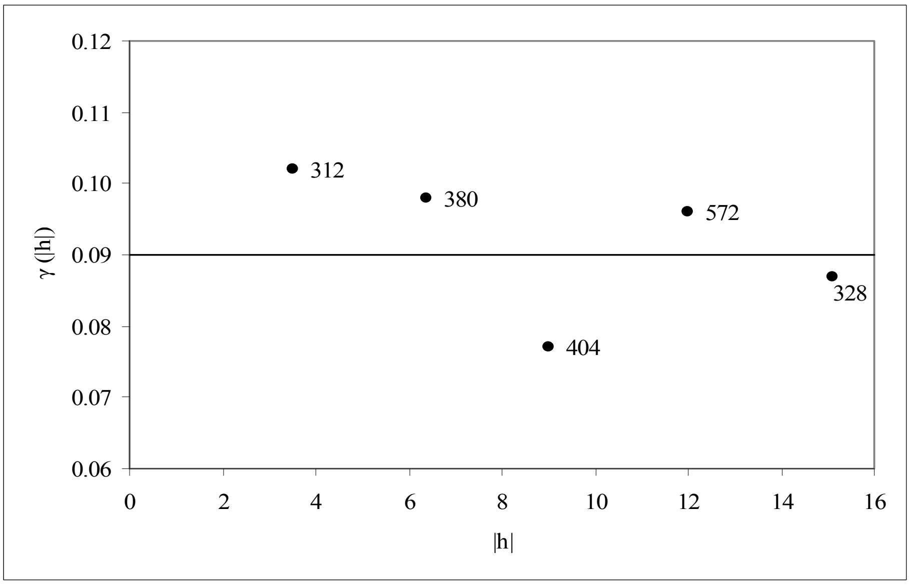


Figure 10.23. Omnidirectional semivariogram of penetration resistance at 0 cm depth in a crop field, showing nugget effect. Numerical figures represent data pairs having the same γ (h) values (lag h in m). From Flores, 1997.

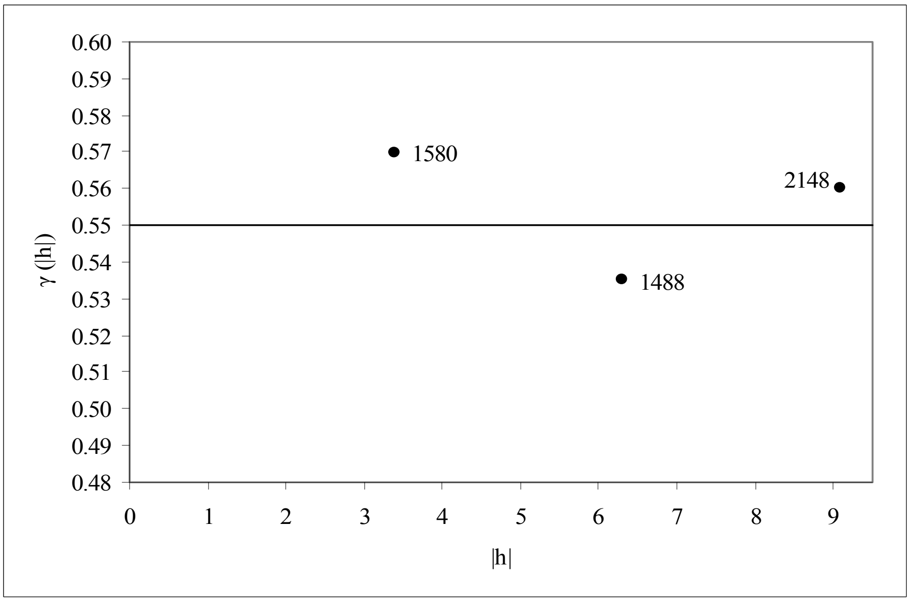


Figure 10.24. Omnidirectional semivariogram of penetration resistance at 0 cm depth at a forest site, showing nugget effect. Numerical figures represent data pairs having the same γ (h) values (lag h in m). From Flores, 1997.

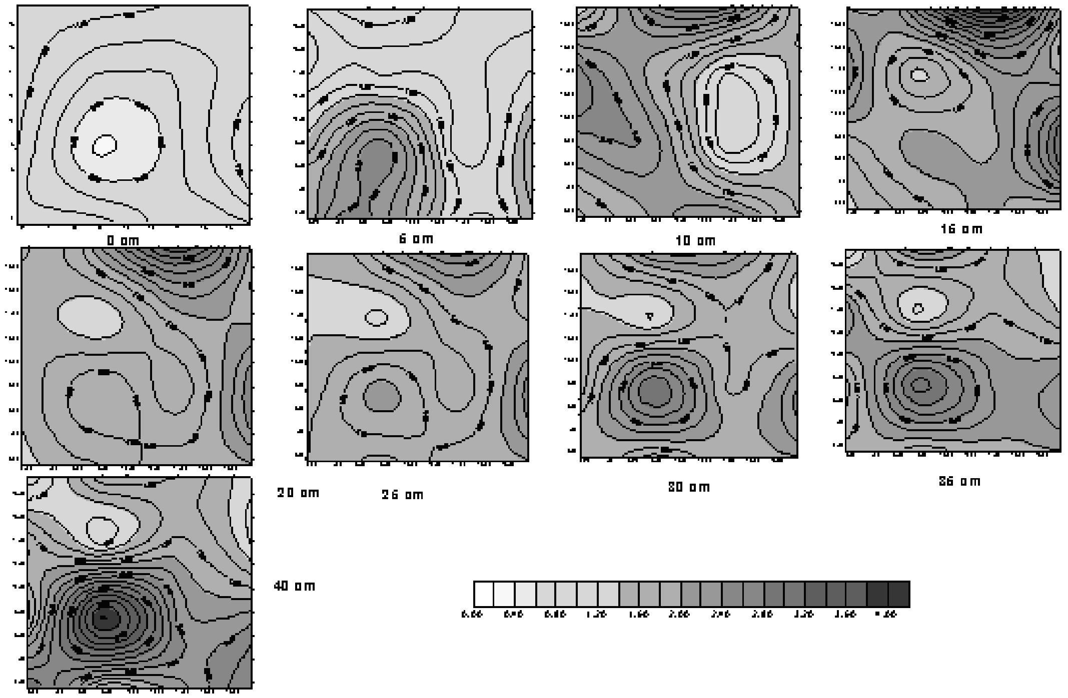


Figure 10.25. Interpolation maps of penetration resistance values (N cm^{-2}) at 5-cm-deep intervals at a crop site on Lobo farm (Burruyacú) from a generalized 6m x 6m grid layout, using minimum curvature technique (from Flores, 1997).

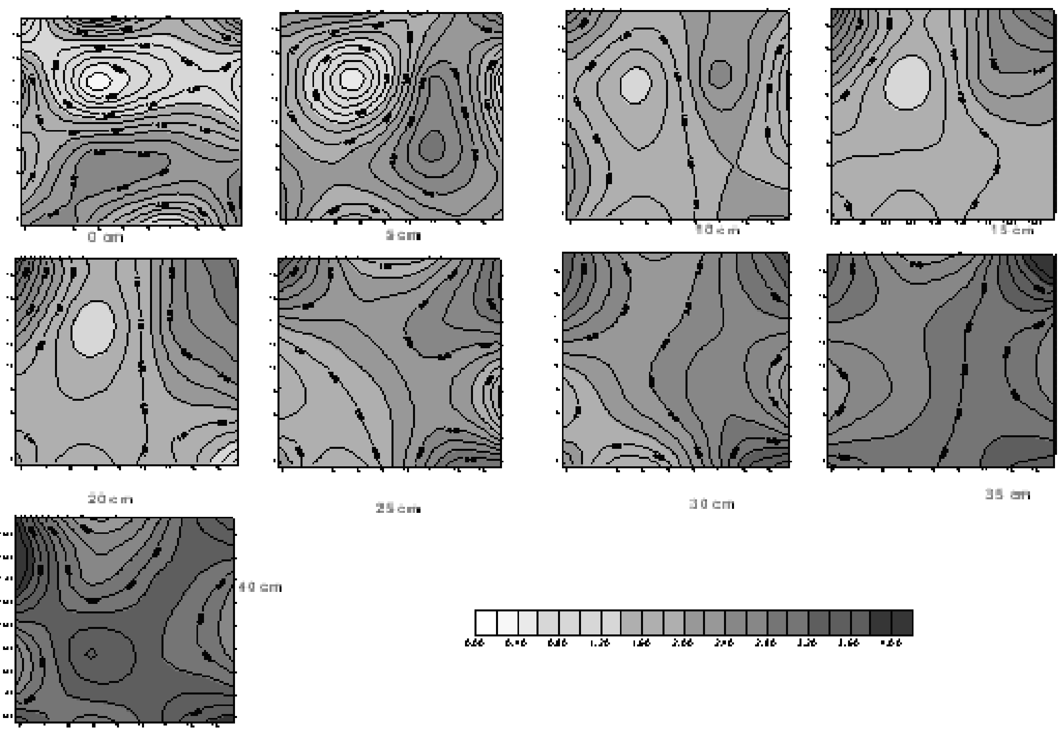


Figure 10.26. Interpolation maps of penetration resistance values (N cm^{-2}) at 5-cm-deep intervals at a forest site on Lobo farm (Burruyacú) from a generalized 6m x 6m grid layout, using minimum curvature technique (from Flores, 1997).

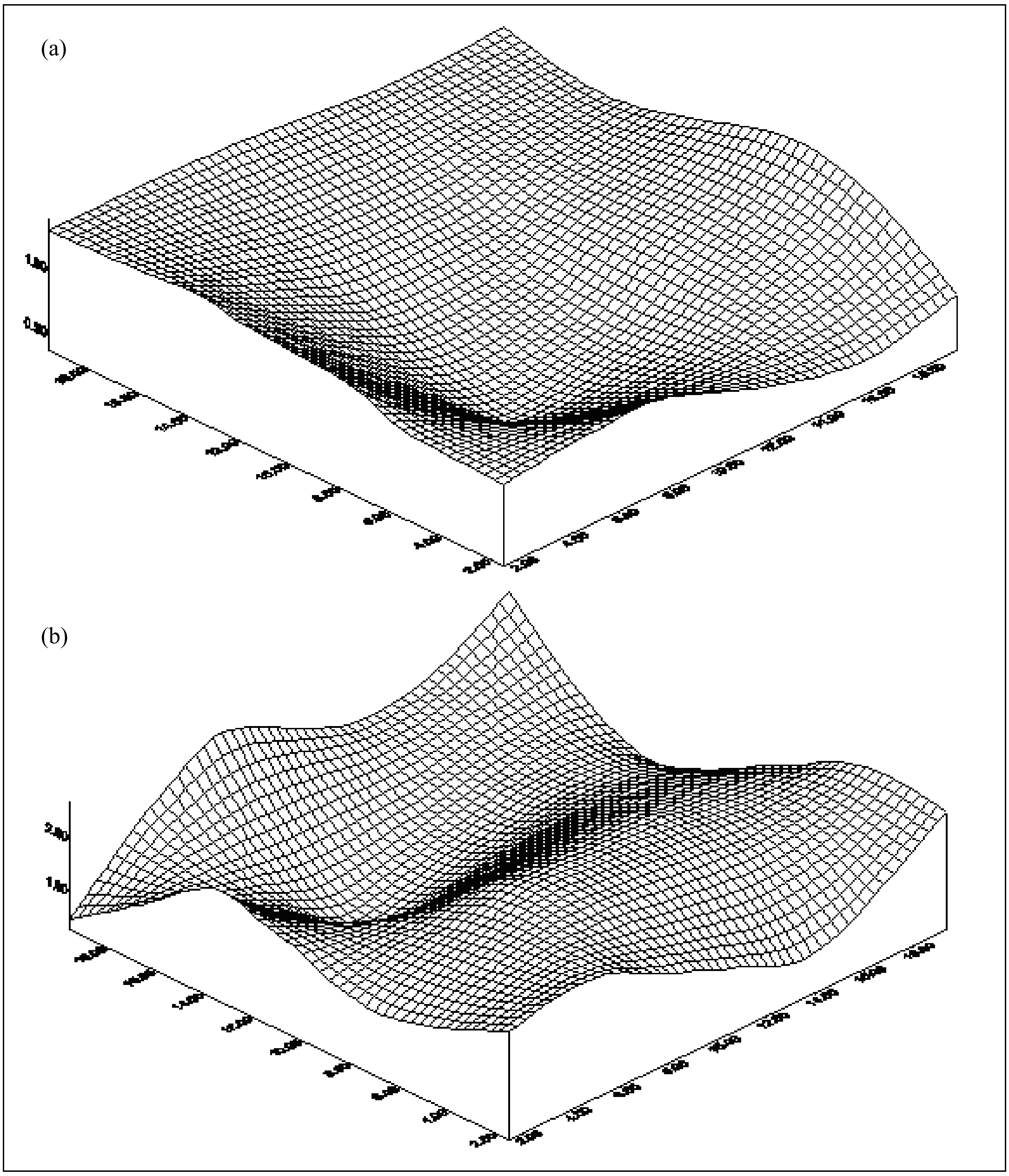


Figure 10.27. Variation of penetration resistance at 0 cm depth at (a) a crop site and (b) a forest site on Lobo farm (Burruyacú) from a generalized 6m x 6m grid layout (from Flores, 1997).

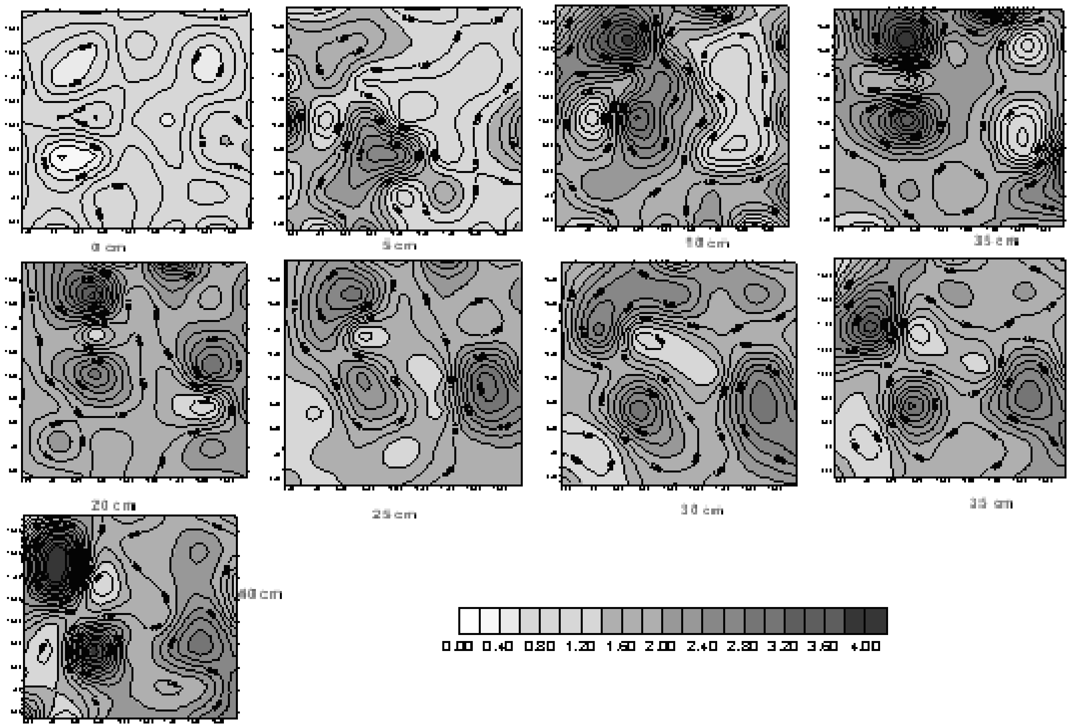


Figure 10.28. Interpolation maps of penetration resistance values (N cm^{-2}) at 5-cm-deep intervals at a crop site on Lobo farm (Burruyacú) from a 3m x 3m grid layout, using minimum curvature technique (from Flores, 1997).

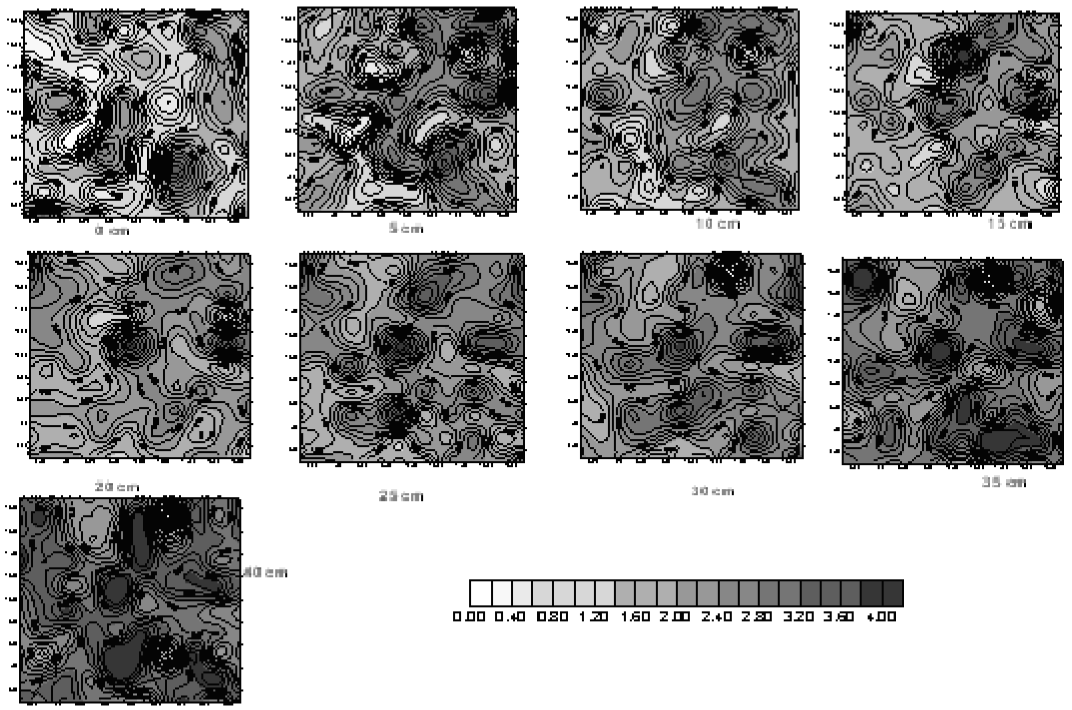


Figure 10.29. Interpolation maps of penetration resistance values (N cm^{-2}) at 5-cm-deep intervals at a forest site on Lobo farm (Burruyacú) from a 2m x 2m grid layout, using minimum curvature technique (from Flores, 1997).

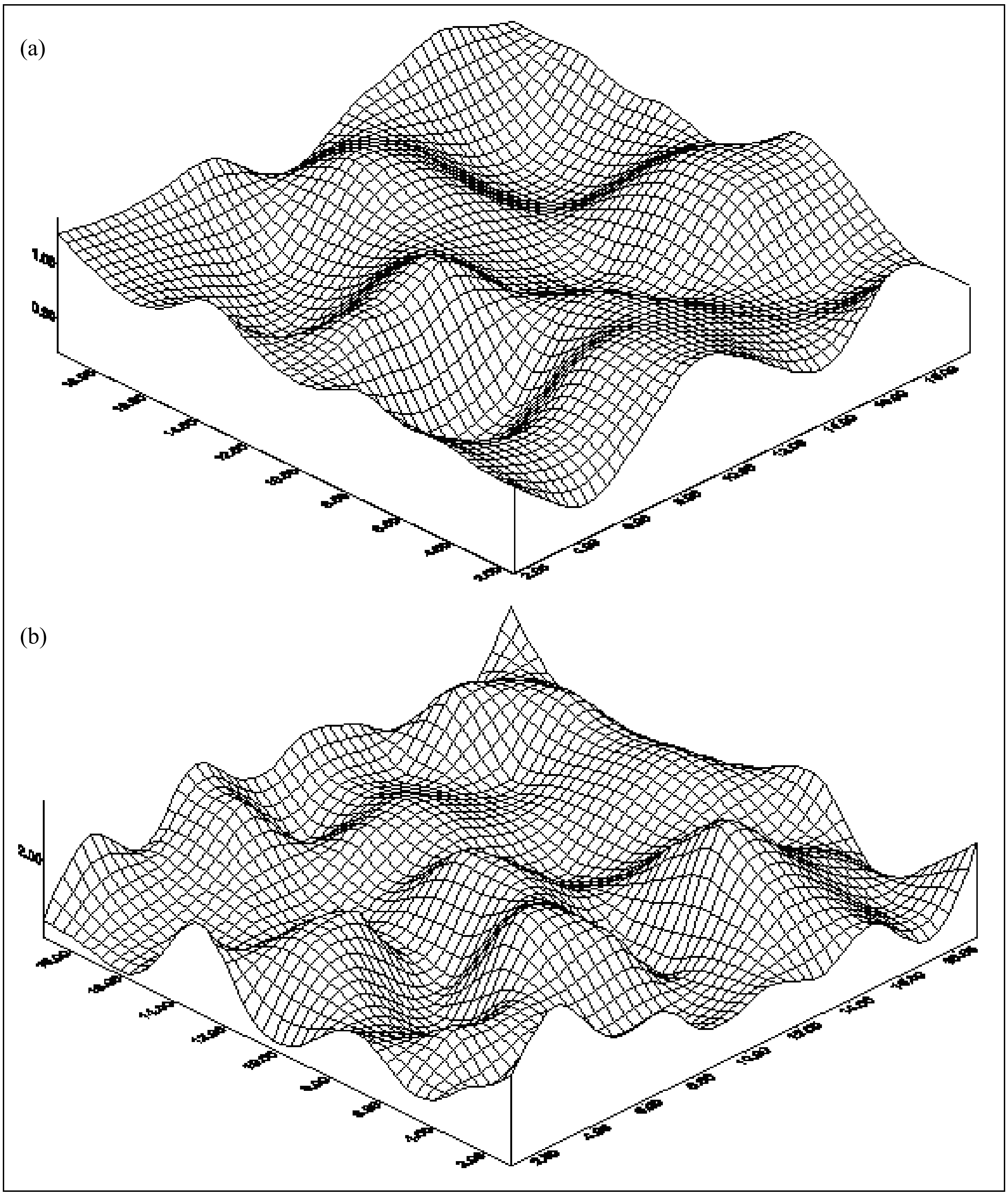


Figure 10.30. Variation of penetration resistance at 0 cm depth at (a) a crop site (3m x 3m) and (b) a forest site (2m x 2m) on Lobo farm, Burruyacú (from Flores, 1997).

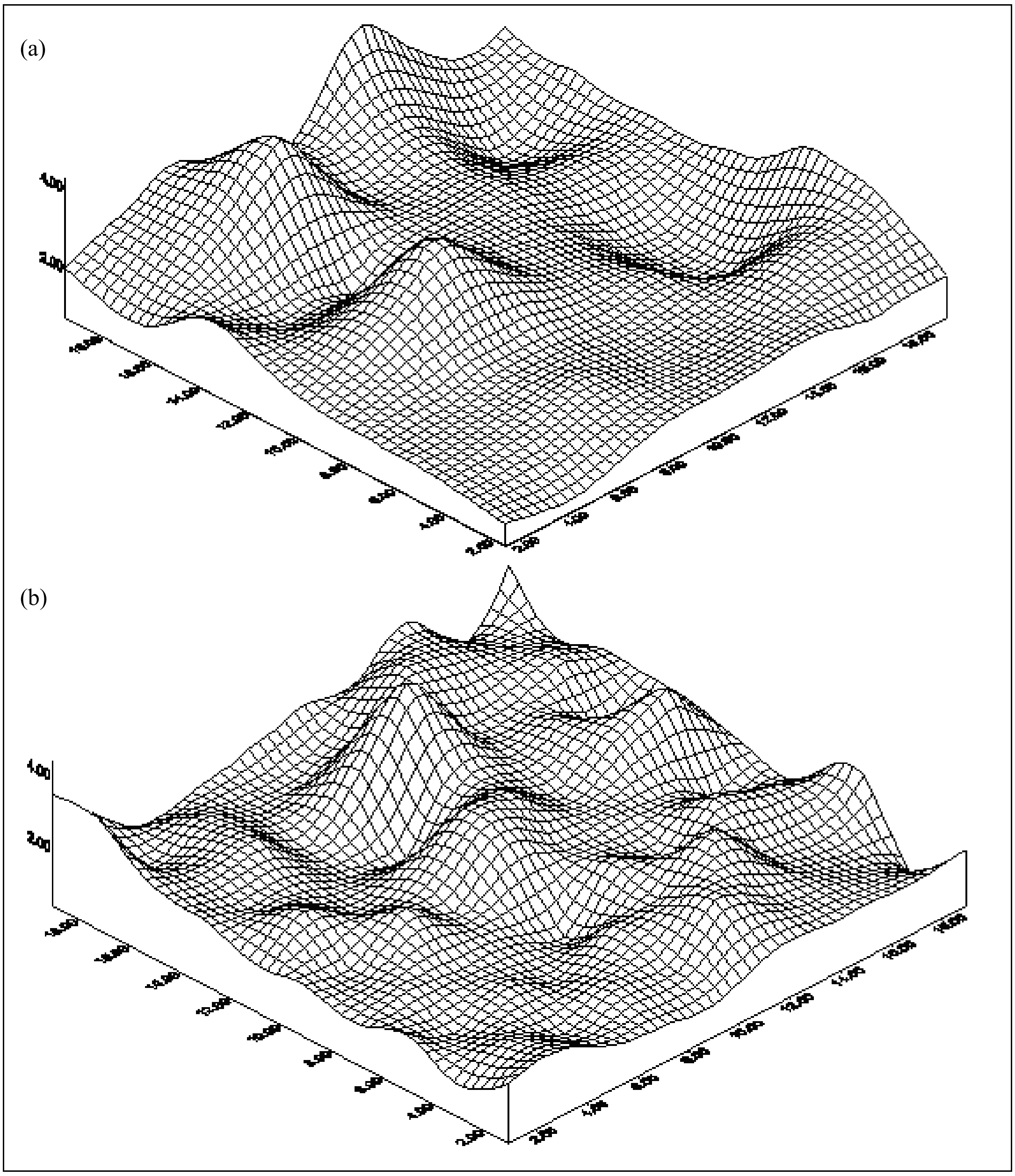


Figure 10.31. Variation of penetration resistance at 15 cm depth at (a) a crop site (3m x 3m) and (b) a forest site (2m x 2m) on Lobo farm, Burruyacú (from Flores, 1997).

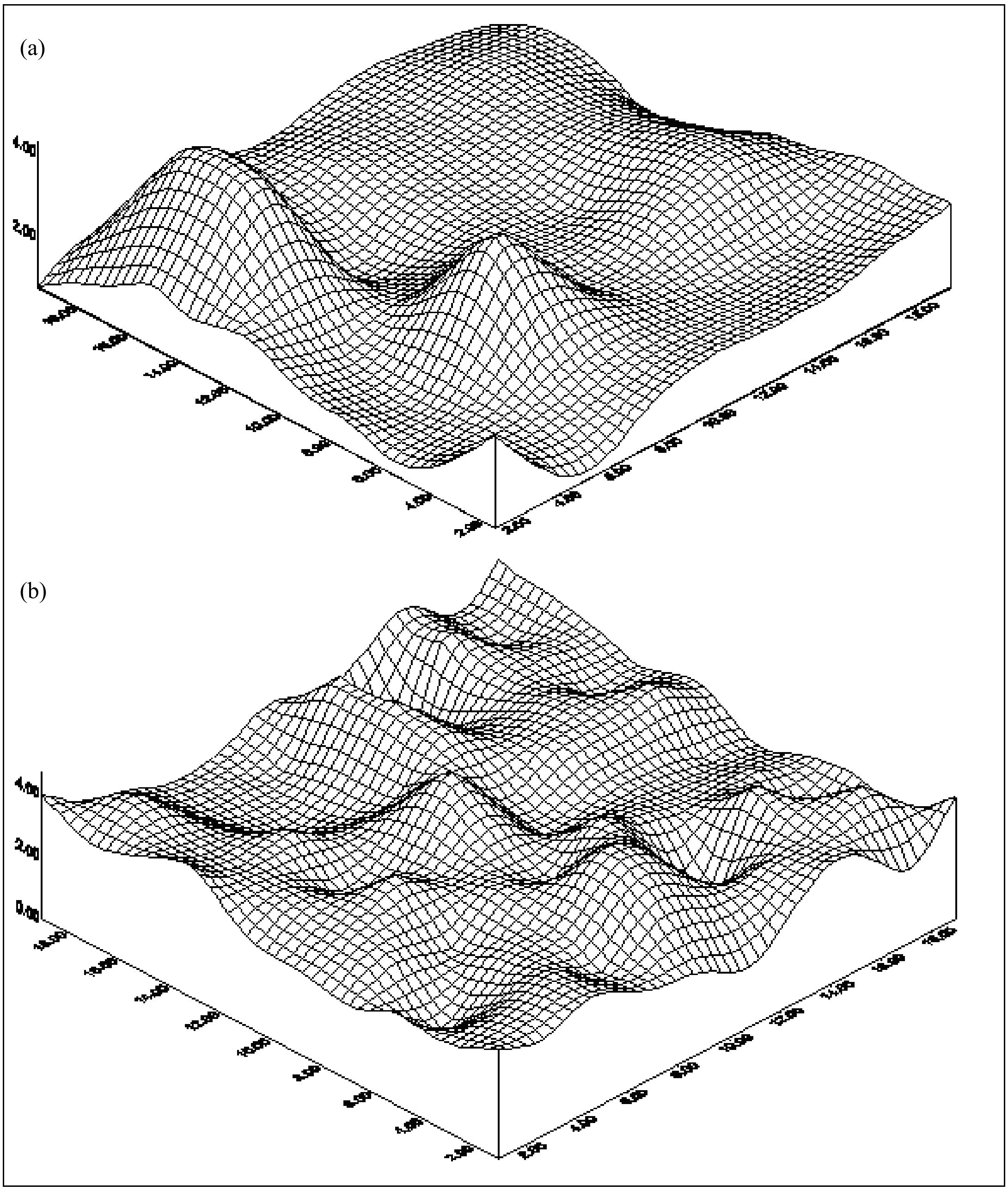


Figure 10.32. Variation of penetration resistance at 40 cm depth at (a) a crop site (3m x 3m) and (b) a forest site (2m x 2m) on Lobo farm, Burruyacú (from Flores, 1997).

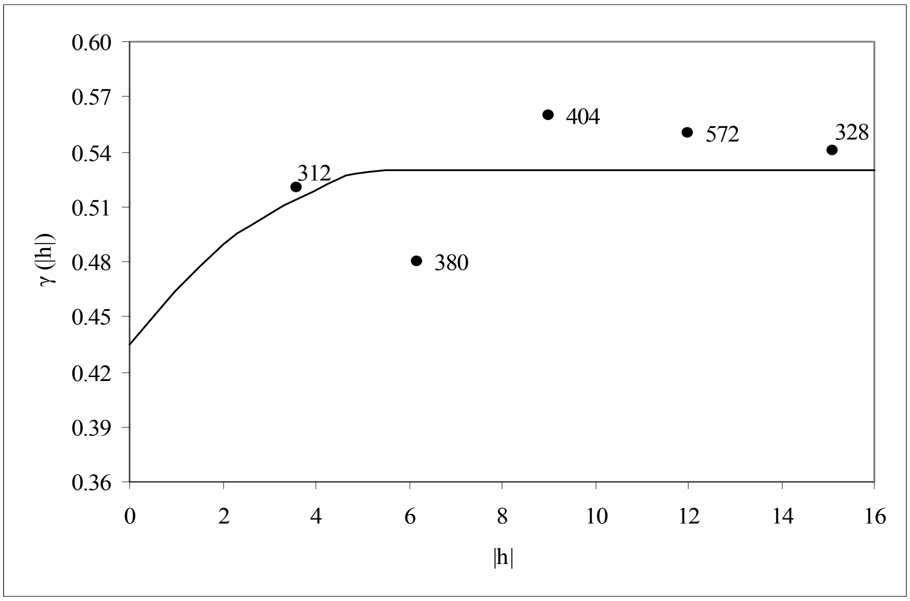


Figure 10.33. Omnidirectional semivariogram used for interpolation of penetration resistance data by kriging at 15 cm depth at a forest site on Lobo farm, Burruyacú (from Flores, 1997).

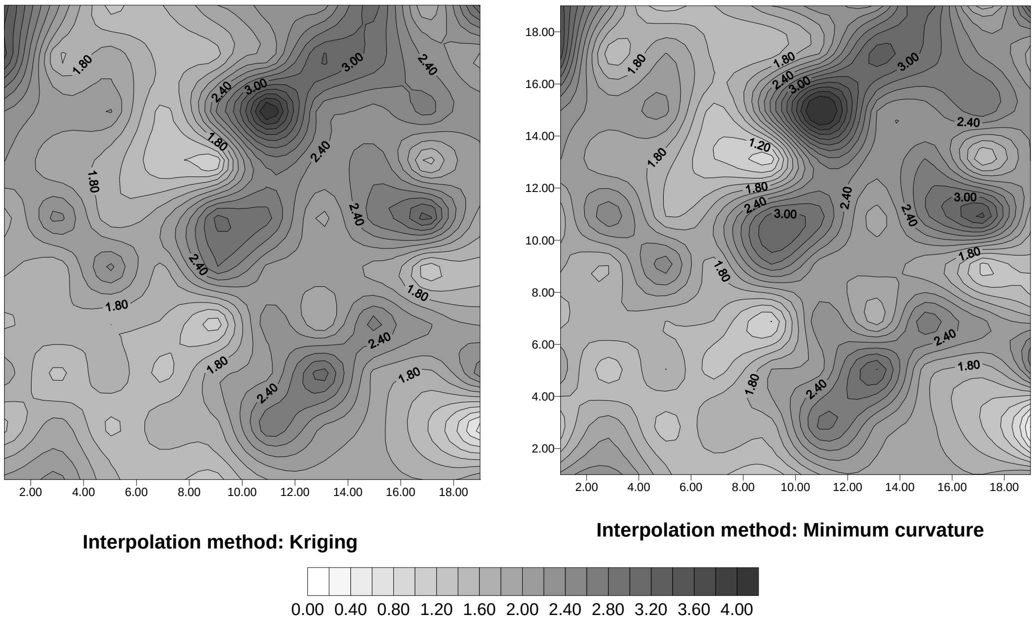


Figure 10.34. Comparison of isopleth maps obtained from two different interpolation techniques (i.e. kriging and minimum curvature, respectively), applied to penetration resistance data (N cm^{-2}) at 15 cm depth at a forest site on Lobo farm, Burruyacú (from Flores, 1997).

10.6.2 Bulk density

To complement the spatial distribution analysis of penetration resistance, samples were collected at selected places within the forest and crop grids for bulk density determination, together with particle size distribution and organic carbon determinations (Tables 10.24, 10.25 and 10.26).

In general, soils show composite profiles, with currently forming Bt horizons as well as buried Bt horizons. Silt is the dominant particle size fraction, reflecting the loessic nature of the parent material. There is a significant relationship between bulk density and penetration resistance in the topsoils and the Bt horizons of both the forest and agricultural soils. Under forest, bulk density was higher along the pathways travelled by browsing cows (P2 site), while it was lower in the areas not affected by cattle trampling (M4 site). In the crop field, topsoil bulk density varies less than under forest because of homogenization of the arable layer by continuous plowing. Higher bulk density in the lower topsoil reflects plow-pan formation.

Table 10.24. Soil profile P1A at a crop site on Lobo farm (Burruyacú).

Horizons Depth (cm)	Ap 0-13	Ad 13-13/15	Bt 13/15-35	BC 35-53	2Btb1 53-90	2Btb2 90-140
Clay %	22	27	28	21	14	23
Silt %	67	65	64	70	68	70
Sand %	11	8	8	9	18	7
Bulk density Mg m^{-3}	1.09	1.36	1.35	1.26	1.09	1.17
Organic carbon %	2.10	1.56	1.08	0.50	0.23	0.32

Table 10.25. Soil profile P2 at a forest site on Lobo farm (Burruyacú).

Horizons Depth (cm)	A1 0-28	Bt 28-52	BC 52-74	C 74-91	2Ab 91-97	2Btb 97-117	2Cb 117-140
Clay %	24	35	28	26	33	36	24
Silt %	71	64	71	72	65	62	74
Sand %	5	1	1	2	2	2	2
Bulk density Mg m^{-3}	1.22	1.42	1.42	1.46	1.27	1.49	1.28
Organic carbon %	4.87	1.02	0.66	0.40	0.64	0.50	0.31

Table 10.26. Bulk density (Mg m^{-3}) at forest and old crop sites on Lobo farm in Burruyacú (depth in cm).

P2 Forest	1.22 (0-28)	1.42 (28-52)	1.42 (52-74)	1.46 (74-91)	1.27 (91-97)	1.49 (97-117)	1.28 (117-140)
M4 Forest	0.71 (0-12/18)	1.07 (12/18-40)	1.40 (40-50)	1.43 (50-60)	- -	- -	- -
P1A Crop	1.09 (0-13)	1.36 (13-13/23)	1.35 (13/23-35)	1.26 (35-53)	1.09 (53-90)	1.17 (90-140)	- -
M3 Crop	1.03 (0-23)	1.24 (23-35)	1.38 (35-60)	- -	- -	- -	- -

10.6.3. Conclusion

High variability in the topsoil and relative uniformity in the subsoil at the forest site, as inferred from bulk density data, match the spatial variability of penetration resistance, as shown on the interpolation map of Figure 10.29. Penetration resistance is higher in the cow paths (e.g. at 5 cm and 10 cm depth) than in the areas lying in-between. In contrast, at the crop site, plowing causes surficial homogenization (Figure 10.28). At both sites, soil material becomes more homogeneous from 35-40 cm downwards because of the presence of argillic horizons. Meshalkina et al. (1995) reached a similar conclusion when comparing forest and farming plots in Russia.

10.7. GENERAL CONCLUSION

The crossing of six geographic locations, strategically distributed in west-east and north-south directions, with five forest reclamation time ranges constitutes a matrix approach to analyzing and assessing land degradation, that allows highlighting simultaneously spatial and temporal trends. Bulk density and penetration resistance were used to monitor soil compaction, while organic carbon, exchangeable calcium and soluble phosphorus were used to monitor fertility depletion. Changes affecting these attributes over a period of 25-30 years (<1971-1996) reveal a clear tendency to deterioration of soil quality under mechanized mono-cropping of soybean.

10.7.1. Bulk density

The regional mean value of bulk density in the topsoil is 1.09 Mg m^{-3} in the first horizon and 1.23 Mg m^{-3} in the second one, corresponding to an increase of 13%. In all study areas, average BD values in agricultural fields are higher in the lower topsoil than in the upper one. At the majority of the sites, increases are less than 30%, with an average median of 14% when considering all reclaimed sites together, in comparison to the forest sites. Thus, while the physical conditions of the arable layer in the upper topsoil are overall good, there is a general tendency of compaction in the second horizon, with plow-pan formation. A regional trend is visible in the northern transect, where bulk density values seem to parallel the displacement of the agricultural frontier from west to east, with the highest values in the oldest reclamation areas in the west (Burruyacú and La Argentina).

In general, there is a slight increase in bulk density in both topsoil horizons from the younger to the older fields. Upon reclamation, the physical conditions of the upper topsoil seem to be improved, probably because annual tillage removes the earlier trampling effect of the cattle browsing in the Chaco forest. In all land reclamation ranges considered, BD is higher in the lower topsoil than in the upper one, reflecting compaction beneath the arable layer through plow-pan formation. In conclusion, soil compaction takes place in all deforestation time ranges, mainly in the lower topsoil, and increases with time in proportions not yet dramatic. Intensive farming for commercial crop production and the use of heavy machinery are the main factors causing soil compaction.

10.7.2. Penetration resistance

There is a clear difference of penetration resistance between forest and crop sites. The topsoil is more homogeneous in the cropland than under forest, because yearly plowing over two to three decades caused homogenization of the surface soil. The presence of a plow-pan is reflected by the increase of penetration resistance between 10 cm and 20 cm depth, especially at 15 cm depth. In contrast, the dense rooting system in the forest topsoil makes penetration resistance more variable.

Also, the pattern of the penetration resistance isolines varies between forest and crop sites. In the crop field, PR isolines tend to be concentrical. In the forest, the isolines are elongated between 0 cm and 35 cm depth, corresponding to soil compaction along the pathways repeatedly used by roaming cattle when browsing the Chaco forest.

At both the forest and crop sites, PR increases from 35-40 cm downwards, indicating the presence of Bt horizons in the subsurface soil. At similar depths, PR is less variable at the crop site than at the forest site. Under the long-lasting effect of plowing, the arable soil has become more uniform, especially between 15 cm and 40 cm depth. In contrast, the upper forest soil mantle shows short-distance variability because of its dense rooting system and intense biological activity, and the effect of these properties on soil structure and aeration. Thus, the original short-distance pedodiversity, typical of the forest environment, has been significantly impoverished through monocultural farming.

Penetration resistance is highly related to soil moisture and the density of the rooting system. PR values are higher in the drier east than in the wetter west. Thus, comparison of penetration resistance values between the different areas does not make sense. The homogenization of the upper topsoil by plowing makes penetration resistance less variable than in the lower topsoil.

10.7.3. Organic carbon

In all study areas, average organic carbon content is higher in the first horizon (2.55%) than in the second (1.53%), corresponding to a difference of 40%. When compared to conventional standards, these OC contents can be considered medium to high in the upper part of the topsoil and low in its lower part. Organic carbon clearly decreases from west to east in both topsoil horizons, paralleling a west-east decrease in annual rainfall. This might reflect the influence of the climate gradient on biomass production and organic matter incorporation into the soil. After accelerated depletion in the first couple of years following deforestation, OC content decreases slowly over time to reach about 60% of the original forest content in the oldest crop fields (from 2.54% to 1.77% over the period <1970-1996). The lower topsoil layer does not show significant variations in OC content over time. García et al. (1993) got similar results from their work in the Chaco-Pampean plain east of Tucumán, with 40 % reduction of total organic carbon after 25 years of agricultural use of loess-derived Haplustolls. However, in spite of continuous depletion, the OC status at regional level is not yet limiting for agriculture.

10.7.4. Exchangeable calcium

Exchangeable calcium is high throughout the topsoil, with average values slightly higher in the first horizon (17.5 cmol kg^{-1}) than in the second one (14.9 cmol kg^{-1}). In the southern transect (La Ramada-Piedrabuena), Ca^+ decreases from west to east in the whole topsoil. The long-term tendency is one of declining Ca^+ in both topsoil horizons, with some kind of stabilization in old crop fields at around one third of the original Ca^+ content under forest conditions.

10.7.5. Soluble phosphorus

On average, there is about two times more soluble phosphorus in the first horizon than in the second one (26.2 mg kg^{-1} and 13.4 mg kg^{-1}, respectively). When compared to the other selected topsoil parameters, Ps shows a different spatial pattern, with values increasing at the same time from west to east and from south to north. According to conventional standards, Ps contents of the study region can be considered low to very low everywhere. Gobernador Piedrabuena is the study area with the highest Ps content, while La Ramada and La Virginia are particularly poor in Ps. There is clearly an overall trend of decreasing Ps content in the upper topsoil with time. After 10-15 years of agricultural use, the Ps content in cultivated land is 40-60% lower than that in soils under forest. In one place, the Ps left over after 40 years of cropping was only 17% of the original forest content. García et al. (1993) report a 90% loss of available phosphorus in the Chaco-Pampean plain east of Tucumán after only 10 years of agricultural use. In the lower topsoil, the Ps content is in general half that of the upper topsoil in agricultural fields as well as under forest. The temporal depletion pattern of the Ps content is similar to that shown by organic carbon.

10.8. REFERENCES

Ahmed, H., Schuman, E., Hart, R., 1987. Soil bulk density and water infiltration as affected by grazing systems. Journal of Range Management 40: 307-309.

Aronoff, S., 1989. Geographic informations systems: a management perspective. WDL Publications, Ottawa, Canada.

Aweto, A.O., Adejumbodi, D.O., 1991. Impact of grazing on soil in the southern Guinea savannah zone of Nigeria. The Environmentalist 11: 27-32.

Barber, R.G., Romero, D., 1994. Effects of bulldozer and chain clearing on soil properties and crop yields. Soil Science Society of America Journal 58: 1768-1775.

Bezkorowajnyj, P.G., Gordon, A.M., McBride, R.A., 1993. The effect of cattle foot traffic on soil compaction in a silvo-pastoral system. Agroforestry Systems 21: 1-10.

Bono, A., Fernandez, S., Aimar, S., Buschiazzo, D.E., 1993. Resistencia a la penetración y contenido de humedad en diferentes suelos de la región semiárida pampeana central. XIV Congreso Argentino de la Ciencia del Suelo, Mendoza, Argentina.

Briggs, J., Courtney, F., 1989. Agriculture and environment. The physical geography of temperate agricultural systems. Longman Scientific & Technical, London, UK.

Burton, S., Shah, P.B., Shreier, H., 1989. Soil degradation from converting forest land into agriculture in the Chitwan district of Nepal. Mountain Research and Development 9: 393-404.

Campbell, D.J., 1994. Determination and use of soil bulk density in relation to soil compaction. In: B.D. Soane and C. van Ouwerkerk (eds.), Soil compaction in crop production. Elsevier, Amsterdam, The Netherlands, pp.113-140.

Casas, R.R., Michelena, R.O., 1983. La degradación de los suelos y la expansión de la frontera agropecuaria en el Parque Chaqueño Occidental. IDIA-INTA, Buenos Aires. Suplemento 36: 141-146.

Casas, R.R., Irurtia, C.B., Michelena, R.O., 1997. Deforestation and soil degradation in the north of Argentina. (unpublished).

Colburg, A.E., 1972. Soil compaction effects. Effects of livestock grazing on a crested wheat grass seeding in Southern Idaho. Journal of Range Management 29: 147-151.

Davis, J.C., 1986. Statistics and data analysis in geology. 2nd Edition. John Wiley & Sons, New York, USA.

Domzal, H., Hodara, J., Slowinska Jurkiewicz, A., Turski, R., 1992. Agricultural utilization as a factor in increasing bulk densities of soils. Zeszyty Problemowe Postepow Nauk Rolniczych 398: 27-35 (from abstract in English).

Eden, M.J., Furley, P.A., McGregor, D.F.M., Milliken, W., Ratter, J.A., Leopoldo, P.R., 1988. Effect of forest clearance and burning on soil properties in northern Roraima, Brazil. In: Amazonia: deforestation and possible effects. Selected Papers from 46th International Congress of Americanists. Forest Ecology and Management 38: 3-4.

Eijkelkamp, 1989. Soil Penetrograph Catalog. Giesbeek, The Netherlands.

Ellis, S., Mellor, A., 1995. Soils and environment. Routledge, London, UK.

Flores, E., 1997. Monitoring land use changes and comparing soil physical properties between arable and forest land in the western Chaco plain, NW Argentina. MSc Thesis. ITC, Enschede, The Netherlands.

García, J.R., Bleckwedel, C., Giménez, D., Cáceres, M.R., Pietroboni, A.M., 1993. La degradación de los suelos agrícolas del este tucumano. Actas XII Congreso Latinoamericano de la Ciencia del Suelo. Ministerio de Agricultura, Pesca y Alimentación. Salamanca, España, pp. 1280-1285.

García, J.R., Giménez, R., Sanzano, G.A., Corbella, R.D., 1996. Influencia de la infiltración de diferentes capas de un suelo agrícola del este tucumano. Avance Agroindustrial, Marzo de 1996. S.M. de Tucumán, Argentina.

Garwood, E.A., Tyson, K.C., Clement, C.R., 1977. A comparison of yield and soil conditions during 20 years of grazed grass and arable cropping. Grassland Research Institute, Technical Report 21, Hurley.

Ingram, P., 1996. Introduction to geostatistics. School of Earth Sciences, Macquarie University, Sydney, Australia.

Lal, R., 1986. Soil surface management in the tropics for intensive land use and sustained production. In: B.A. Stewart (ed.), Advances in Soil Science 5. Springer-Verlag, Berlin, Germany, pp.1-109.

Lal, R., 1994. Methods and guidelines for assessing sustainable use of soil and water resources in the tropics. SMSS Tech. Bulletin, Volume 21. USDA Soil Conservation Service, Washington D.C., USA.

Lal, R., Stewart, B.A., 1990a. Need for action: research and development priorities. In: R. Lal and B.A. Stewart (eds.), Soil degradation. Advances in Soil Science 11. Springer-Verlag, Berlin, Germany.

Lal, R., Stewart, B.A., 1990b. Soil degradation: a global threat. In: R. Lal and B.A. Stewart (eds.), Soil degradation. Advances in Soil Science 11. Springer-Verlag, Berlin, Germany.

Ley, G.J., Laryea, K.B., 1994. Spatial variability in penetration resistance of a hardsetting tropical Alfisol. Soil & Tillage Research 29: 367-381.

Martínez, L.J., 1992. Effect of livestock on soil degradation processes in the Colombian Amazon region: a case study of the Guaviare colonization area. MSc Thesis. ITC, Enschede, The Netherlands.

Martínez, L.J., Zinck, J.A., 1994. Modelling spatial variations of soil compaction in the Guaviare colonization area, Colombian Amazonia. ITC Journal 1994-3: 252-263.

Martínez, L.J., Zinck, J.A., 2004. Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. Soil & Tillage Research 75: 3-17.

Martins, P.F.d.S., Cerri, C.C., Volkoff, B., Andreux, F., Chauvel, A., 1991. Consequences of clearing and tillage on the soil of a natural Amazonian ecosystem. Forest Ecology and Management 38: 273-282.

Meshalkina, J.L., Stein, A., Dmitriev, Ye.A., 1995. Spatial variability of penetration data on Russian plots in different land use. Soil Technology 8: 43-59.

Mulholland, B., Fullen, M.A., 1991. Cattle trampling and soil compaction on loamy sands. Soil Use and Management 7(4): 189-193.

Parker, C.J., Chartres, C.J., 1983. The effects of recent land use changes on red podzolic soils near Sydney, NSW Australia. Catena 10: 61-76.
Raghavan, G., Alvo, P., McKeys, E. 1990. Soil compaction in agriculture. In: R. Lal and B.A Stewart (eds.), Soil degradation. Advances in Soil Science 11. Springer-Verlag, Berlin, Germany.
Soane, B.D., Van Ouwerkerk, C., 1994. Soil compaction problems in world agriculture. In: B.D. Soane and C. Van Ouwerkerk (eds.), Soil compaction in crop production. Elsevier, Amsterdam, The Netherlands.
Spain, A.V., Prove, B.G., Hodgen, M.J., Lee, K.E., 1990. Seasonal variation in penetration resistance and shear strength of three rainforest soils from northeastern Queensland. Geoderma 47: 79-92.
Stein, A., 1996. Spatial statistics for soils and the environment. ITC, Enschede, The Netherlands.
Stephenson, G., Veigel, A., 1987. Recovery of compacted soil on pastures used for winter cattle feeding. Journal of Range Management 40: 46-48.
Trangmar, B.B., Yost, R.S., Uehara, G., 1985. Application of geostatistics to spatial studies of soil properties. In: N.C. Brady (ed.), Advances in Agronomy 38, Academic Press, pp.45-94.
Usman, H., 1994. Cattle trampling and soil compaction effects on soil properties of a northeastern Nigerian sandy loam. Arid Soil Research and Rehabilitation 8: 69-75.
Valentin, C., 1985. Effects of grazing and trampling on soil deterioration around recently drilled water holes in the Sahelian zone. Soil Erosion and Conservation, pp.51-65.
Van Haveren, B., 1983. Soil bulk density as influenced by grazing intensity and soil type on a shortgrass prairie site. Journal of Range Management 36: 586-588.
Vázquez, L., Myhre, D.L., Hanlon, E.A., Gallaher, R.N., 1991. Soil penetrometer resistance and bulk density relationships after long-term no-tillage. Communications in Soil Science and Plant Analysis 22: 2101-2117.
Wilding, L.P., Drees, L.R., 1978. Diversity of soils in the Tropics. American Society of Agronomy, Spec. Publ. 34: 1-12.

10.9. APPENDIX: PENETRATION RESISTANCE DATA

10.9.1. Field measurements of penetration resistance

Table 10.27. Penetration resistance ($N\ cm^{-2}$) in Burruyacú.

Depth (cm)	M4 Forest	M3 <1970	M9 1976-85	M15 1985-91	M2 1991-96
0	1.50	0.50	0.70	0.20	0.85
5	2.26	0.80	2.10	0.80	0.80
10	1.96	0.73	3.50	1.43	1.43
15	1.78	1.03	3.50	2.17	1.78
20	1.70	1.46	2.70	3.03	1.86
25	1.66	1.73	1.60	2.90	1.73
30	1.90	1.30	2.50	2.63	2.06
35	2.06	1.23	2.50	2.40	1.65
40	2.15	1.16	2.50	2.23	1.45
45	2.46	1.73	2.40	2.37	1.70
50	2.20	1.60	2.20	2.33	2.30
55	3.03	1.80	3.20	2.53	2.50
60	2.46	2.30		3.10	
65	2.95	2.20		3.67	
70		2.80		3.40	
75				4.80	
80					

Table 10.28. Penetration resistance (N cm^{-2}) in La Argentina.

Depth (cm)	M6 Forest	M8 1970-76	M5 1976-85	M7 1985-91	M16 1991-96
0	2.00	0.95	1.00	1.40	0.25
5	4.30	2.50	2.25	1.40	0.70
10	3.70	3.65	2.45	1.26	1.15
15	3.60	3.55	2.35	1.40	2.00
20	4.80	2.90	2.75	1.50	2.50
25		2.65	3.25	1.80	2.65
30		2.90	3.45	2.13	2.40
35		2.85	3.80	2.43	2.20
40		3.00	4.40	3.75	2.00
45		3.25	4.75	4.00	1.85
50		3.70	4.75	4.20	1.80
55		3.70	4.80	4.60	1.50
60			4.80		1.65
65					1.95
70					2.35
75					2.30
80					

Table 10.29. Penetration resistance (N cm^{-2}) in Gobernador Garmendia.

Depth (cm)	M11 Forest	M10 <1970	M12 1976-85	M13 1985-91	M14 1991-96
0	3.67	0.63	1.30	0.60	1.45
5	3.70	2.53	1.40	1.15	2.85
10	2.60	3.40	1.05	2.25	2.65
15	1.87	3.27	0.90	4.40	2.65
20	2.50	2.67	0.90	4.30	2.55
25	2.10	2.83	3.30	3.35	2.30
30	1.90	2.63	3.10	3.05	2.40
35	1.95	3.00	3.20	2.80	2.30
40	1.60	3.20	2.65	2.80	2.05
45		3.13	2.15	3.05	1.70
50		3.07	2.05	3.15	1.50
55		3.07	2.65	3.20	1.60
60		4.15	3.30	3.40	2.15
65		4.30	3.80	3.35	3.05
70			4.30	3.40	3.25
75			4.20	4.50	3.80
80					

10.9.2. Statistics of penetration resistance

Table 10.30. Penetration resistance (N cm^{-2}) at the crop site in Lobo farm (from Flores, 1997).

Measurement depth cm	V0	V5	V10	V15	V20
Number of cases	49	49	49	49	49
Minimum	0.200	0.800	0.750	0.900	1.050
Maximum	1.450	2.900	3.900	4.300	3.650
Range	1.250	2.100	3.150	3.400	2.600
Mean	0.981	1.412	1.870	2.097	1.935
Variance	0.089	0.278	0.472	0.524	0.275
Standard deviation	0.299	0.527	0.687	0.724	0.524
Skewness (G1)	-0.493	0.908	0.491	1.146	1.217
Median	1.000	1.300	1.950	2.000	1.900

Measurement depth cm	V25	V30	V35	V40	V45
Number of cases	49	49	49	49	47
Minimum	1.150	1.050	0.900	0.800	0.900
Maximum	3.050	3.000	3.500	4.100	3.450
Range	1.900	1.950	2.600	3.300	2.550
Mean	1.818	1.884	1.872	2.005	2.207
Variance	0.209	0.244	0.267	0.503	0.501
Standard deviation	0.457	0.494	0.517	0.709	0.708
Skewness (G1)	0.864	0.570	0.943	1.398	-0.020
Median	1.750	1.800	1.800	1.900	2.150

Measurement depth cm	V50	V55	V60	V65	V70
Number of cases	42	34	20	14	1
Minimum	0.900	1.700	1.600	1.900	4.700
Maximum	4.750	4.700	4.000	4.400	4.700
Range	3.850	3.000	2.400	2.500	0.000
Mean	2.535	2.787	3.100	3.279	4.700
Variance	0.718	0.595	0.471	0.683	-
Standard deviation	0.848	0.771	0.686	0.826	-
Skewness (G1)	0.328	0.819	-0.751	-0.456	-
Median	2.450	2.675	3.225	3.425	4.700

Figure 10.35. Histograms of penetration resistance (N cm^{-2}) at the crop site in Lobo farm (V0 = 0 cm depth, etc). From Flores, 1997.

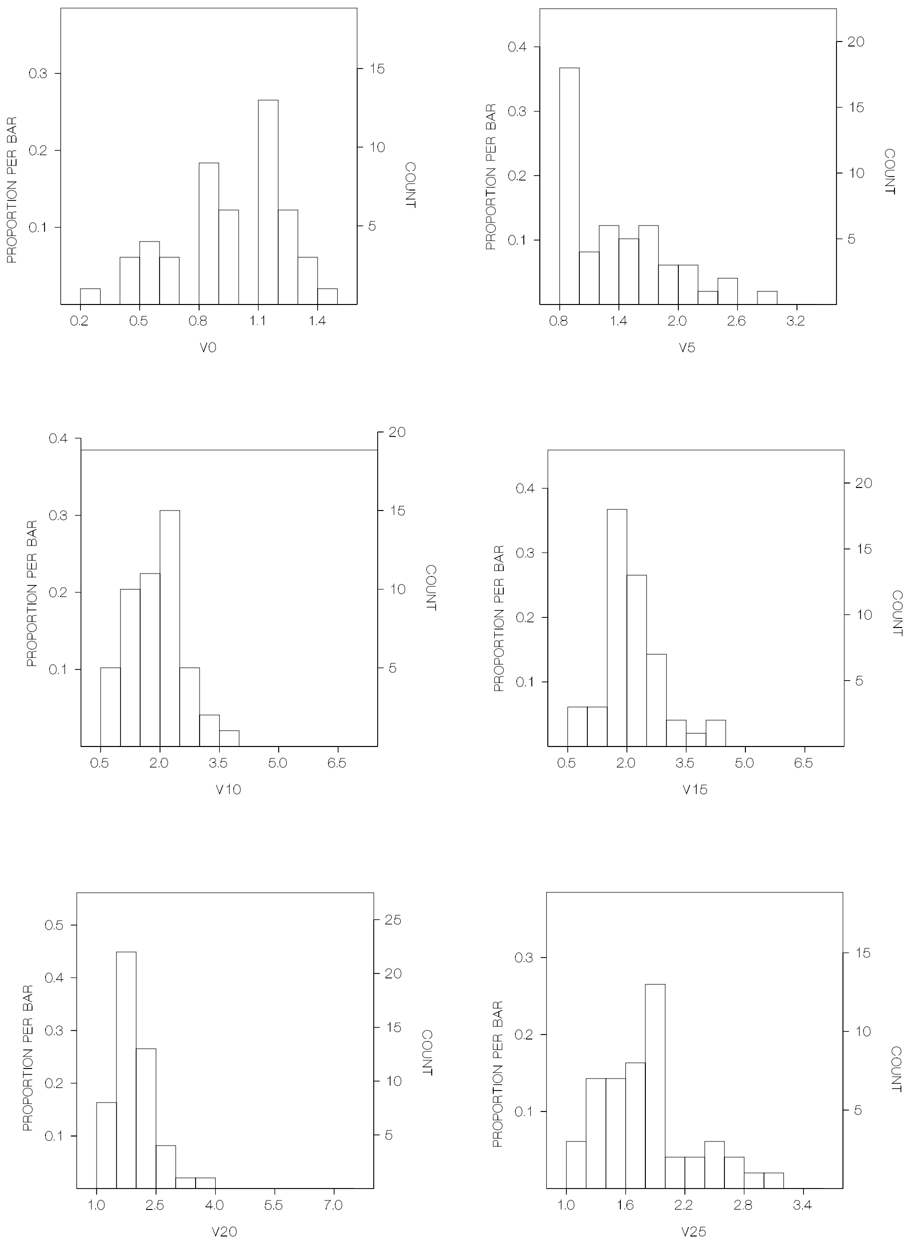


Figure 10.35. Histograms of penetration resistance (N cm^{-2}) at the crop site in Lobo farm (V0 = 0 cm depth, etc). From Flores, 1997.(continued)

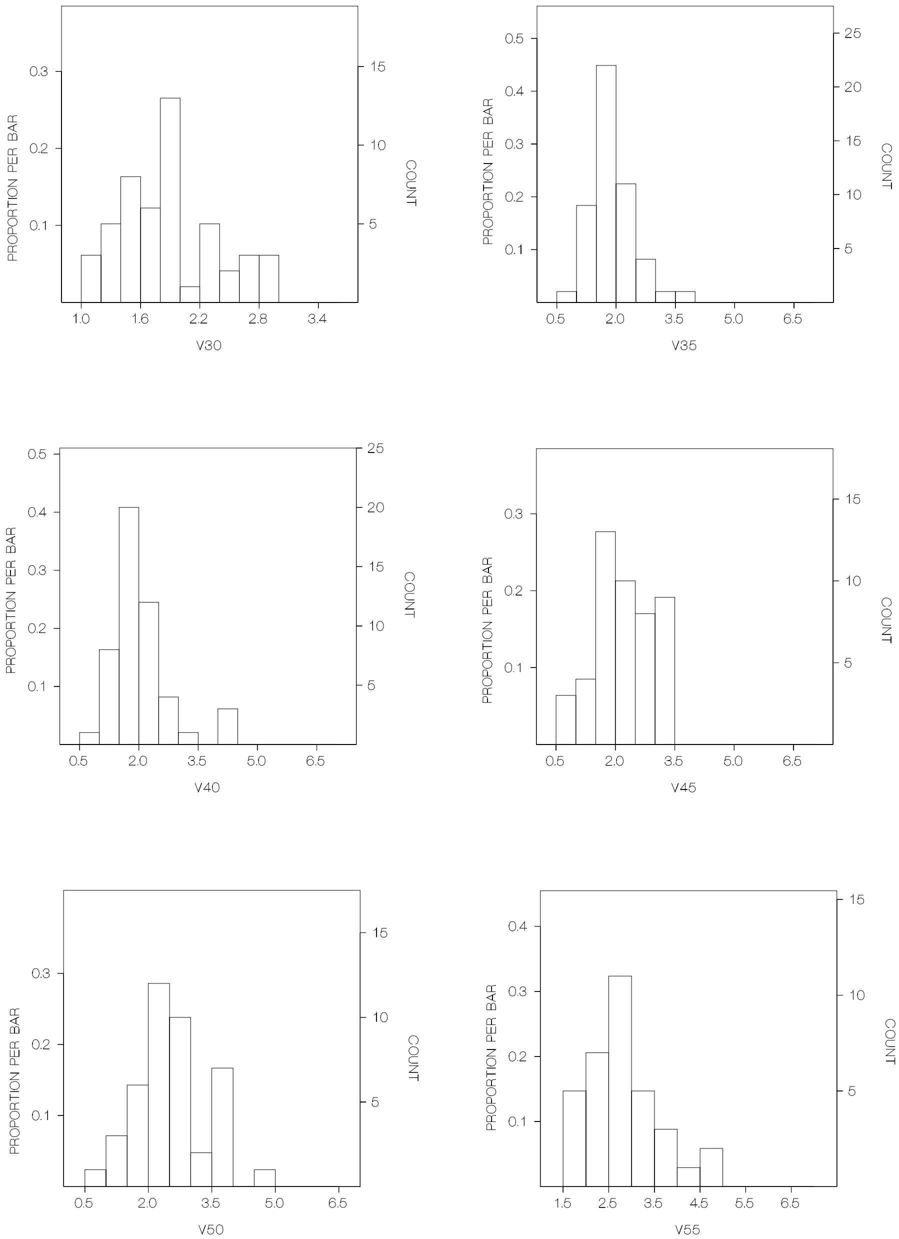


Table 10.31. Penetration resistance (N cm^{-2}) at the forest site in Lobo farm (from Flores, 1997).

Measurement depth cm	F0	F5	F10	F15	F20
Number of cases	100	100	100	100	100
Minimum	0.100	0.100	0.600	0.400	0.900
Maximum	3.600	3.700	3.400	4.450	4.100
Range	3.500	3.600	2.800	4.050	3.200
Mean	1.377	1.958	1.985	2.060	2.199
Variance	0.582	0.551	0.376	0.418	0.346
Standard deviation	0.763	0.742	0.613	0.647	0.588
Skewness (G1)	0.455	-0.112	0.045	0.740	0.529
Median	1.300	2.000	2.000	1.950	2.200

Measurement depth cm	F25	F30	F35	F40	F45
Number of cases	100	99	99	99	98
Minimum	1.250	1.400	1.400	1.300	0.850
Maximum	4.200	4.000	4.800	4.700	4.800
Range	2.950	2.600	3.400	3.400	3.950
Mean	2.397	2.549	2.904	3.166	3.272
Variance	0.425	0.346	0.465	0.440	0.602
Standard deviation	0.652	0.588	0.682	0.664	0.776
Skewness (G1)	0.471	0.519	0.528	0.017	-0.354
Median	2.300	2.500	2.900	3.100	3.300

Measurement depth cm	F50	F55	F60	F65	F70
Number of cases	91	80	55	34	12
Minimum	1.300	1.200	2.300	2.650	2.850
Maximum	4.700	4.800	4.850	4.800	4.800
Range	3.400	3.600	2.550	2.150	1.950
Mean	3.287	3.575	3.765	3.978	3.888
Variance	0.564	0.598	0.441	0.425	0.335
Standard deviation	0.751	0.773	0.664	0.652	0.579
Skewness (G1)	-0.136	-0.581	-0.278	-0.324	-0.024
Median	3.350	3.600	3.800	4.000	3.850

Figure 10.36. Histograms of penetration resistance (N cm^{-2}) at the forest site in Lobo farm (F0 = 0 cm depth, etc). From Flores, 1997.

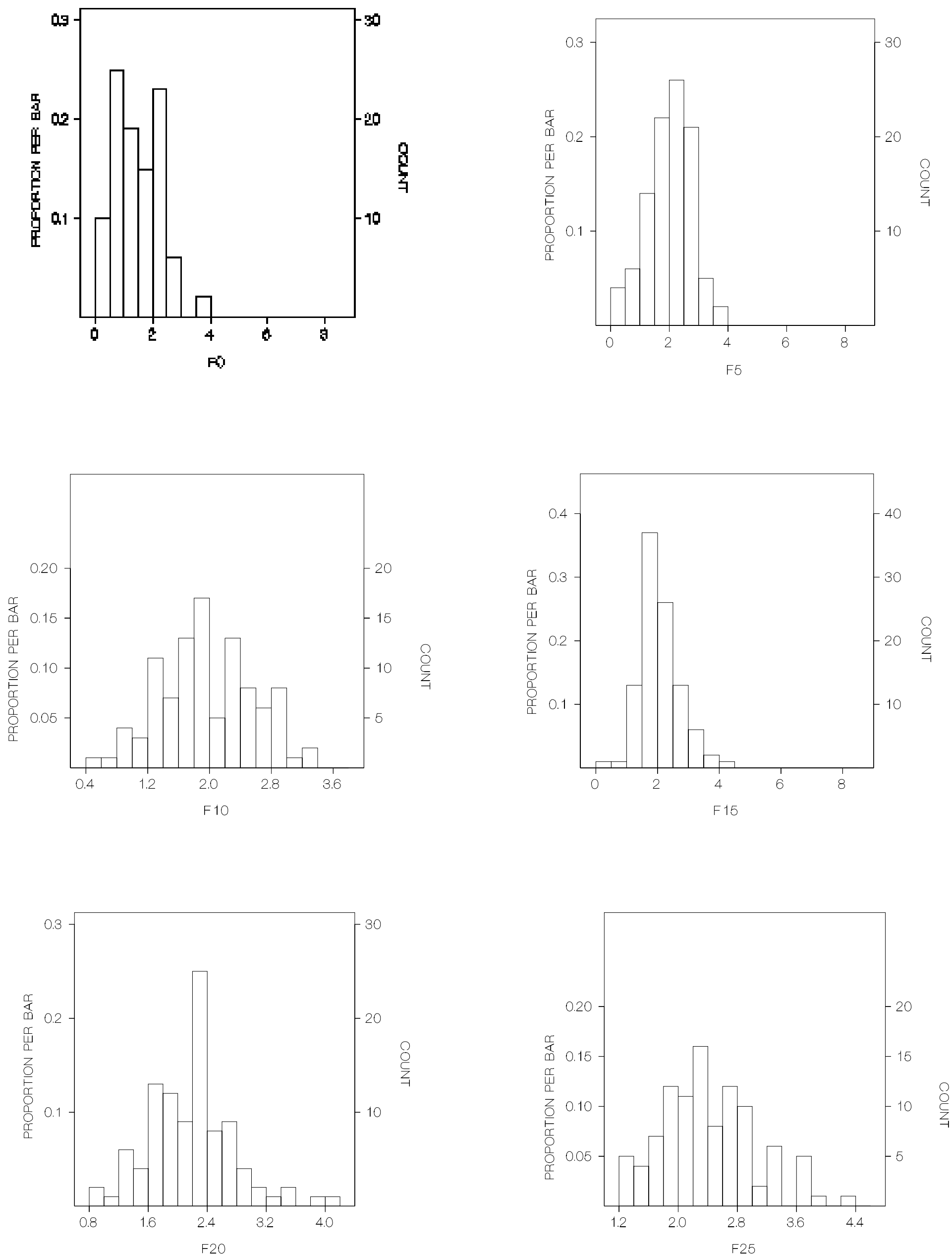


Figure 10.36. Histograms of penetration resistance (N cm^{-2}) at the forest site in Lobo farm (F0 = 0 cm depth, etc). From Flores, 1997. (continued)

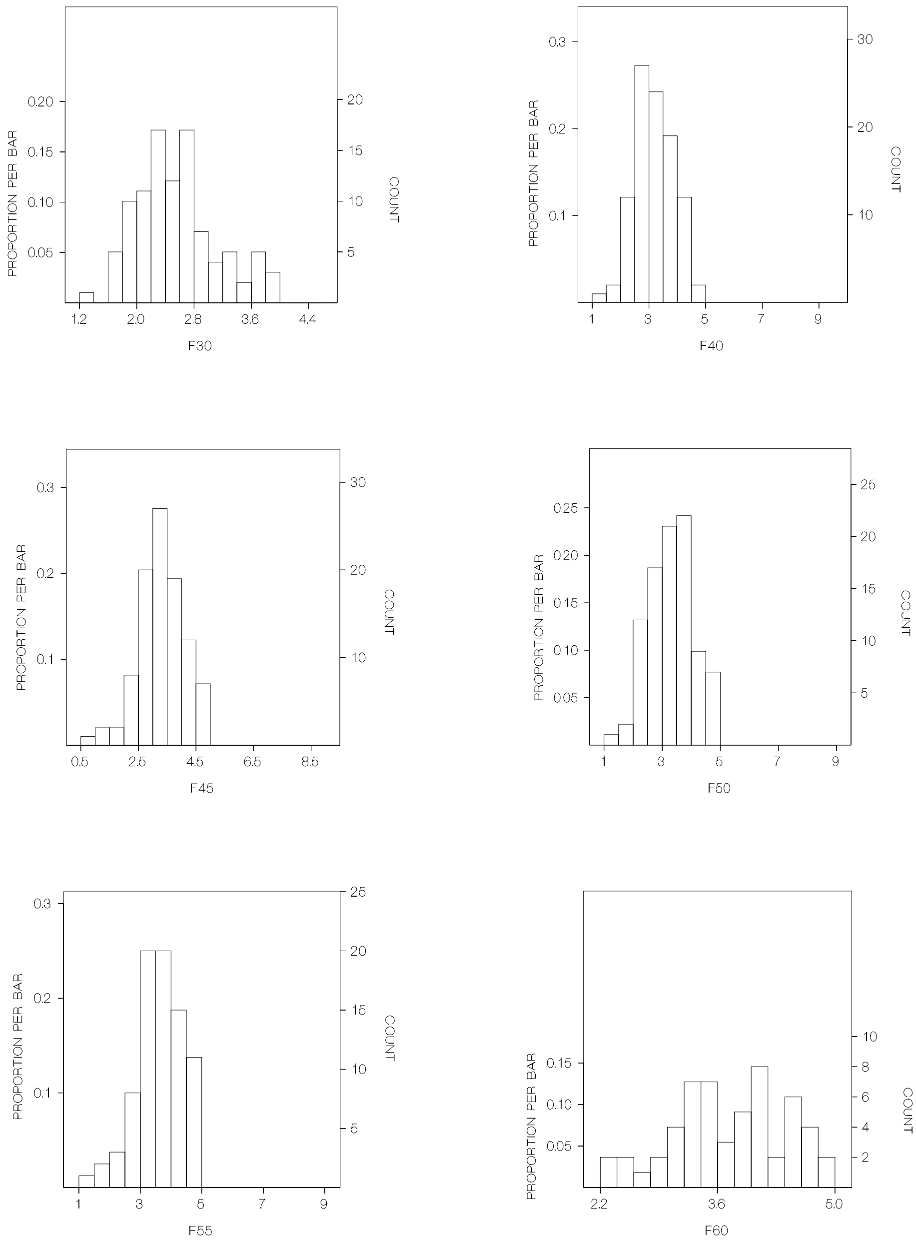
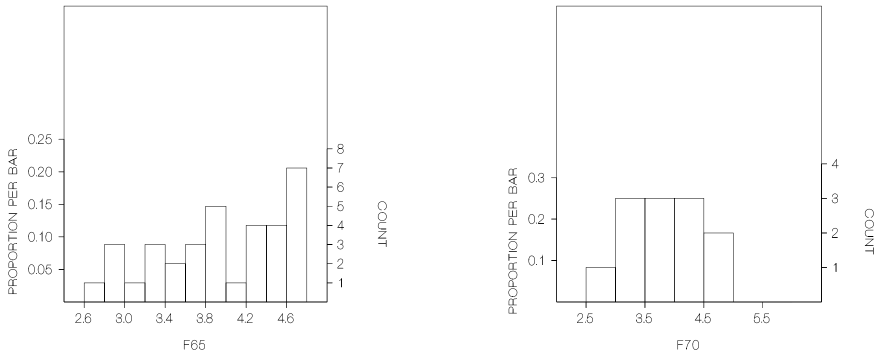


Figure 10.36. Histograms of penetration resistance (N cm^{-2}) at the forest site in Lobo farm (F0 = 0 cm depth, etc). From Flores, 1997. (continued)



CHAPTER 11

LAND SUITABILITY AND LAND USE PLANNING

L. Recatalá, J.A. Zinck

11.1. INTRODUCTION

The study area, including the largest part of the Burruyacú district, has a subtropical semiarid climate (Gomez et al., 1992). Mean annual rainfall ranges from 600 mm in the east to 800 mm in the west. There are irregular climatic cycles with mean annual rainfall lower than 150 mm (dry year) or higher than 1500 mm (rainy year). Mean annual temperature is 18-20°C. Climatic variability within the area results mainly from the influence of the mountain ranges lying to the northwest, that causes a regional gradient of rainfall increase from east to west. The western part of the area has a water surplus from December till April, while the water balance is negative in the eastern part due to lower rainfall and higher evapotranspiration.

The relief is mainly flat, including piedmont and plain landscapes. The Chaco plain with elevation of 300-500 m covers most of the study area. The western fringe belongs to the sub-Andean mountain ranges. In-between, the piedmont has elevation of 500-650 m and gentle slopes facing southeast.

A Precambrian crystalline basement and Tertiary sedimentary cover layers constitute the geology of the study area. The piedmont and Chaco plain are formed by alluvial, colluvial and eolian deposits. Loess rich in volcanic glass is the main cover material. During the Quaternary, loess was spread over large areas in the Pampa and Chaco plains of Argentina (Teruggi, 1975; Clapperton, 1993; Imbelloni & Teruggi, 1993; Sayago et al., 1996).

Fertile soils have developed mainly from loess deposits. Mollisols are the dominant soils, followed by Entisols (Gomez et al., 1992). The soil moisture regime varies from aridic bordering ustic in the east to udic in the west. A soil map established in 1992 (Gomez et al., 1992) was used to delineate the perimeter of the study area.

Natural vegetation changes gradually from east to west according to rainfall increase from scrubland to Chaco forest to subtropical forest. The Chaco forest, which is located east of the 800 mm rainfall line, dominates in the study area (Zuccardi & Fadda, 1972).

Soybean is the most important crop, followed by maize, wheat, citrus, sugarcane and safflower. Agriculture is mainly rain-fed, although sugarcane, soybean and citrus are also found irrigated in places where water resources are available. Soybean and maize are summer crops, whereas wheat is cultivated in winter (Zuccardi & Fadda, 1985). The Chaco forest is exploited for timber extraction and livestock browsing (Gomez et al., 1992).

At present, crop production is the most important economic activity in the study area, resulting from the rapid expansion of agriculture since the early 1970s. The main factors favouring this expansion were population increase, attractive market prices, easy accessibility, favourable annual rainfall, fertile soils and adapted land tenure (Minetti & Sierra, 1983). The extension of cropland has resulted in substantial reduction of the Chaco forest, while causing physical land degradation, especially soil compaction under mechanized farming. From 1971 to 1991, over 57,000 ha of forest have been converted to cropland (Flores, 1997).

Market conditions were the main factor controlling the crop pattern and promoting especially soybean production, while local institutions (e.g. the Agricultural Experimental Station of Tucumán, University of Tucumán) had started supporting soybean since the 1960s (Flores, 1997).

In view of the fast land use changes taking place in the area, together with the lack of any kind of land use control and monitoring, the threat the land use changes represent for the preservation of the Chaco forest and the land degradation they are causing, it was considered opportune to carry out an evaluation of the land suitability to support land use planning and identify alternative land use options to soybean monoculture.

11.2. LAND SUITABILITY FOR AGRICULTURAL USES

11.2.1. Introduction

Land evaluation supports land use planning by providing information on the land use potential for selected land utilization types. As pointed out by FAO (1976), "the land evaluation process does not itself determine the land use changes that are to be carried out, but provides data on which such decisions can be taken".

The FAO framework for land evaluation (FAO, 1976) provides principles and procedures for assessing the potential of land (or land suitability). The framework was developed to achieve standardization of the usually dispersed and non-exchangeable information derived from the particular and specific land evaluation approaches of each country. The worldwide success of the FAO framework and the subsequent guidelines for applying it in diverse types of land uses and land areas (FAO, 1983; 1984; 1985; 1991) further encouraged its use (Johnson & Cramb, 1991; Sys et al., 1991; León, 1992; Rossiter, 1996).

The FAO framework refers to two kinds of land suitability: physical and economic. Physical suitability emphasizes the relatively permanent factors of land suitability, such as climate, landscape and soil, irrespective of economic conditions. Although the FAO framework states that the evaluation process should include both kinds of suitability because land use decisions are very often based on economic considerations, it may be difficult to follow this principle when information on economic conditions is not available. In such cases, the advantage of a physical land suitability evaluation is that the results do not change as quickly as they do when economic conditions are taken into account. There is also the possibility of carrying out a physical land suitability evaluation in the first stages of the land use planning process and then take into account the economic conditions in later stages when dealing with the formulation of planning policies for developing alternative land use options. This approach is particularly useful when specific economic data are missing but trends are known and can be considered in defining planning policies.

Using the FAO framework, a physical land suitability evaluation was carried out in the Burruyacú district. Located in the Chaco plain at the foothills of the sub-Andean mountain ranges, the area presents favourable conditions for agriculture. Crop patterns are strongly influenced by market prices (Minetti & Sierra, 1983; Flores, 1997), but other factors such as population increase, accessibility, annual rainfall, soils and land tenure also contributed to the rapid expansion of the agricultural frontier over the last decades, with main crops being soybean, maize, wheat, sugarcane, citrus and safflower. This has resulted in a drastic reduction of the forest area, causing conflicts between farming and the conservation and management of the Chaco forest.

Both physical and economic land suitability evaluations were initially planned to be carried out. For the purpose of collecting data on the economic conditions of the farming activity in the area, such as capital intensity, power sources, income levels, land tenure, technology employed, among other features, a questionnaire was distributed to the landholders, generating unfortunately very few answers. This is an issue frequent in developing countries where landholders are not involved in regional land use planning and do not feel confident in providing information concerning their management systems. As a consequence, only a physical land suitability evaluation was carried out.

The FAO framework for land evaluation allows the classification of land into suitability classes from highly suitable to permanently not suitable, reflecting increasing land limitations for specific land utilization types. The evaluation of the soil map units of the study area provided a basis for developing land use options that can address the issue of land use conflicts through land use planning.

11.2.2. Soil database

To assess the land suitability of the area, use was made of the soil map prepared by INTA at scale 1:77,000 (Gomez et al., 1992). The map was digitized using the ILWIS software (ITC, 1997) (Figure 11.1). Soil information comprised a set of non-overlapping polygons belonging to 23 different map units, established and delineated on the basis of soil-landscape relationships. Each map unit was composed of two or three soil phases, except for a few units characterized as undifferentiated soil groups. Each map unit, including its soil phases, was assessed individually. Undifferentiated soil groups and units representing riverbeds, streams and infrastructures, were not evaluated for land use suitability.

Climate, landscape and soil parameters were used for assessing the physical land suitability of the map units for the selected land utilization types. The rainfall of the growing cycle (1st, 2nd, 3rd and 4th months) was used for some crops (e.g. soybean, maize), while the mean annual rainfall was used for others (e.g. citrus, safflower). Climate data were taken from rainfall time series recorded at Gobernador Piedrabuena, Siete-de-Abril, Burruyacú, La Ramada, Benjamín Aráoz and El Puestito. Landscape data included slope and flooding risk. Soil data comprised drainage, texture, structure, coarse fragments, soil depth, percentage of carbonate, apparent CEC (cationic exchange capacity), base saturation, sum of basic cations, soil reaction (pH in water), organic carbon, salinity and alkalinity. Landscape and soil data were extracted and/or elaborated from the soil survey report of INTA (Gomez et al., 1992). Table 11.8 in Appendix contains the database used for land evaluation.

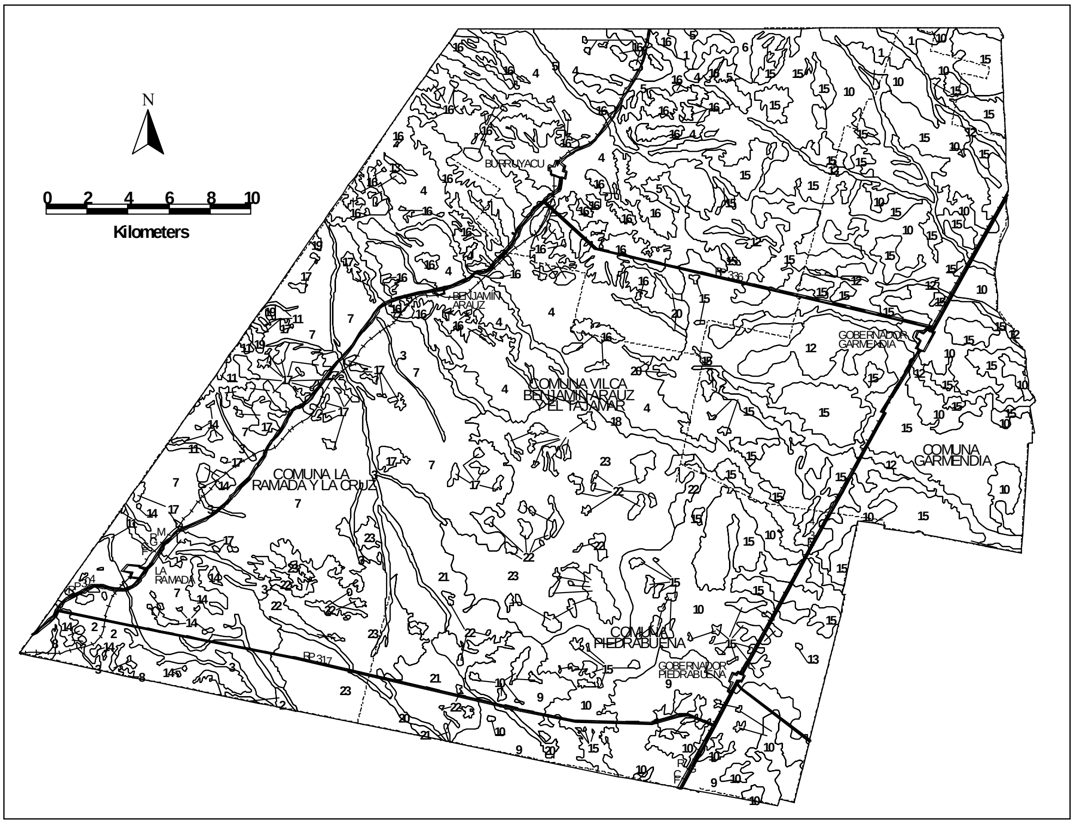


Figure 11.1. Soil map of Burruyacú district (INTA, 1992).
Numbers refer to soil map units and letters to local names given to soil units by INTA. 1-Abr (7-de-Abril), 2-Ald (Alderete), 3-BA (Benjamín Aráoz), 4-BU (Burruyacú), 5-Chi (Chilcas), 6-EA (El Atacal), 7-EC (El Chañar), 8-ETi (El Timbo), 9-Ga (Garmendia), 10-GP (Gobernador Piedrabuena), 11-HV (Huerta Vieja), 12-Jul (Juliana), 13-L (Lagunas), 14-LC (La Cruz), 15-LEz (La Esperanza), 16-LMo (Los Morros), 17-LR (La Ramada), 18-NT (Ríos Nio-Tajamar), 19-PMo (Padre Monti), 20-SGe (San Gerónimo), 21-Taj (El Tajamar), 22-TP (Tala Pozo), 23-Vir (Virginia).

11.2.3. Evaluation procedure

(1) Land utilization types and land use requirements

Following the procedure of the FAO framework (FAO, 1976), land map units were matched with selected land utilization types. Land utilization types should be relevant for the study area. According to this principle, the following land utilization types were first selected, including soybean, maize, wheat, sugarcane, citrus and safflower. Alfalfa was added to the list as possible green manure to be opportunely grown, in crop rotation or alone, in map units affected by physical soil degradation. Although the Chaco forest is the native vegetation in the study area and could be thus considered in first instance as the most appropriate land use in all map units, it was assessed for the purpose of natural regeneration in comparison with the other land utilization types. The soil map provided the land map units for the suitability assessment.

Land utilization types are described by a set of land use requirements, which are the land conditions necessary for successful farming. Land map units are described by a set of land characteristics, which are land attributes that influence land suitability for given land utilization types.

Land use requirements, in terms of climate, landscape and soil, for the selected land utilization types (crops) were taken from Sys et al. (1993). Although the reference tables provided by the above-mentioned authors should be considered as mere guidelines and be critically reviewed and possibly adapted to specific area conditions, they were applied here without further modifications in view of the lack of appropriate local data. Land use requirements for the natural regeneration of the Chaco forest were created from expert experience (Table 11.9 in Appendix).

(2) Land suitability assessment steps

The soil map units could not be directly matched to the land utilization types, as the former were composite units including different kinds of soil in variable proportions. For this reason, the suitability assessment was carried out in two steps. First, the soil phases of each map unit were matched to the land utilization types. Then, a comprehensive land suitability class for each land utilization type was determined for each map unit as a function of the percentages of the soil phases and their specific suitability classes.

In the first step, a major-limitation approach was used to establish the land suitability class of each soil phase for each land utilization type. Thus, the land suitability class of a soil phase was determined by the most severely limiting characteristic. Using this approach, a rapid and realistic qualitative evaluation was achieved.

In the second step, a weighting-rating method was applied to evaluate the land suitability classes of the map units, based on the percentage of each soil phase in a given map unit and the suitability class of that soil phase. The percentages of soil phases were considered as weights, since they expressed the importance of each soil phase in each map unit. The suitability classes of the soil phases were considered as rates. To apply the weighting-rating method, it was necessary to express suitability classes in numerical values. For that purpose, the rating scale proposed in the tables of crop requirements was used (Sys et al., 1993). The average of the two values defining a suitability class in the rating scale was assigned to each soil phase according to its suitability class. To scale the values between 0 and 1 after application of the assessment procedure, the weights were divided by 100. The suitability class of each map unit for each crop was established by matching the numerical value obtained to the rating scale of the tables.

According to the cropping trends in the study area, maize, wheat, alfalfa and safflower were considered as rain-fed crops, sugarcane as irrigated crop, and soybean and citrus as both rain-fed and irrigated crops. Land suitability for irrigated cropping was carried out considering the case of furrow irrigation.

As the mean annual rainfalls are extremely variable in relatively short periods of time, with cycles of dry years and cycles of rainy years lasting about 9-10 years, land suitability assessment took into account this factor to determine the adaptability of the selected crops to the study area under extreme climatic conditions. In rainy years, it was considered that the flooding risk would increase land limitation by one degree (e.g. from moderate to high) in the most vulnerable map units (e.g. map units with flat topography and adjacent to riverbeds).

The assessment results were expressed in four physical land suitability classes. The currently and permanently non-suitable classes (N1 and N2) were merged into one non-suitable class (N), because some land characteristics (e.g. percentage of coarse fragments) were reported in the land requirement tables with the same degree of limitation for both classes, so that no distinction between N1 and N2 was possible.

11.2.4. Results and discussion

(1) Physical limitations to cropping

Land units highly suitable for most of the rain-fed crops cover only 16.4% of the study area, reflecting the impact of the physical restrictions on the productivity of the selected crops (Figures 11.2, 11.3 and 11.4). The most important limitations for cropping are limited rainfall and risk of flooding in the east of the area, and flooding and topography (slope) in the west. While an annual water surplus favours the west, coinciding with the growing cycle of most of the crops, the water balance is negative in the east, causing moderate (e.g. soybean, maize) to severe (e.g. citrus) limitation to crop adaptability. Flooding is a severe farming limitation in the units located near riverbeds or in piedmont areas exposed to overland flow during the rainy season. Topography is a severe limitation in the units with steep slopes, located in the piedmont adjacent to the mountain ranges.

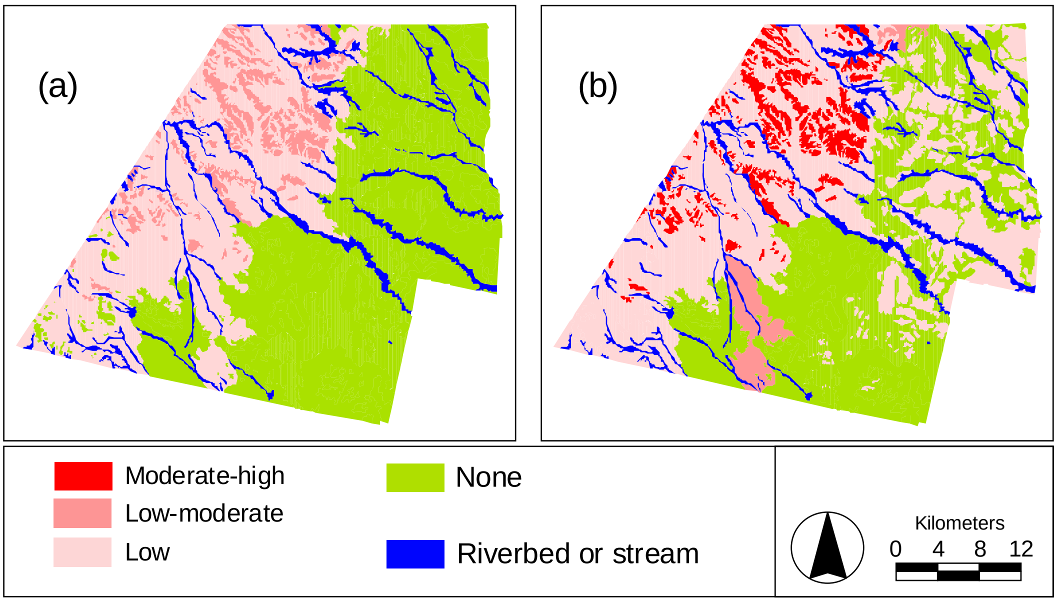


Figure 11.2. Current (a) and potential (b) soil erosion in Burruyacú district.

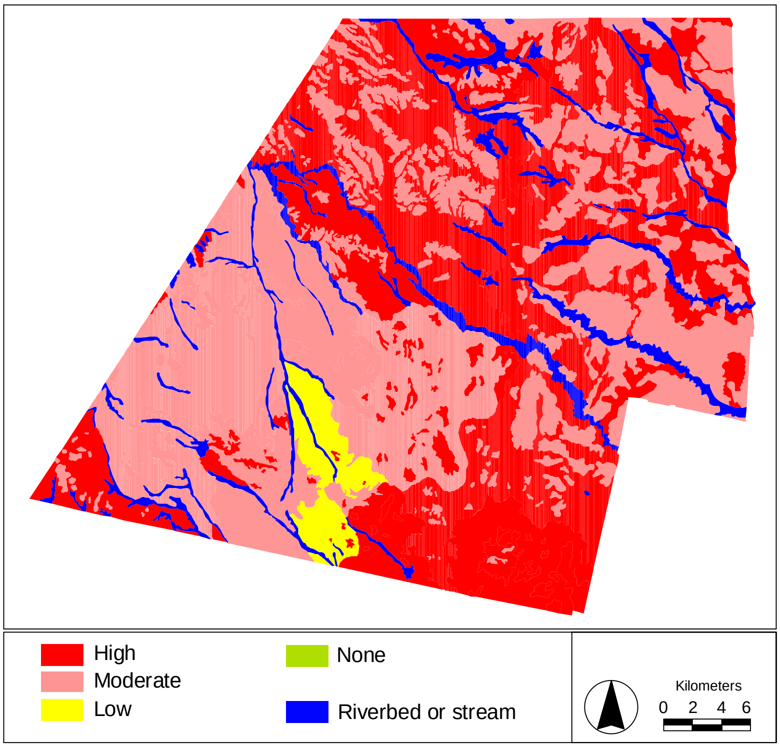


Figure 11.3. Soil susceptibility to physical degradation in Burruyacú district.

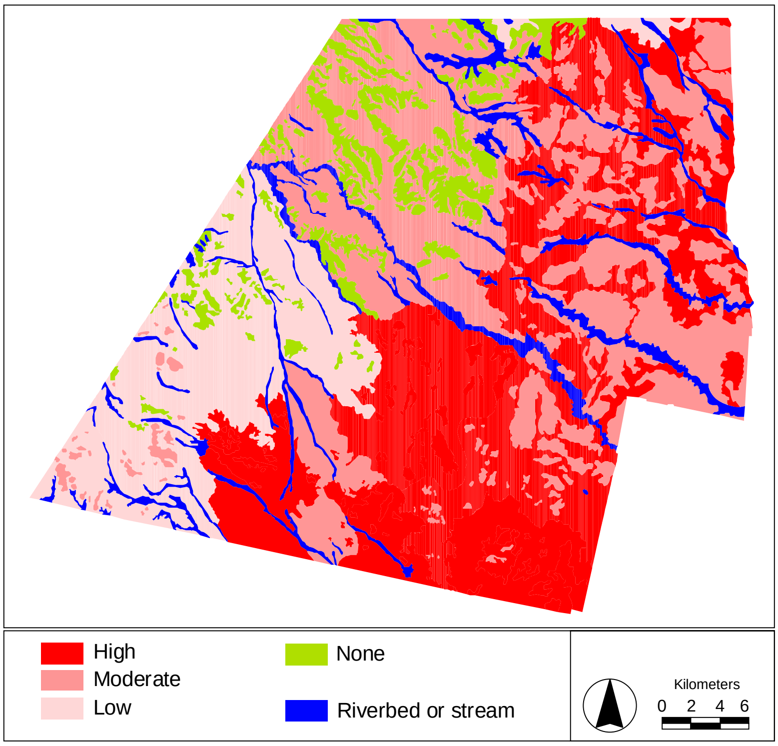


Figure 11.4. Flooding risk in Burruyacú district.

(2) Physical land suitability for selected crops

Tables 11.1 and 11.2 show the physical land suitability of the map units for each land utilization type under rain-fed and irrigated conditions, respectively (see Tables 11.10 and 11.11 in Appendix for details). These tables were introduced into the ILWIS software (ITC, 1997) to produce automatically several sets of land suitability maps. Figures 11.5, 11.6, 11.7 and 11.8 show the land suitability for rain-fed crops, irrigated crops and natural regeneration of the Chaco forest, respectively.

Wheat is the best adapted crop in view of less restrictive climate, landscape and soil requirements. In contrast, citrus is the least adaptable crop because of climate limitation in the east and a combination of climate, flooding and topography in the west.

Soybean, maize and alfalfa present similar cropping possibilities as they have similar land requirements. High physical land suitability for these crops is achieved in the southwest where climate, soil and landscape offer the most favourable cropping conditions, including water surplus coinciding with the growing season, good physical and chemical soil properties, flat or smooth topography, and no flooding risk. Physical land suitability is moderate in the east of the area, with negative water balance, presence of coarse fragments, unfavourable texture and flooding risk. Land suitability is marginal mainly in the northwest because of severe cropping limitations due to shallow soil depth, abundance of coarse fragments, steep slopes and flooding by overland flow (excessive water flow from adjacent mountain ranges during rainy periods).

Physical land suitability for safflower is moderate in almost all the study area. Climate causes moderate limitation in the west because of excess water in the last month of the growing cycle, whereas the presence of coarse fragments, unfavourable soil pH and flooding represent moderate limitations in the flat areas of the east.

Physical land suitability for natural regeneration of the Chaco forest shows a spatial distribution similar to that of soybean, maize and alfalfa. This means that the map units having the best land conditions for annual crops, such as seasonal water surplus, good physical and chemical soil characteristics, and flat or smooth topography, are also the most suitable for natural regeneration of the native vegetation, while map units with severe land limitations for cropping, such as steep slopes, shallow soils and high flooding risk, are also less favourable for the recovery of the Chaco forest. However, on the basis of its original distribution before deforestation, native vegetation can be expected to recover everywhere with different levels of success.

The spatial pattern of land suitability for irrigated soybean is the same as that for irrigated sugarcane, as both crops have similar land requirements for irrigation. Irrigated citrus has less potential due to more restrictive land requirements (e.g. slope and soil depth).

Table 11.1. Land suitability for rain-fed agriculture.

Map unit	Soybean	Soybean -alfalfa	Maize	Maize-alfalfa	Wheat	Alfalfa	Citrus	Safflower
1	S2	S2	S2	S2	S3	S2	N	S2
2	S1	S1	S1	S1	S1	S1	S3	S2
4	S3	S3	S3	S3	S2	S3	N	S2
6	S2	S2	S2	S2	S2	S3	N	S2
7	S1	S1	S1	S1	S1	S1	S3	S2
9	S2	S2	S2	S2	S2	S2	N	S2
10	S2	S2	S2	S2	S2	S2	N	S2
14	S3	S3	S3	S3	S3	S3	S3	S3
15	S2	S2	S2	S2	S2	S2	N	S2
16	S3	S3	S3	S3	S3	S3	S3	S3
17	S3	S3	S3	S3	S3	S3	S3	S3
19	S3	S3	S3	S3	S3	S3	N	N
21	S3	S3	S3	S3	S2	S3	N	S2
22	S3	S3	S3	S3	S2	S3	N	S2
23	S2	S2	S2	S2	S1	S2	N	S2

Missing map units correspond to riverbeds, streams and narrow floodplains that have not been evaluated; S1, S2, S3 and N refer to levels of land suitability from high to low.

Table 11.2. Land suitability for irrigated agriculture.

Map unit	Soybean	Citrus	Sugarcane
1	S2	S2	S2
2	S2	S2	S2
4	S3	N	S3
6	S3	S3	S3
7	S2	S2	S2
9	S2	N	S2
10	S2	N	S2
14	S3	S3	S3
15	S2	S3	S2
16	N	N	N
17	N	N	N
19	N	N	N
21	S3	N	S3
22	S3	N	S3
23	S2	N	S2

Missing map units correspond to riverbeds, streams and narrow floodplains that have not been evaluated; S1, S2, S3 and N refer to levels of land suitability from high to low.

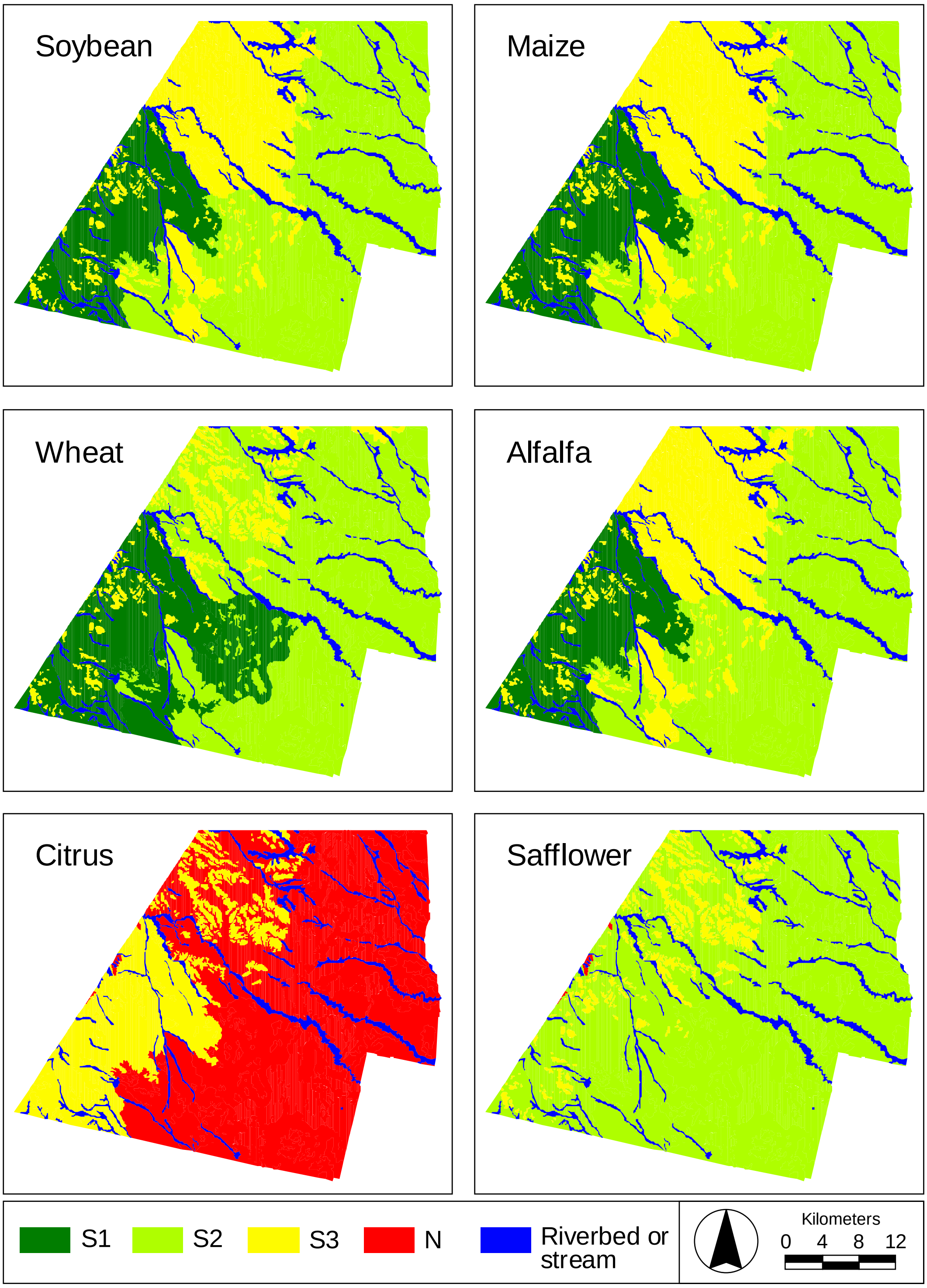


Figure 11.5. Physical land suitability for selected rain-fed crops in Burruyacú district (S1, S2, S3 and N refer to levels of land suitability from high to low).

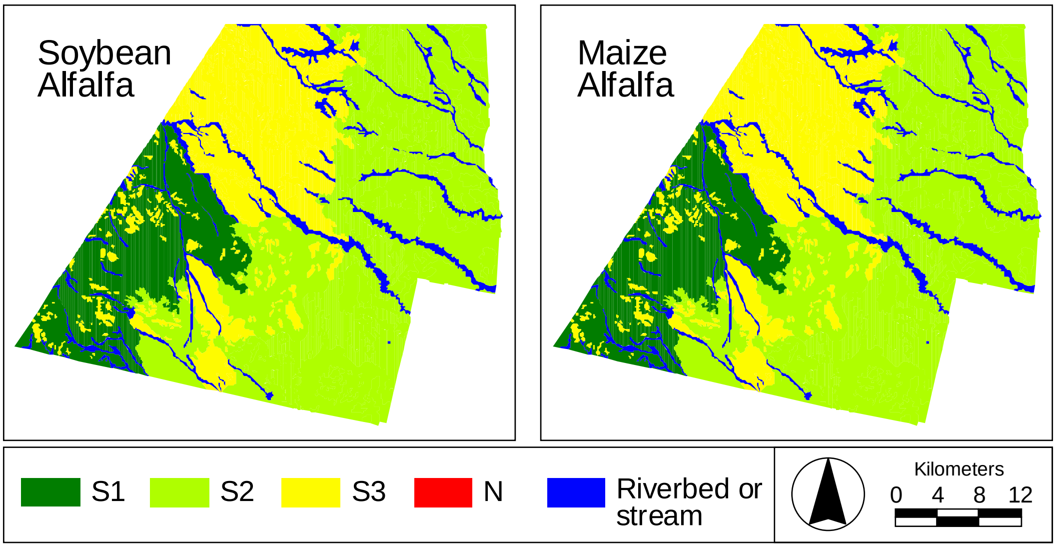


Figure 11.6. Physical land suitability for selected rain-fed crop rotations in Burruyacú district (S1, S2, S3 and N refer to levels of land suitability from high to low).

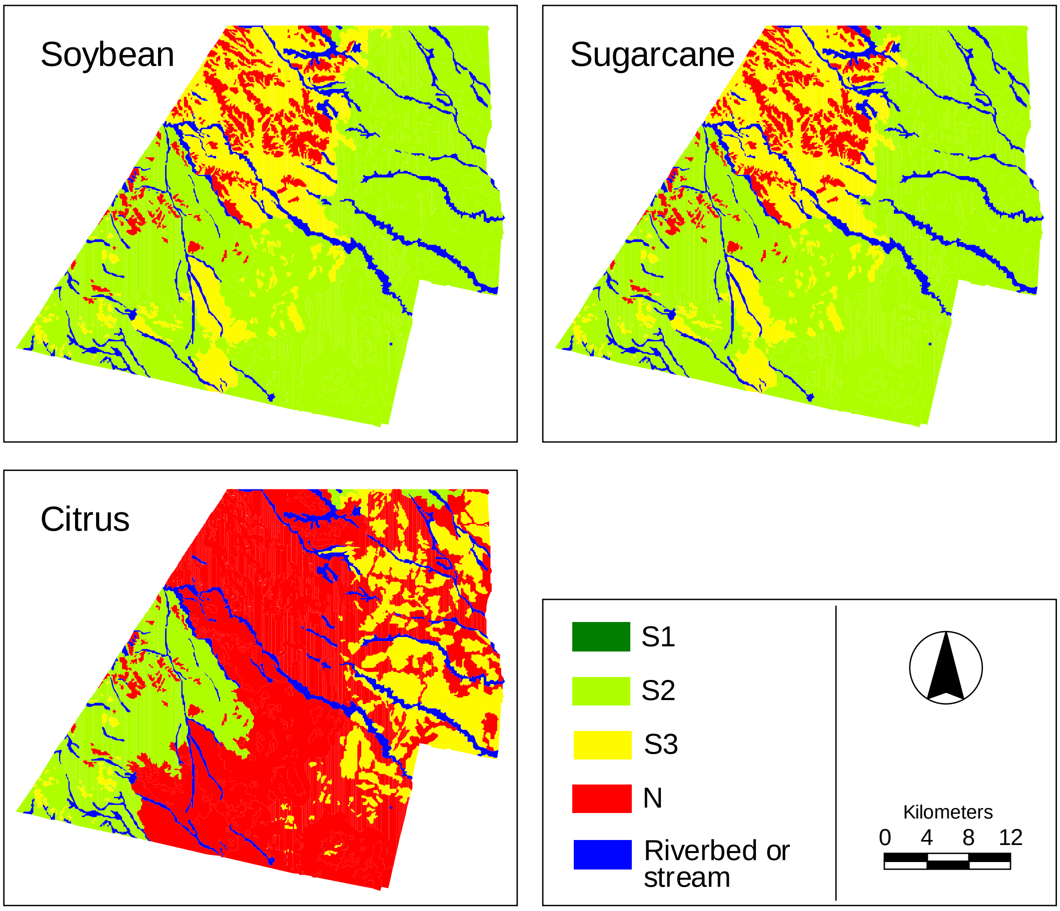


Figure 11.7. Physical land suitability for selected irrigated crops in Burruyacú district (S1, S2, S3 and N refer to levels of land suitability from high to low).

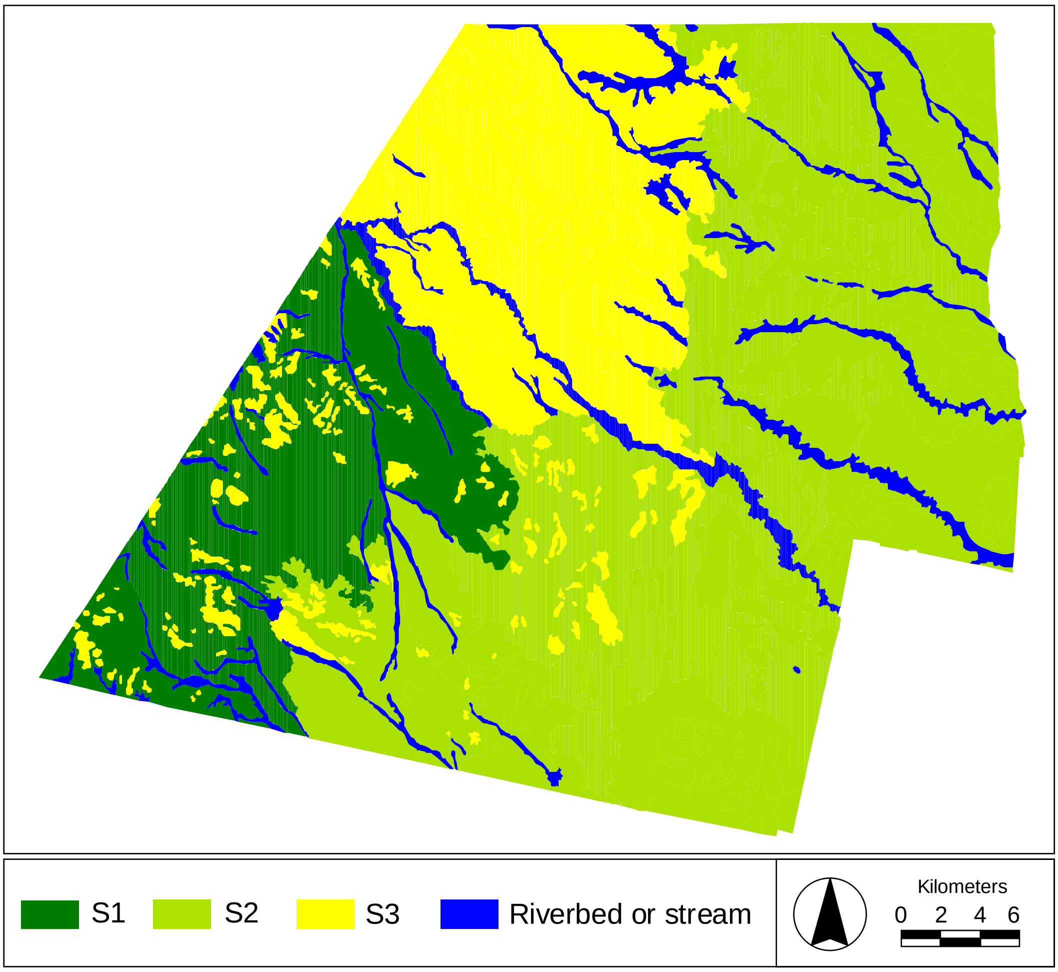


Figure 11.8. Physical land suitability for natural regeneration of the Chaco forest in Burruyacú district (S1, S2, S3 and N refer to levels of land suitability from high to low).

(3) Rain-fed versus irrigated farming

In Figures 11.9 and 11.10, expected yields of soybean and citrus under rain-fed and irrigated conditions, respectively, are compared. For the same suitability class, both crops generate higher yields when irrigated. Thus, in places where water is available, it would be more cost-effective or profitable to switch to irrigated agriculture. However, changing from rain-fed to irrigated farming could also create new risks, especially in sloping areas, causing for instance increased soil loss under irrigated soybean cropping if furrow irrigation were used instead of drip irrigation (Figure 11.11). In contrast, irrigation improves physical land suitability for citrus in some map units, otherwise marginally suitable or even non-suitable for rain-fed citrus, as water supply would attenuate the prevailing climate limitation (Figure 11.12).

As rainfall varies over relatively short periods of time, with recurrent cycles of dry and rainy years, land suitability for the selected crops was also assessed under extreme climatic conditions. Under rainy-year conditions, almost all the study area is non-suitable or marginally suitable for most of the crops, including soybean, maize, alfalfa and citrus, but with less effect on wheat and safflower as these crops are less sensitive to wetness (Figure 11.13 and Table 11.3; see Table 11.12 in Appendix for details). Under dry-year conditions, the study area is non-suitable for all crops except safflower, more drought-resistant.

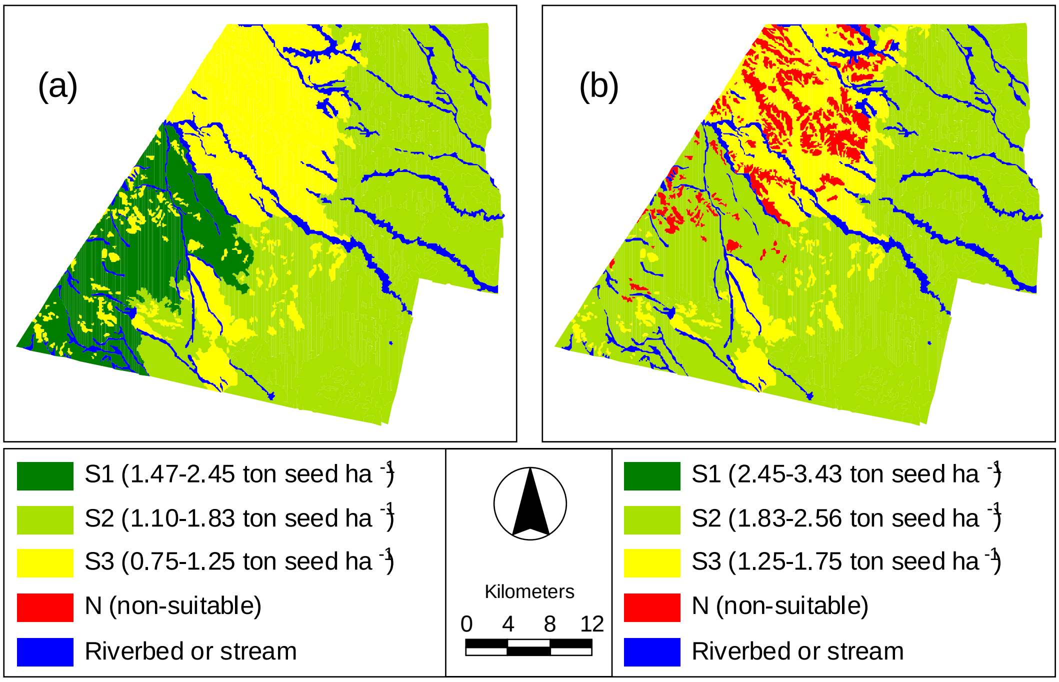


Figure 11.9. Physical land suitability and expected yields for (a) rain-fed and (b) irrigated soybean in Burruyacú district (S1, S2 and S3 refer to levels of land suitability from high to low).

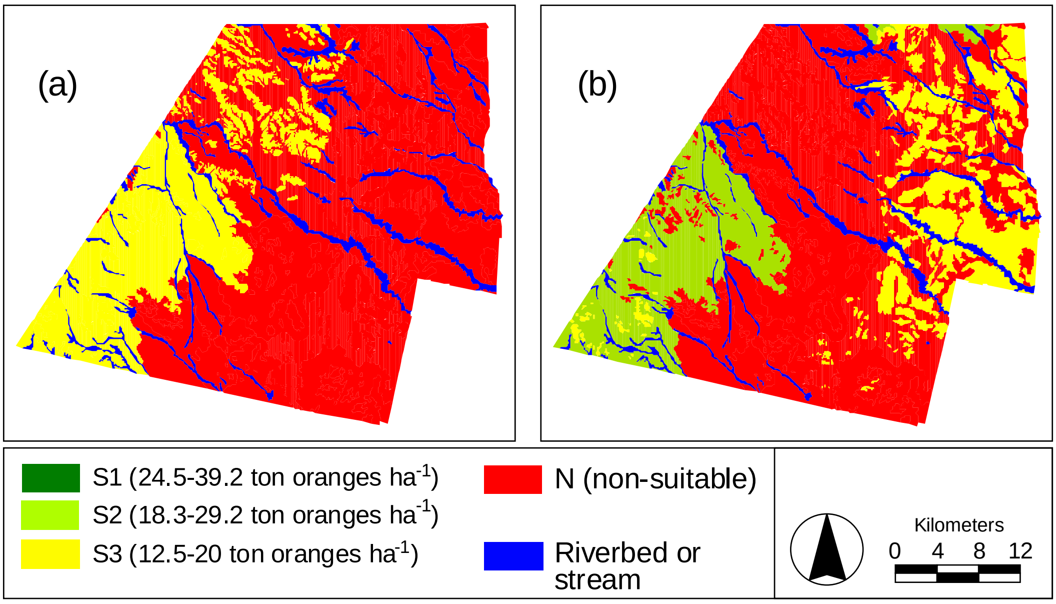


Figure 11.10. Physical land suitability and expected yields for (a) rain-fed and (b) irrigated citrus in Burruyacú district (S1, S2 and S3 refer to levels of land suitability from high to low).

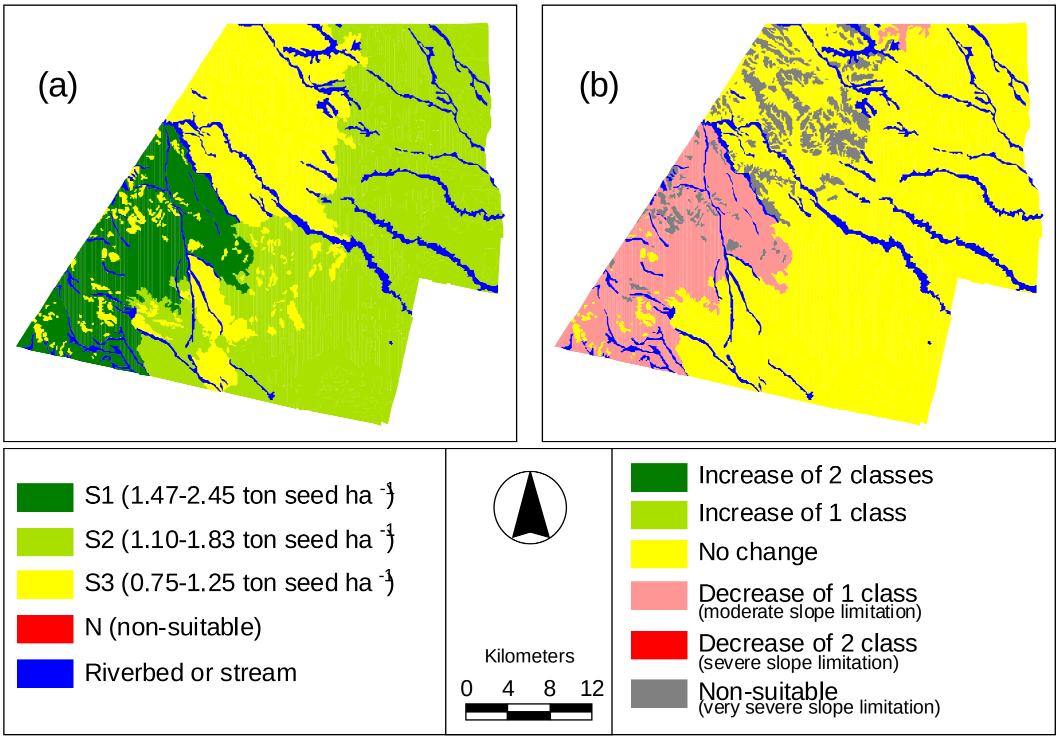


Figure 11.11. Changes in physical land suitability from (a) rain-fed to (b) irrigated soybean in Burruyacú district (S1, S2 and S3 refer to levels of land suitability from high to low).

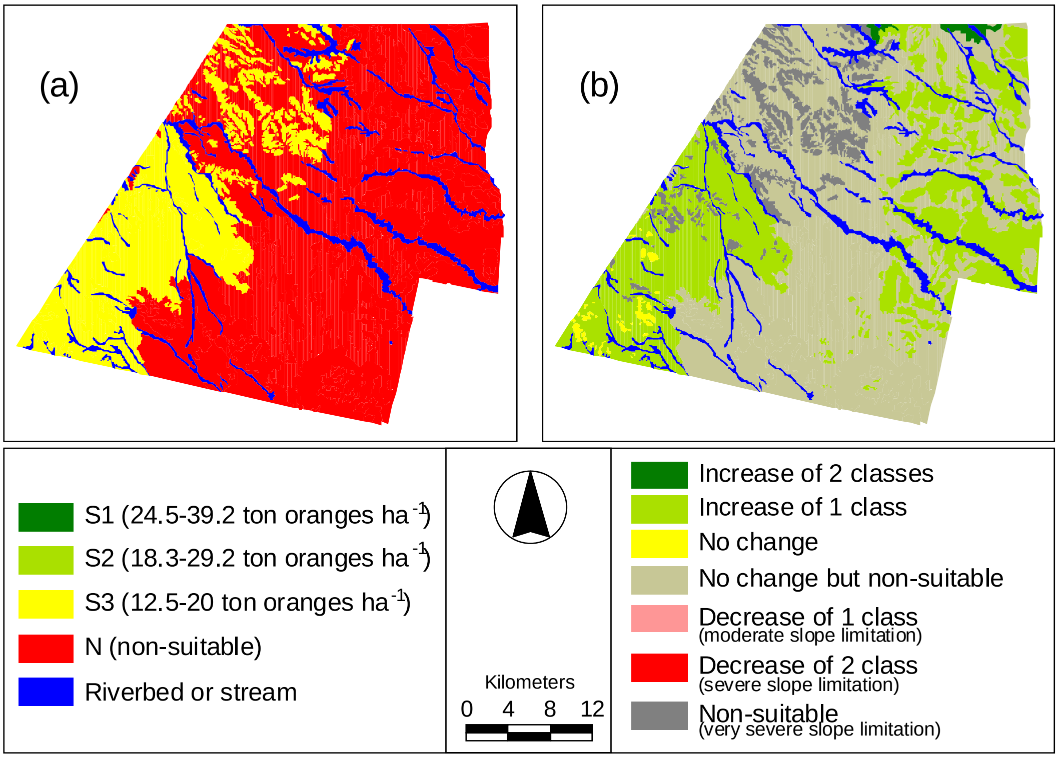


Figure 11.12. Changes in physical land suitability from (a) rain-fed to (b) irrigated citrus in Burruyacú district (S1, S2 and S3 refer to levels of land suitability from high to low).

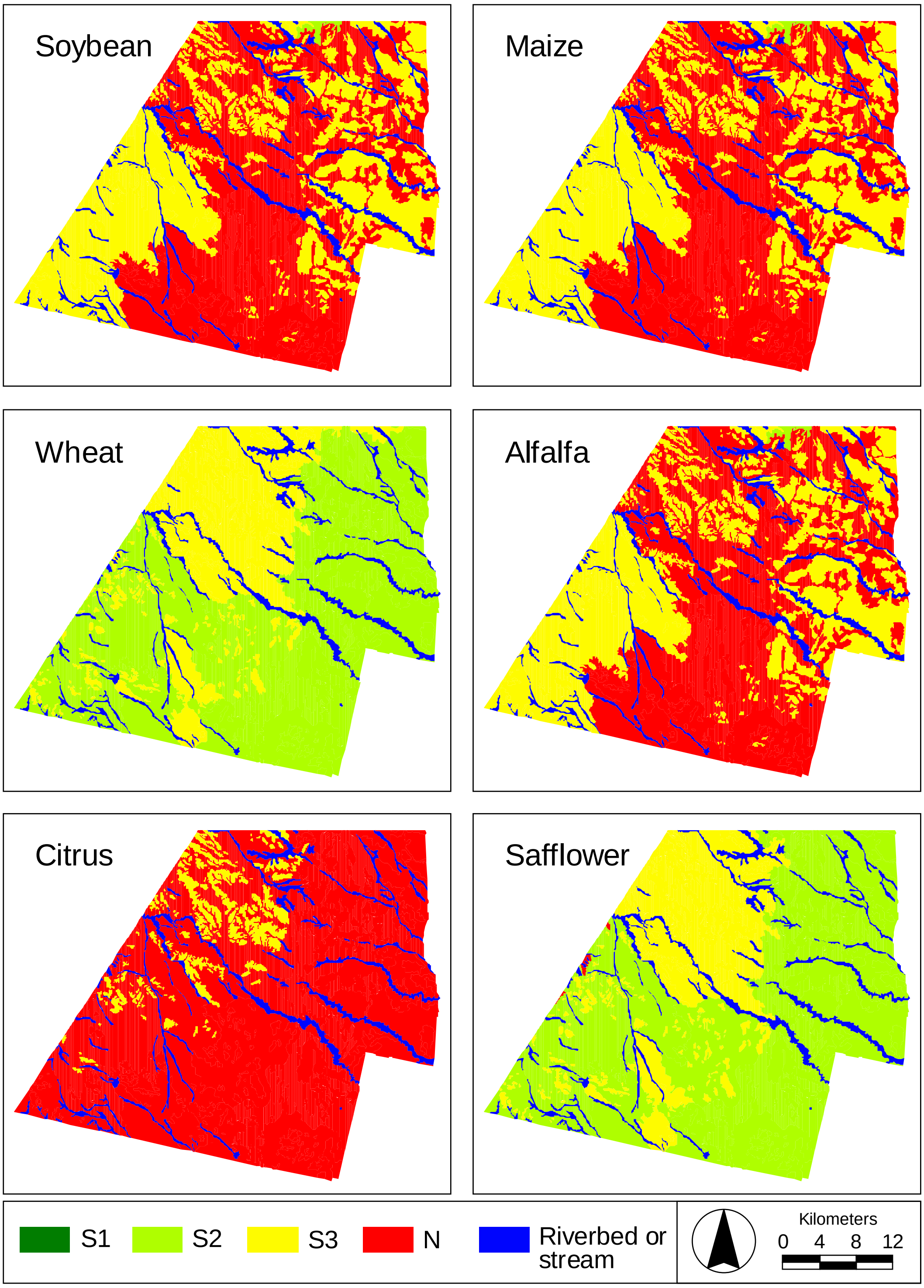


Figure 11.13. Physical land suitability under rainy-year conditions for rain-fed crops in Burruyacú district (S1, S2, S3 and N refer to levels of land suitability from high to low).

Table 11.3. Land suitability for rain-fed agriculture under rainy-year conditions.

Map unit	Soybean	Maize	Wheat	Alfalfa	Citrus	Safflower
1	S3	S3	S3	S3	N	S2
2	S3	S3	S2	S3	N	S2
4	N	N	S3	N	N	S3
6	S2	S2	S3	S2	N	S2
7	S3	S3	S2	S3	N	S2
9	N	N	S2	N	N	S2
10	N	N	S2	N	N	S2
14	S3	S3	S3	S3	N	S3
15	S3	S3	S2	S3	N	S2
16	S3	S3	S3	S3	S3	S3
17	S3	S3	S3	S3	S3	S3
19	S3	S3	S3	S3	N	N
21	N	N	S3	N	N	S3
22	N	N	S3	N	N	S3
23	N	N	S2	N	N	S2

Missing map units correspond to riverbeds, streams and narrow floodplains that have not been evaluated; S1, S2, S3 and N refer to levels of land suitability from high to low.

(4) Land suitability for competing uses

Physical land suitability data are useful for land use allocation in the context of land use planning. For instance, decision-makers could prefer wheat or safflower over more wetness-sensitive crops in a rainy year. But under average climatic conditions, decision problems can arise when dealing with competing land uses, for instance in the case of map units having similar physical land suitability for two or more land utilization types (e.g. a map unit equally highly suitable for soybean, maize and alfalfa). Such map units are areas where competition between land utilization types is critical for land use allocation. Using the ILWIS software (ITC, 1997), the location and extent of such critical areas were identified. Figure 11.14 highlights areas exposed to potential crop competition according to such factors as level of land suitability, number of competing crops and type of farming system (i.e. rain-fed or irrigated). The better the land suitability and the greater the number of crops involved, the more critical is the degree of competition between land utilization types and the more difficult is the decision to reach the right land use allocation. Map units with critical degree of crop competition are located in the southwest of the area, where climate, landscape and soil conditions, including water surplus coinciding with the growing cycle, good physical and chemical soil properties, and flat or smooth topography, are the most suitable for cropping. These units are also the most favourable for natural regeneration of the Chaco forest.

Because more than one land utilization type could be allocated to several map units, it follows that more than one land use option is possible for addressing current or potential land use conflicts. The land utilization types finally allocated to the respective units, in such cases of multiple options, depend on the priorities given by decision-makers or stakeholders when formulating and applying planning policies. For instance, high priority given to a planning policy stating the following: “give preference to soybean in map units with high physical land suitability for soybean and easy accessibility” (under a commercial farming perspective), would result in allocating soybean to the map units located in the southwest of the study area, while high priority given to a policy stating the following: “give preference to crop rotation soybean-alfalfa in map units with high physical land suitability for soybean-alfalfa and soils highly susceptible to physical degradation” (under a conservative/conventional farming perspective), would result in allocating soybean-alfalfa to the same map units. In contrast, high priority given to the policy “give preference to the natural regeneration of the Chaco forest in map units with high physical land suitability for natural regeneration of the Chaco forest” (under a conservationist perspective) would result in allocating native vegetation to the-above mentioned map units.

The results of the land suitability assessment are a good basis for formulating land use options in the context of land use planning, as they provide decision-makers with information on the opportunities (possibilities and limitations) to apply the selected land utilization types to the study area.

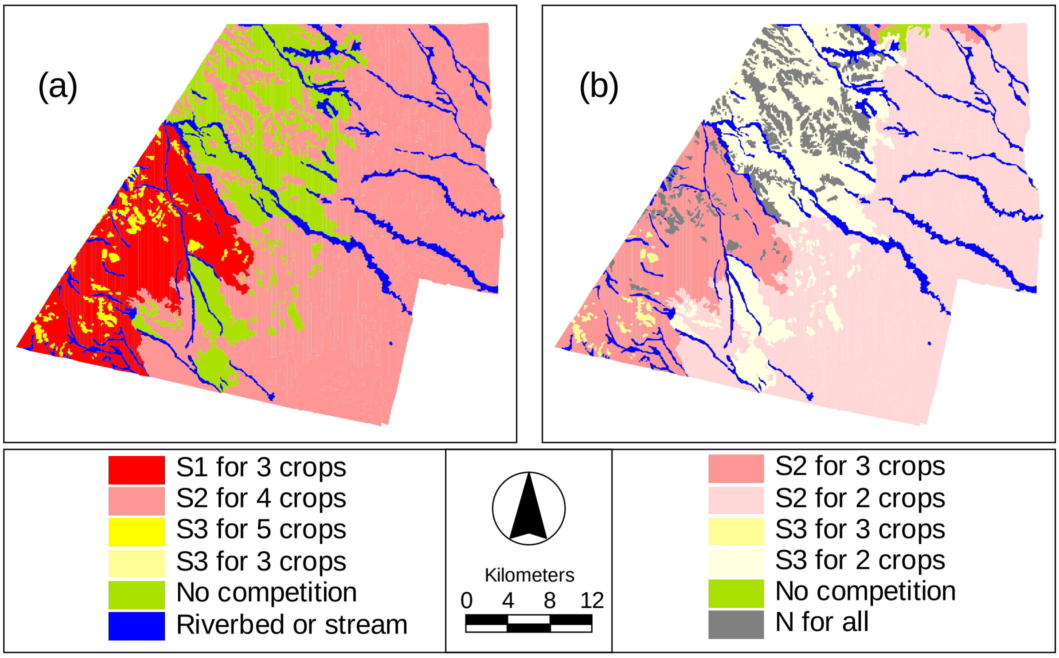


Figure 11.14. Crop competition for different land suitability areas under (a) rain-fed and (b) irrigated conditions in Burruyacú (S1, S2, S3 and N refer to levels of land suitability from high to low).

11.3. LAND USE PLANNING OPTIONS

11.3.1. Introduction

Burruyacú has been traditionally an area with rural activities based on the exploitation of the Chaco forest for timber and livestock browsing (Gomez et al., 1992). From the early 1970s, a rapid expansion of agriculture took place, favoured by population increase, market prices, accessibility, annual rainfall, soils and land tenure (Minetti & Sierra, 1983). In fact, crop pattern was greatly influenced by market conditions, with soybean becoming rapidly the most important crop. Local institutions (e.g. the Agricultural Experimental Station of Tucumán, University of Tucumán) had started promoting soybean since the 1960s due to favourable land conditions and good market prices (Flores, 1997).

The extension of cropland has resulted in substantial reduction of the Chaco forest. From 1971 to 1991, deforestation was intense with 57,000 ha of forest converted to cropland, causing land use conflicts between agriculture and forest cover (Flores, 1997). Moreover, environmental problems such as physical soil degradation and soil erosion emerged from heavily mechanized cropping. Soils derived from loess have high silt content and are therefore susceptible to compaction. Continuous mechanized farming of soybean, without rotation with other crops or green manure allowing soil condition to recover, led to soil compaction and depletion of soil fertility over the last three decades. Consequently, land use planning for solving land use conflicts and minimizing land degradation became a relevant issue to secure the sustainability of the agricultural activities in the area. To that end, the land-use-planning model LUPIS (Land Use Planning and Information System) was selected (Ive & Cocks, 1983, 1988; Ive, 1992).

Land use plans were developed according to the perspectives of three categories of stakeholders, including commercial farmers, conservative/conventional farmers, and conservationists. To make diverse and sometimes contrasting land use options compatible, a consensus plan addressing the land use conflicts and environmental issues of the study area was prepared.

11.3.2. The LUPIS planning model

Land use planning is primarily a technical-political instrument for resolving, mitigating, avoiding or forestalling land use conflicts (Cocks, 1992; Zinck, 1996). The technical component of land use planning assesses land suitability for competing uses according to their resource requirements and the resource base of the study area, while the political component allows allocating land according to the demands formulated by stakeholders for competing land uses. These two land-use-planning components are clearly and explicitly recognized by the LUPIS model through policy rating and policy voting, respectively (Ive & Cocks, 1983, 1988; Ive, 1992).

LUPIS is a microcomputer-based spatial decision support system developed at CSIRO (Commonwealth Scientific and Industrial Research Organization) in Australia. After decades of conducting research on land evaluation methods and their application (Stewart, 1968), focus moved in the early 1970s towards developing rational methods for allocating land resources and resolving land use conflicts (Austin & Cocks, 1978; Cocks & Ive, 1996). A variety of methods appeared allowing to evaluate land for selected single purposes (e.g. Hopkins, 1977; Steiner, 1983), but methods for allocating land to a range of competing uses were lagging behind for some time. LUPIS was developed to facilitate the integration of two closely related methods of land use planning: SIRO-PLAN (Cocks et al., 1983) and SIRO-MED (Cocks & Ive, 1996). Central to both methods is the premise that land use planning should be issue-driven (Ive, 1992). An issue is a statement from a stakeholder perspective that should be considered when allocating land. Both methods are geared towards responding to each issue in the form of one or more resource allocation policies (Cocks et al., 1986), which seek to identify, in principle, resource requirements for relevant uses. As a consequence, land uses are allocated as far as possible in accordance with their preferred resource requirements, conditional upon the resource base of the area and the resource demands of competing land uses. It is against each of the identified issues and their component policies that a land use plan should be formally evaluated (Ive, 1992).

The core capabilities of LUPIS allow the user to routinely complete the following operations (Ive & Cocks, 1988; Ive, 1992; Cocks & Ive, 1996): (1) computerize a matrix of data items against map units; (2) for each map unit, calculate ratings from these data items that permit to measure how well any comprehensive land use plan satisfies each allocation policy; (3) adjust any existing or previously generated land use plan to increase the extent to which formulated policies are satisfied; and (4) summarize the features of any generated land use plan in terms of maps, charts, tables of area per land use and tables of policy achievement levels. More details on LUPIS capabilities can be found in Ive and Cocks (1988), Ive (1992), and Cocks and Ive (1996). LUPIS has been successfully essayed in many different regions (e.g. Recatalá, 1995; Rodríguez, 1995). Hereafter, the system is applied to a new area in a different context, the Chaco plain.

11.3.3. Establishing land use options

(1) Land use issues

Current land use conflicts in the study area derive from the rapid expansion of large-scale, heavily mechanized farming, mainly for soybean production, at the expense of the native Chaco forest, causing physical soil degradation, principally compaction and erosion. Figure 11.3 shows soil susceptibility to physical degradation, while Figure 11.2 highlights the current and potential soil erosion in the study area.

From the issues identified in the area, three land use alternatives were recognized to compete currently and/or potentially for space occupation: agriculture, forestry and conservation. Agriculture includes a set of crops ecologically adapted to the regional context and supported by farming experience in the area, such as soybean, maize, citrus, wheat, sugarcane and safflower. Alfalfa was added to this list as green manure cultivated in rotation or alone on soils highly susceptible to physical degradation. Forestry covers activities of extensive grazing and wildlife management in the Chaco forest. Conservation refers to the natural regeneration and conservation of the Chaco forest. For completeness, a land use called “non-use” was added to include riverbeds, streams and infrastructure.

Although soybean and citrus would produce substantially higher yields under irrigation than in rain-fed conditions, only rain-fed cropping was considered here because of the lack of data on water resource availability. Wheat was not handled as an individual land use option for developing land use plans, as it is rotated as winter crop with soybean or maize as summer crops.

(2) Stakeholder types

There are three stakeholder categories in the study area: commercial farmers, conservative/traditional farmers and conservationists.

Commercial farmers promote large-scale mechanized agriculture. Crops are selected according to national or international market conditions. This group aims to maximize agricultural production, while minimizing costs, and to expand farming to areas with good land characteristics currently under natural cover. Externalities such as environmental costs are in general not of strong concern, except for a few progressive farmers, and land degradation, especially soil compaction, is not recognized yet a major threat to soil productivity and crop performance. Soybean, citrus and maize are the crops most preferred by these farmers, but priority is given to soybean due to good market prices.

Conservative farmers promote long-term sustained agriculture. Crops are selected by taking into account both economic benefits and environmental costs. Soybean and maize, both in rotation with alfalfa, alfalfa and safflower are the crops most preferred by these farmers. Priority is given to soybean-alfalfa and alfalfa, as these are considered the best land use options to achieve a balance between economic returns and soil conservation. Soybean-alfalfa is recommended in soils of low to moderate susceptibility to physical degradation and alfalfa in soils of high susceptibility. For areas marginally suitable to agriculture, this kind of farmer promotes extensive grazing or wildlife management, depending on the degree of land susceptibility to degradation. Wildlife management is preferred in areas already degraded or highly susceptible to degradation.

Conservationists promote the recuperation and conservation of the Chaco forest, mainly in areas susceptible to degradation or already degraded. They sustain that agriculture should be restricted as much as possible to the areas less susceptible to environmental degradation, thus less prone to soil compaction and/or erosion. This group also wishes to conserve the most scenic landscapes.

(3) Land use policies

Taking into account the diverse and sometimes contrasting perspectives of the various stakeholders, twenty-one policies were formulated in response to the issues identified in the study area (Table 11.4). The purpose of such policies is to suggest the resource requirements preferred by each land use.

Policies were grouped into imperative ones (exclusion and commitment policies) and indicative ones (preference and avoidance policies) (Cocks et al., 1986). Imperative policies firmly and unequivocally state how a particular map unit should be used (a commitment policy) or should not be used (an exclusion policy). For instance, the policy saying “Exclude soybean from map units that are physically non-suitable for soybean” is an exclusion policy, which restricts soybean cropping to map units having adequate land characteristics. In contrast, the policy saying “Commit non-use to map units corresponding to riverbeds, streams and infrastructure” is a commitment policy, which protects the prevailing land use as riverbeds, streams or infrastructures.

Indicative policies only suggest how a particular map unit should (a preference policy) or should not be used (an avoidance policy). For instance, the following policies are respectively preference and avoidance policies: (1) “As far as possible, give preference to extensive grazing in map units marginally suitable for cropping but resistant to physical degradation”; (2) “As far as possible, give preference to land uses other than agricultural uses in map units highly susceptible to physical degradation, with priority for natural regeneration and conservation of Chaco forest”.

Policy achievement level, usually measured as a percentage, quantifies the extent to which a particular policy is met in a particular land use plan. Policy achievement levels may reach 100% when all map units to which the policy applies have been allocated to the proposed land use. A policy achievement profile summarizes the achievement levels for the set of allocation policies in a particular plan (Cocks et al., 1995). It is against its component policy achievement profile that a land use plan should be evaluated (Ive, 1992).

Table 11.4. Policy votes for specific stakeholder plans and a consensus plan (-- = 0).

Land use policies	Commercial farmer plan	Conservationist plan	Conservative farmer plan	Stakeholder consensus plan
Preference policies:				
(1) Encouraging soybean	10	--	--	10
(2) Encouraging soybean (road access)	10	--	--	10
(3) Encouraging citrus	5	--	--	5
(4) Encouraging maize	5	--	--	5
(5) Encouraging soybean-alfalfa	--	--	10	20
(6) Encouraging maize-alfalfa	--	--	5	5
(7) Encouraging safflower	--	--	5	5
(8) Encouraging alfalfa	--	--	10	20
(9) Encouraging extensive grazing	--	--	10	30
(10) Encouraging wildlife management	--	--	10	30
(11) Encouraging Chaco forest	--	10	--	20
Avoidance policies:				
(1) Avoiding agricultural uses (high susceptibility to soil degradation)	--	10	--	10
(2) Avoiding agricultural uses (high susceptibility to soil erosion)	--	10	--	10

(4) Database

A feasible, necessary and sufficient data set is required to operationalize the LUPIS procedure and evaluate how policies are achieved in a plan (Cocks et al., 1995). A set of 14 data items was necessary to mobilize the allocation policies, including: type of map unit; physical land suitability for soybean, citrus, maize, soybean-alfalfa, maize-alfalfa, alfalfa, safflower, and natural regeneration of the Chaco forest; soil susceptibility to physical degradation; current soil erosion; potential soil erosion; slope; and road accessibility.

The database in Table 11.5 was fed with data generated by physical land suitability assessment and additional data extracted from Gomez et al. (1992). The soil map at scale 1:77,000 (Figure 11.1), prepared by INTA (Gomez et al., 1992) and digitized using the ILWIS software (ITC, 1997), was taken as cartographic base to determine the land use options possible in each map unit. In LUPIS terminology, a map unit is a parcel of land on which an allocation decision is made (Ive & Cocks, 1988; Cocks et al., 1995). The map included 414 polygons belonging to 23 different soil map units, defined on the basis of soil-landscape relationships. Each map unit was individually assessed against the land use allocation policies.

(5) Policy ratings and votes

Policy rating determines the relative attractiveness of a map unit for the land use referred to in the policy in terms of policy resource requirements. It is a number between 0 and 1, alternatively 0-10 or 0-100, representing the extent to which the selection of a particular land use on a particular map unit satisfies a particular policy. For each policy, an algorithm was written in BASIC for calculating the policy rating from the data items for each map unit.

A policy vote provides a means for adjusting the relative importance attributed to an indicative policy during the plan-making process. Policies considered most important by a stakeholder receive a higher vote than those that are considered less important. In general, as votes for a given policy increase, more map units become successively allocated to the land use referred to in the policy. Finally, the map units most attractive for competing land uses are identified using the assessment algorithm.

Table 11.5. Database used for land use planning in Burruyacú district.

Map unit	Soybean	Alfalfa	Soybean-alfalfa	Maize	Maize-alfalfa	Citrus	Safflower	Chaco forest	Soil susceptibility to physical degradation	Current soil erosion	Potential soil erosion	Slope	Road accessibility
1	S2	S2	S2	S2	S2	N	S2	S2	M	NN	L	2	L
2	S1	S1	S1	S1	S1	S3	S2	S1	H	L	L	2	M
4	S3	S3	S3	S3	S3	N	S2	S3	H	L	L	2	H
6	S2	S3	S2	S2	S2	N	S2	S2	M	L	LM	3	M
7	S1	S1	S1	S1	S1	S3	S2	S1	M	L	L	2	H
9	S2	S2	S2	S2	S2	N	S2	S2	H	NN	NN	1	H
10	S2	S2	S2	S2	S2	N	S2	S2	H	NN	NN	1	L
14	S3	S3	S3	S3	S3	S3	S3	S3	M	NN	L	1	M
15	S2	S2	S2	S2	S2	N	S2	S2	M	NN	L	1	L
16	S3	S3	S3	S3	S3	S3	S3	S3	M	LM	MH	4	M
17	S3	S3	S3	S3	S3	S3	S3	S3	M	LM	MH	4	H
19	S3	S3	S3	S3	S3	N	N	S3	H	LM	MH	4	M
21	S3	S3	S3	S3	S3	N	S2	S2	L	L	LM	3	M
22	S3	S3	S3	S3	S3	N	S2	S3	H	NN	NN	1	H
23	S2	S2	S2	S2	S2	N	S2	S2	M	NN	NN	1	H

Map units missing in the list correspond to riverbeds, streams and narrow floodplains that have not been evaluated; all evaluated map units include several soil phases.
S1 = high suitability; S2 = moderate suitability; S3 = marginal suitability; N = not suitable; NN = none; L = low; M = moderate; LM = low-moderate; MH = moderate-high; H = high; slope: 1 = 0-1%, 2 = 1-3%, 3 = 3-10%, 4 = 10-25%.

(6) Land use plan generation

In the plan generation phase, preference and avoidance policies are voted first in an attempt to achieve the stakeholder expectations. The study team in charge of guiding the plan-making process used information received from stakeholder representatives. It was consensually agreed to give votes between 0 and 10.

By selectively assigning votes to the preference/avoidance policy set, land use plans were developed giving emphasis to the policies preferred by the stakeholders to show the possibilities for widely accommodating their prioritized land uses in areas of high suitability. Specifically, a land use plan was developed for each stakeholder category, on the basis of the information received from the stakeholder representatives. Such land use plans emphasize those policies that encourage the allocation of land uses preferred by each stakeholder category. Policies encouraging land uses of second-order priority by stakeholders were moderately promoted. Obviously, stakeholders tend to disregard policies that support land uses they do not favour or oppose. Table 11.4 contains the specific votes assigned by each stakeholder category in making its respective land use plan.

As the objectives of the stakeholders were not the same, the plans showed significant discrepancies of land use allocation between stakeholder categories, calling for an effort of compatibilization to generate a common plan suitable to address current and potential land use conflicts and environmental problems. While recognizing that all stakeholder priorities could not be simultaneously achieved, it was agreed by the stakeholder representatives to jointly emphasize the preference/avoidance policies by adding votes after having completed negotiations leading to a consensus. Conservative farmers acted as the key negotiation group, as their allocation perspective was intermediate between those of commercial farmers and conservationists.

During the negotiation process, commercial farmers recognized that cropping is usually of marginal profitability in map units of low physical land suitability for agricultural uses. An agreement was made with conservative farmers to give emphasis to the policies that encourage alternative land uses in low-suitability map units, including extensive grazing and wildlife management. On the other hand, conservationists recognized that promoting forestry uses over all the study area would not be realistic in view of the large demand for agricultural products. They agreed with conservative farmers to give emphasis to the policies encouraging soybean-alfalfa and alfalfa, as these are the most adequate agricultural options to achieve a balance between economic benefits and soil protection from physical degradation processes. Conservationists gave support to conservative farmers for emphasizing policies encouraging extensive grazing and wildlife management, as these land uses would not compromise the conservation of the Chaco forest. In return, they obtained support for promoting the natural regeneration and conservation of the Chaco forest in map units with the most scenic landscapes, which anyway are usually slope-limited for cropping, and in map units with severe current or potential soil erosion. As an alternative, conservative farmers would commit themselves to apply adequate land management practices for soil conservation (e.g. terraces, strip cropping), if crops were allocated to erosion-prone map units. After completing the negotiation rounds, votes were given to the policy set according to the achieved agreements for developing a consensus plan (Table 11.4).

All land use plans developed are usually evaluated by the stakeholders against their respective policy achievement profile. When the policy achievement profile associated with a given land use plan is judged unsatisfactory, the votes attributed to the policies are selectively readjusted until a satisfactory policy achievement profile is reached. This was not necessary for the different land use plans developed in this exercise.

11.3.4. Results and discussion

The percentages of area occupied by each land use in the three individual stakeholder plans and in the consensus plan are shown in Table 11.6. Policy achievement profiles in percentages for the same land use plans are reported in Table 11.7. Figure 11.15 represents the preferred-land-use maps for the four alternatives.

Table 11.6. Percentages of area allocated to each land use in the selected plans (-- = 0).

Land uses	Commercial farmer plan	Conservationist plan	Conservative farmer plan	Stakeholder consensus plan
Soybean	92.6	--	--	15.9
Citrus	--	--	--	--
Maize	--	--	--	--
Soybean-alfalfa	--	--	29.7	15.3
Maize-alfalfa	--	--	--	--
Alfalfa	--	--	41.6	36.0
Safflower	--	--	--	--
Extensive grazing	--	--	5.8	0.7
Wildlife management	--	--	15.5	14.4
Chaco forest	--	92.6	--	10.2
Non-use	7.4	7.4	7.4	7.4

(1) Commercial farmer plan

In the commercial farmer plan, soybean, the land use prioritized by this category of stakeholders, was allocated to all map units of the study area, except in the case of committed uses, but including even the units only marginally suitable for soybean in the northwest. This plan maximizes the commercial farmers' expectations, as reflected in the policy achievement profile associated with the plan (Table 11.7). Preference policies 1 and 2, encouraging soybean in map units with high physical suitability for soybean and good road accessibility, achieve 100%. However, the implementation of this plan would intensify land degradation, especially soil compaction and erosion, in the most vulnerable areas, since intensive cultivation of soybean under commercial purposes leads usually to land degradation (Figure 11.15a and b). This is also reflected in the policy achievement profile, as avoidance policies 1 and 2, which aim at avoiding agricultural uses in map units prone to physical degradation and erosion, achieve 0%.

Table 11.7. Policy achievement profiles for the plans generated in the exercise (-- = 0).

Land use policies	Commercial farmer plan	Conservationist plan	Conservative farmer plan	Stakeholder consensus plan
Preference policies:				
(1) Encouraging soybean	100	--	--	22
(2) Encouraging soybean (road access)	100	--	--	27
(3) Encouraging citrus	--	--	--	--
(4) Encouraging maize	--	--	--	--
(5) Encouraging soybean-alfalfa	--	--	37	16
(6) Encouraging maize-alfalfa	--	--	--	--
(7) Encouraging safflower	--	--	--	--
(8) Encouraging alfalfa	--	--	46	41
(9) Encouraging extensive grazing	--	--	61	7
(10) Encouraging wildlife management	--	--	81	77
(11) Encouraging Chaco forest	--	100	--	100
Avoidance policies:				
(1) Avoiding agricultural uses (high susceptibility to physical soil degradation)	--	100	--	8
(2) Avoiding agricultural uses (high susceptibility to soil erosion)	--	100	--	100

(2) Conservationist plan

The conservationist plan maximizes the conservationists' expectations, as the option of natural regeneration and conservation of the Chaco forest was allocated to all map units, similarly to what happened with soybean in the commercial farmer plan. Avoidance policies 1 and 2, restricting agricultural uses in the areas most vulnerable to land degradation, and preference policy 11 that encourages the natural regeneration and conservation of the Chaco forest in map units having the most scenic landscapes, achieve 100%. Such a (unrealistic) plan would minimize environmental problems in the study area, since only native vegetation would be allowed to develop.

(3) Conservative farmer plan

The conservative farmer plan obviously maximizes the stakeholder expectations but also offers a variety of land use options, instead of only one as in the previous two plans. This land use plan fairly approaches the consensus plan, as it was generated from a more balanced land use perspective. Preference policies (5, 8, 9 and 10) emphasized by the stakeholders did not achieve maximum level of satisfaction (Table 11.7). This is because the land uses prioritized in this plan were allocated only to map units satisfying their respective resource requirements, conditional upon the resource demands from competing land uses. For instance, soybean-alfalfa and alfalfa, which compete for map units suitable for cropping, were selectively allocated to given map units depending on their susceptibility to physical degradation. Specifically, soybean-alfalfa was allocated to all map units having at the same time moderate to high suitability for this kind of crop rotation and low susceptibility to physical degradation. In places where soils were highly susceptible to physical degradation, alfalfa gained the competition and was allocated. Similarly, in map units marginally suitable for cropping, the allocation of extensive grazing or wildlife management was additionally conditioned by soil susceptibility to physical degradation. Wildlife management was allocated to map units of low suitability for cropping and high susceptibility to physical soil degradation.

In first instance, the conservative farmer plan seems not to care about environmental problems, as avoidance policies score 0% achievement. This happens because the forest cover option was not allocated to the map units vulnerable to soil physical degradation and erosion. But, environmental problems will be actually minimized under other land use options and by appropriate land management practices. Soil degradation will be mitigated by allocating alfalfa and wildlife management to the most vulnerable soils, while soil erosion will be controlled by applying adapted conservation practices (e.g. terracing, strip cropping) to which conservative farmers feel strongly committed.

(4) Stakeholder consensus plan

Each stakeholder representative estimated satisfactory the policy achievement profile associated with its own land use plan. However, such plans are neither realistic nor practical, as they do not solve the land use conflicts and/or environmental problems of the study area. The commercial farmer plan would intensify the environmental problems and lead to the elimination of the Chaco forest. In contrast, the conservationist plan would minimize the environmental problems, but banish agricultural uses. The conservative farmer plan would also minimize environmental problems, but ignore the other stakeholders' perspectives. These issues and other interest conflicts were addressed by the consensus plan when trying to compatibilize the three stakeholder plans.

In the consensus plan, all land uses prioritized by the various stakeholders were allocated, generating a satisfactory policy achievement profile. Only non-emphasized preference policies achieved 0%. Land use allocation was optimized according to the agreements reached through negotiation. Soybean was allocated to the map units having the most suitable land characteristics for that purpose, with the best road accessibility and water surplus during the growing cycle, thus primarily in the west of the study area. Soybean-alfalfa and alfalfa as green manure were preferred in map units with respectively moderate and high susceptibility to physical degradation. Extensive grazing and wildlife management were allocated to map units marginally suitable for cropping, with the former restricted to units resistant to physical degradation to avoid soil compaction by cattle trampling. Natural regeneration and conservation of the Chaco forest were the best option for the map units most vulnerable to soil erosion because of slope and having the most scenic landscapes.

The consensus plan contributes to minimizing land degradation thanks to allocating two conservation land uses, specifically alfalfa and wildlife management, to the most vulnerable map units. Low achievement (8%) of avoidance policy 1 is mainly due to the fact that the Chaco forest option was not allocated to all map units highly susceptible to physical degradation. No special conservation practices to counteract soil erosion would be necessary, as the most vulnerable map units would be devoted to natural regeneration and conservation of the Chaco forest. This is reflected in the 100% achievement profile of avoidance policy 2, which aims at avoiding agricultural uses in map units with high current and/or potential soil erosion.

It is thus possible to simultaneously address land use conflicts and environmental problems through comprehensive land use planning. The LUPIS model facilitates agreement among stakeholders by identifying the land units exposed to competing land uses and by proposing consensual solutions to land use conflicts. The land allocation procedure clearly recognizes the two essential components (technical and political) of the planning process through policy rating and voting, and encourages explicitness and transparency by involving multiple stakeholders into the task of achieving a consensus plan sensitive to the issues of the study area.

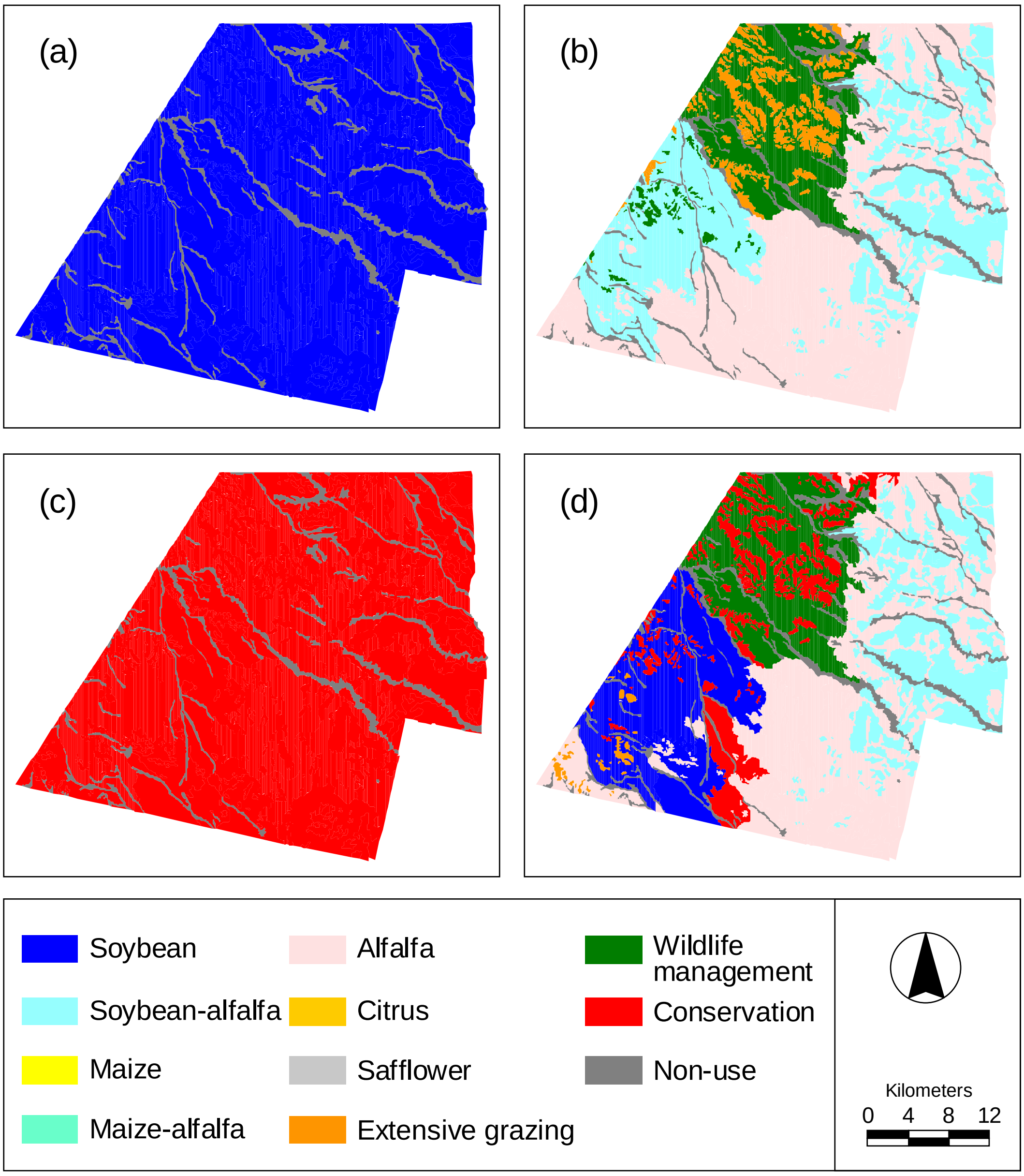


Figure 11.15. Most preferred land use plans:
(a) Commercial farmers
(b) Conservative farmers
(c) Conservationists
(d) All stakeholders using a consensus procedure

11.4. CONCLUSIONS

Physical land suitability and land use planning were conducted in the Burruyacú district, leading to the following conclusions:

- Only 16.4% of the study area has high suitability for most of the selected land utilization types. The most promising farming area is located in the southwest, where the physical land conditions are most favourable for cropping on the basis of climate, landscape and soil features, including water surplus during the growing cycle of the crops, good physical and chemical soil characteristics, and flat or smooth topography.

- Major limitations for cropping are low annual rainfall and flooding in the east of the study area, and sloping topography and flooding in the west.
- Rain-fed citrus is the crop least adapted to the area, with a few map units satisfying only marginally some of its land requirements (e.g. appropriate annual rainfall, low flooding risk).
- Soybean and citrus cultivated under irrigation in the areas provided with groundwater would generate yields substantially higher than those obtained under rain-fed conditions. Drip irrigation would be more adequate than furrow irrigation to avoid soil erosion.
- Cropping could be hazardous in periods of extreme climatic conditions (rainy or dry years). Wheat and safflower would be the only options, with moderate to marginal potential, under rainy-year conditions, while only safflower would be marginally adapted under dry-year conditions.
- Map units having the best land characteristics for cropping are also the most favourable for regeneration of the Chaco forest. However, the latter would be successful almost everywhere, as it is the native vegetation of the study area.
- Areas with high physical land suitability for most of the crops are exposed to competition between several land utilization types and thus critical for land use allocation. Map units offering competing land use options are mainly located in the southwest of the study area. They are also the most favourable for natural regeneration of the Chaco forest.
- The physical land suitability assessment provided results appropriate for formulating land use options to address issues of current and potential land use conflicts in the study area.
- A consensual land use allocation plan was generated from a variety of proposed land use options, respecting the priorities given to each land utilization type by decision-makers and stakeholders in the context of formulating and implementing planning policies.

11.5. REFERENCES

Austin, M.P., Cocks, K.D., (eds.), 1978. Land use on the south coast of New South Wales: a study in methods of acquiring and using information to analyze regional land use options. Volumes 1-4. CSIRO, Melbourne, Australia.

Clapperton, C., 1993. Quaternary geology and geomorphology of South America. Elsevier. Amsterdam, The Netherlands.

Cocks, D., 1992. Use with care. Managing Australia's natural resources. In: The Twenty First Century. New South Wales. New South Wales University Press, Australia.

Cocks, D., Ive, J., 1996. Mediation support for forest land allocation: the SIRO-MED system. Environmental Management 20: 41-52.

Cocks, D., Ive, J., Clark, J. (eds.), 1995. Forest issues: processes and tools for inventory, evaluation, mediation and allocation. CSIRO Division of Wildlife and Ecology Project Report 7. CSIRO, Canberra, Australia

Cocks, K.D., Ive, J.R., Davis, J.R., 1986. Policy guidelines for the management of public natural lands. Land Use Policy 3: 9-20.

Cocks, K.D., Ive, J.R., Davis, J.R., Baird, I.A., 1983. SIRO-PLAN and LUPLAN: an Australian approach to land use planning. 1: The SIRO-PLAN land use planning method. Environment and Planning B 10: 331-346.

FAO, 1976. A framework for land evaluation. Soils Bulletin 32. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 1983. Guidelines: land evaluation for rain-fed agriculture. Soils Bulletin 52. Food and Agriculture Organization of the United Nations, Rome, Italy

FAO, 1984. Land evaluation for forestry. Forestry Paper 48. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 1985. Guidelines: land evaluation for irrigated agriculture. Soils Bulletin 55. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 1991. Guidelines: land evaluation for extensive grazing. Soils Bulletin 58. Food and Agriculture Organization of the United Nations, Rome, Italy.

Flores, E., 1997. Monitoring land use changes and comparing soil physical properties between arable and forest land in the western Chaco plain, NW Argentina. MSc Thesis. ITC, Enschede, The Netherlands.

Gomez, L.A., Ferrao, R.F., Casen, M.L., 1992. Carta básica de suelos del Departamento de Burruyacú, Provincia de Tucumán. Instituto Nacional de Tecnología Agropecuaria (INTA), Centro de Investigaciones de Recursos Naturales, Instituto de Suelos. Castelar, Argentina.

Hopkins, L., 1977. Methods for generating land suitability maps: a comparative evaluation. Journal of the American Institute of Planners 43: 368-400.

ITC, 1997. Integrated Land and Water Information System - ILWIS. International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

Imbelloni, P.A., Teruggi, M.E., 1993. Paleosols in loess deposits of the Argentina Pampas. Quaternary International 17: 49-55.

Ive, J.R., 1992. LUPIS: Computer assistance for land use allocation. Resource Technology 92 Taipei: Information technology for environmental management. Taiwan.

Ive, J.R., Cocks, K.D., 1983. SIRO-PLAN and LUPLAN: an Australian approach to land use planning. 2: The LUPLAN land use planning package. Environment and Planning B: Planning and Design 10: 347-355.

Ive, J.R., Cocks, K.D., 1988. LUPIS: a decision-support system for land planners and managers. In: P.W. Newton, M.A.P. Taylor, R. Sharpe (eds.), Desktop planning: microcomputer applications for infrastructure and services planning and management. Hargreen, Melbourne, Australia.

Johnson, A.E.K., Cramb, R.A., 1991. Development of a simulation-based land evaluation system using crop modeling, expert systems and risk analysis. Soil Use and Management 7 (4): 239-245.

León, J.C., 1992. Aplicación del Sistema Automatizado para la Evaluación de Tierras (ALES) en un sector de la cuenca del río Sinú (Córdoba, Colombia). Revista C.I.A.F. 13 (1): 19-42.

Minetti, J., Sierra, E., 1984. Expansión de la frontera agrícola en Tucumán y el diagnóstico climático. Rev. Ind. y Agric. de Tucumán 62 (2): 69-77.

Recatalá, L., 1995. Propuesta metodológica para planificación de los usos del territorio y evaluación de impacto ambiental en el ámbito mediterráneo Valenciano. Tesis Doctoral, Universitat de València. Valencia, Servei de Publicacions de la Universitat de València, España.

Rodríguez, O., 1995. Land use conflicts and planning strategies in urban fringes: a case study of Western Caracas (Venezuela). PhD Thesis. ITC Publication 27. International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands.

Rossiter, D.G., 1996. A theoretical framework for land evaluation. Geoderma 72: 165-202.

Sayago, J.M., Collantes, M., Neder, L., 1996. Hidrogeomorfología de la cuenca paleofluvial del Río Tajamar, Dpto. Burruyacú, Tucumán. Reporte interno, INGEMA. Tucumán, Argentina.

Soil Survey Staff, 1996. Soil Taxonomy. Soil Conservation Service, US Department of Agriculture. Washington DC, USA.

Steiner, F., 1983. Resource suitability: methods for analysis. Environmental Management 7: 401-420.

Stewart, G.A. (ed.), 1968. Land evaluation. Macmillan Company. Melbourne, Australia.

Sys, C., Van Ranst, E., Debaveye, J., 1991. Land Evaluation, Part 1: Principles in land evaluation and crop production calculations. Agricultural Publications 7. General Administration for Development Cooperation, Brussels, Belgium.

Sys, C., Van Ranst, E., Debaveye, J., 1991. Land Evaluation, Part 2: Methods in land evaluation. Agricultural Publications 7. General Administration for Development Cooperation, Brussels, Belgium.

Sys, C., Van Ranst, E., Debaveye, J., Beernaert, F., 1993. Land Evaluation, Part 3: Crop requirements. Agricultural Publications 7. General Administration for Development Cooperation, Brussels, Belgium.

Teruggi, M. E., 1975. The nature and origin of Argentinean loess. In: I. J. Smalley (ed.), Loess: lithology and genesis. Benchmark Papers in Geology, vol. 26. Reprinted from J. Sed. Petrol. (1957), 27(3): 322-332.

Zinck, J.A., 1996. La información edáfica en la planificación del uso de las tierras y el ordenamiento territorial. In: J. Aguilar Ruíz, A. Martínez Raya, A. Roca Roca (eds.), Evaluación y manejo de suelos. Consejería de Agricultura (Junta de Andalucía), Sociedad Española de Ciencia del Suelo y Universidad de Granada, pp.49-75.

Zuccardi, R.B., Fadda, G.S., 1972. Mapa de reconocimiento de suelos de la Provincia de Tucumán. Publicación Especial, Volúmen 3. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina.

Zuccardi, R.B., Fadda, G.S., 1985. Bosquejo agrológico de la Provincia de Tucumán. Miscelánea 86. Facultad de Agronomía y Zootecnia, Universidad Nacional de Tucumán. San Miguel de Tucumán, Argentina.

11.6. APPENDIX: LAND EVALUATION DATA

Table 11.8. Soil database used for land evaluation in Burruyacú district.

Soil map unit			Sp	Fl	Dr	Tx	Cf	De	Cb	CEC	BS	SBC	pH	OC	EC	ESP
No	Local name	Soil phases (%)														
1	Abr	SdA (50)	2	1	1	5	1	2	1	1	1	1	5	4	1	1
		EAt (30)	2	1	1	1	4	2	4	1	1	1	6	4	1	1
		LdC (20)	2	1	1	2	3	2	1	1	1	1	5	1	1	1
2	Ald	Al (50)	2	1	1	1	1	2	1	1	1	1	4	2	1	2
		ECh (30)	2	1	1	1	1	2	1	1	1	1	3	2	1	1
		Ca (20)	2	1	1	1	1	2	1	1	1	1	4	2	1	1
4	BU	Bu (50)	2	2	1	2	1	2	1	1	1	1	11	1	1	1
		PdH (30)	2	2	3	1	1	2	1	1	1	1	5	2	1	2
		EPu (20)	2	1	1	1	2	2	1	1	1	1	5	2	1	1
6	EA	EAt (50)	3	1	1	3	4	2	4	1	1	1	6	4	1	1
		SdA (30)	3	1	1	5	1	2	1	1	1	1	5	4	1	1
		LdC (20)	3	1	1	2	3	2	1	1	1	1	5	1	1	1
7	EC	ECh (50)	2	1	1	1	1	2	1	1	1	1	3	2	1	1
		ESu (30)	2	1	1	1	1	2	1	1	1	1	5	1	1	2
		SAl (20)	2	1	1	3	2	2	5	1	1	1	4	1	1	1
9	Ga	Ga (50)	1	1	2	1	1	2	1	1	1	1	3	3	1	1
		Ra (30)	1	2	2	3	1	2	1	1	1	1	4	2	1	1
		So (20)	1	2	2	2	1	2	1	1	1	1	9	2	1	1
10	GPi	GPi (50)	1	1	1	1	1	2	1	1	1	1	4	3	1	1
		Ra (30)	1	2	1	3	1	2	1	1	1	1	4	2	1	1
		So (20)	1	2	1	2	1	2	1	1	1	1	9	2	1	1
14	LC	LCr (50)	1	1	1	3	4	2	6	1	1	1	9	2	1	1
		LRa (30)	1	1	1	3	2	1	1	1	1	1	3	2	1	1
		EPo (20)	1	1	1	4	5	2	6	1	1	1	4	4	1	1
15	LEz	LEz (50)	1	1	1	3	2	2	2	1	1	1	6	4	1	2
		Ra (30)	1	2	1	3	1	2	1	1	1	1	4	2	1	1
		Ga (20)	1	1	1	1	1	2	1	1	1	1	3	3	1	1
16	LMo	LMo (50)	4	1	1	3	2	3	5	1	1	1	5	1	1	1
		EAt (30)	3	1	1	1	4	2	4	1	1	1	6	4	1	1
		LdC (20)	4	1	1	2	3	2	1	1	1	1	5	1	1	1
17	LR	LRa (50)	4	1	1	3	2	1	1	1	1	1	3	2	1	1
		CPo (30)	4	1	1	1	1	2	1	1	1	1	6	2	1	1
		Stone (20)														
19	PMo	PMo (50)	4	1	1	4	1	5	1	1	1	1	1	2	1	1
		LCa (30)	4	1	1	3	2	2	1	1	1	1	4	2	1	1
		Stone (20)														
21	Taj	ETa (50)	3	2	1	5	3	2	1	1	1	1	5	4	1	1
		Vi (30)	3	1	1	1	1	2	1	1	1	1	4	2	1	1
		TPo (20)	3	2	2	1	1	2	1	1	1	1	5	2	1	3
22	TP	TPo (50)	1	2	2	1	1	2	1	1	1	1	5	2	1	3
		SRo (30)	1	2	1	1	1	2	1	1	1	1	4	1	1	1
		Vi (20)	1	1	1	1	1	2	1	1	1	1	4	2	1	1
23	Vir	Vi (50)	1	1	1	1	1	2	1	1	1	1	4	2	1	1
		TPo (30)	1	2	2	1	1	2	1	1	1	1	5	2	1	3
		ETa (20)	1	2	1	5	3	2	1	1	1	1	5	4	1	1

Table 11.8. Soil database used for land evaluation in Burruyacú district (continued).

Numbers refer to soil map units; units missing in the list correspond to riverbeds, streams and narrow floodplains that have not been evaluated.
Local names given to soil units by INTA are: Abr (Siete-de-Abril), Ald (Alderete), BU (Burruyacú), EA (El Atacal), EC (El Chañar), Ga (Garmendia), GPi (Gobernador Piedrabuena), LC (La Cruz), LEz (La Esperanza), LMo (Los Morros), LR (La Ramada), PMo ((Padre Monti), Taj (El Tajamar), TP (Tala Pozo), Vir (Virginia).
Names given to soil phases by INTA are: SdA (Siete-de-Abril), EAt (El Atacal), LdC (Lomas de Cosoles), Al (Alderete), ECh (El Chañar), Ca (Cañete), Bu (Burruyacú), PdH (Puesto de Hunco), EPu (El Puestito), ESu (El Sunchal), SAl (San Alberto), Ga (Garmendia), Ra (Rapelli), So (Soledad), GPi (Gobernador Piedrabuena), LCr (La Cruz), LRa (La Ramada), EPo (El Porvenir), LEz (La Esperanza), LMo (Los Morros), CPo (Cebil Pozo), PMo (Padre Monti), LCa (La Calera), ETa (El Tajamar), Vi (Virginia), TPo (Tala Pozo), SRo (Santa Rosa).
Sp (slope %): 1 = 0-1; 2 = 1-3; 3 = 3-10; 4 = 10-25.
Fl (flooding risk): 1 = no risk; 2 = moderate risk; 3 = high risk.
Dr (drainage): 1 = good; 2 = moderate; 3 = imperfect.
Tx (soil texture): 1 = silt loam; 2 = silty clay loam; 3 = loam; 4 = sandy clay loam; 5 = sandy loam.
Cf (coarse fragments %): 1 = 0-3; 2 = 3-15; 3 = 15-35; 4 = 35-55; 5 > 55.
De (soil depth cm): 1 > 150; 2 = 100-150; 3 = 75-100; 4 = 50-75; 5 = 25-50; 6 < 25.
Cb (carbonate %): 1 = 0-3; 2 = 3-5; 3 = 5-6; 4 = 6-10; 5 = 10-15; 6 = 15-20; 7 > 20.
CEC (cationic exchange capacity): 1 > 24 cmol(+)/kg clay.
BS (base saturation): 1 > 80%.
SBC (sum of basic cations): 1 > 8 cmol(+)/kg soil.
pH (soil reaction in water): 1 = 5.8-6.0; 2 = 6.0-6.2; 3 = 6.2-6.5; 4 = 6.5-6.6; 5 = 6.6-7.0; 6 = 7.0-7.4; 7 = 7.4-7.5; 8 = 7.5-7.6; 9 = 7.6-7.8; 10 = 7.8-8.0; 11 = 8.0-8.2.
OC (organic carbon %): 1 > 2; 2 = 1.5-2; 3 = 1.2-1.5; 4 = 0.8-1.2; 5 = 0.5-0.8; 6 < 0.5.
EC (electrical conductivity): 1 < 1 dS/m.
ESP (exchangeable sodium percentage %): 1 < 4; 2 = 4-8; 3 = 8-12; 4 = 12-15.

Table 11.9. Land use requirements established for natural regeneration of the Chaco forest.

Land characteristics	Class, degree of limitation and rating scale				
	S1		S2	S3	N
	100	90	70	50	25
Topography					
Slope (%)	0-1	3-10	10-25	> 25	
Wetness					
Flooding risk	None	None	None	Moderate	High
Drainage	Good	Good	Moderate	Imperfect	
Physical characteristics					
Texture	SiL, SiCL, L	SCL	SL		
Coarse fragments (%)	0-3	3-15	15-35	35-55	
Soil depth (cm)	> 150	100-150	75-100	50-75	
Soil fertility					
CEC (cmol(+)/kg clay)	> 24	16-24	< 16		
Base saturation (%)	> 50	35-50	20-35	< 20	
Sum of basic cations (cmol(+)/kg soil)	> 5	3.5-5	2-3.5	< 2	
Organic carbon (%)	> 2	1.2-2	0.8-1.2	< 0.8	
Salinity and alkalinity					
ECe (dS/m)	< 2	2-4	4-6	6-8	> 8
ESP (%)	0-4	4-8	8-12	12-15	> 15

Texture: SiL = silt loam; SiCL = silty clay loam; l = loam; SCL = sandy clay loam; SL = sandy loam.

Table 11.10. Land suitability for rain-fed agriculture in Burruyacú district.

Soil map unit			Soybean	Soybean-alfalfa	Alfalfa	Maize-alfalfa	Maize	Wheat	Citrus	Safflower
No	Local name	Soil phases (%)								
1	Abr	SdA (50)	S2(s)		S2(c)		S2(c)	S3(s)	N(c)	S2(f)
		Eat (30)	S3(s)		S3(s)		S3(s)	S3(s)	N(c)	S3(s)
		LdC (20)	S2(s)		S2(c)		S2(c)	S2(s)	N(c)	S2(s)
		WRV	0.66	0.66	0.66	0.66	0.66	0.55		0.66
		SMU	S2	S2	S2	S2	S3	S3	N	S2
2	Ald	Al (50)	S1(f)		S1(c)		S1(c)	S1	S3(c)	S2(c)
		Ech (30)	S1(f)		S1(c)		S1(c)	S1(f)	S3(c)	S2(c)
		Ca (20)	S1(s)		S1(c)		S1(c)	S1(s)	S3(c)	S2(c)
		WRV	0.90	0.90	0.90	0.90	0.90	0.94	0.50	0.73
		SMU	S1	S1	S1	S1	S1	S1	S3	S2
4	BU	Bu (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S3(f)
		PdH (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(w)
		Epu (20)	S1(s)		S1(c)		S1(c)	S1(s)	S3(c)	S2(c)
		WRV	0.58	0.58	0.58	0.58	0.58	0.76	0.10	0.62
		SMU	S3	S3	S3	S3	S3	S2	N	S2
6	EA	Eat (50)	S3(s)		S3(s)		S3(s)	S3(s)	N(c)	S3(s)
		SdA (30)	S2(s)		S2(c)		S2(c)	S3(s)	N(c)	S2(f)
		LdC (20)	S2(s)		S2(c)		S2(c)	S2(s)	N(c)	S2(s)
		WRV	0.62	0.62	0.62	0.62	0.62	0.55		0.62
		SMU	S2	S2	S2	S2	S2	S3	N	S2
7	EC	Ech (50)	S1(f)		S1(c)		S1(c)	S1(f)	S3(c)	S2(c)
		Esu (30)	S1		S1(c)		S1(c)	S1	S3(c)	S2(c)
		Sal (20)	S1(s)		S1(c)		S1(c)	S1(s)	S3(c)	S2(c)
		WRV	0.93	0.91	0.90	0.90	0.90	0.93	0.50	0.73
		SMU	S1	S1	S1	S1	S1	S1	S3	S2
9	Ga	Ga (50)	S1(c)		S2(c)		S2(c)	S1(w)	N(c)	S1(c)
		Ra (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		So (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S3(f)
		WRV	0.70	0.66	0.62	0.62	0.62	0.82		0.77
		SMU	S2	S2	S2	S2	S2	S2	N	S2
10	GPi	GPi (50)	S1(c)		S2(c)		S2(c)	S1(f)	N(c)	S1(c)
		Ra (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		So (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S3(f)
		WRV	0.70	0.66	0.62	0.62	0.62	0.82		0.77
		SMU	S2	S2	S2	S2	S2	S2	N	S2
14	LC	LCr (50)	S3(s)		S3(s)		S3(s)	S3(s)	S3(c)	S3(s)
		LRa (30)	S2(s)		S1(c)		S2(s)	S3(s)	S3(c)	S2(c)
		EPo (20)	N(s)		N(s)		N(s)	N(s)	N(s)	N(s)
		WRV	0.47	0.50	0.52	0.50	0.47	0.40	0.40	0.47
		SMU	S3	S3	S3	S3	S3	S3	S3	S3
15	LEz	LEz(50)	S2(f)		S2(c)		S2(c)	S2(f)	N(c)	S2(f)
		Ra (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		Ga (20)	S1(c)		S2(c)		S2(c)	S1(f)	N(c)	S1(c)
		WRV	0.70	0.67	0.65	0.65	0.65	0.76		0.76
		SMU	S2	S2	S2	S2	S2	S2	N	S2
16	LMo	LMo (50)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		EAt (30)	S3(s)		S3(s)		S3(s)	S3(s)	S3(c)	S3(s)
		LdC (20)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		WRV	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
		SMU	S3	S3	S3	S3	S3	S3	S3	S3

Table 11.10. Land suitability for rain-fed agriculture in Burruyacú district (continued).

Soil map unit			Soybean	Soybean-alfalfa	Alfalfa	Maize-alfalfa	Maize	Wheat	Citrus	Safflower
No	Local name	Soil phases (%)								
17	LR	LRa (50)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		CPo (30)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		Stone (20)								
		WRV	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
		SMU	S3	S3	S3	S3	S3	S3	S3	S3
19	PMo	PMo (50)	S3(t)		S3(t)		S3(t)	S3(t)	N(s)	N(s)
		LCa (30)	S3(t)		S3(t)		S3(t)	S3(t)	S3(t)	S3(t)
		Stone (20)								
		WRV	0.4	0.4	0.4	0.4	0.4	0.4	0.15	0.15
		SMU	S3	S3	S3	S3	S3	S3	N	N
21	Taj	ETa (50)	S3(w)		S3(w)		S3(w)	S2(t)	N(w)	S2(c)
		Vi (30)	S2(t)		S2(t)		S2(t)	S2(t)	S3(c)	S2(c)
		TPo (20)	S3(w)		S3(w)		S3(w)	S2(t)	N(w)	S2(c)
		WRV	0.57	0.57	0.57	0.57	0.57	0.73	0.15	0.73
		SMU	S3	S3	S3	S3	S3	S2	N	S2
22	TP	TPo (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		SRo (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(w)
		Vi (20)	S1(f)		S1(c)		S1(c)	S1	S3 (c)	S2(c)
		WRV	0.58	0.58	0.58	0.58	0.58	0.78	0.1	0.73
		SMU	S3	S3	S3	S3	S3	S2	N	S2
23	Vir	Vi (50)	S1(f)		S1(c)		S1(c)	S1	S3(c)	S2(c)
		TPo (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		ETa (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		WRV	0.7	0.7	0.7	0.7	0.7	0.86	0.25	0.73
		SMU	S2	S2	S2	S2	S2	S1	N	S2

Soil map units missing in the list correspond to riverbeds, streams and narrow floodplains that have not been evaluated.
S1 = high suitability; S2 = moderate suitability; S3 = marginal suitability; N = not suitable.
Letters in brackets refer to major limitations: c = climate; t = slope; w = wetness (flooding and/or drainage); s = physical soil characteristics; f = soil fertility characteristics.
WRV = average of the values assigned to each soil phase according to its suitability class.
SMU = suitability class of each map unit for each crop.

Table 11.11. Land suitability for irrigated agriculture in Burruyacú district.

Soil map unit			Soybean	Citrus	Sugarcane
Number	Local name	Soil phases (%)			
1	Abr	SdA (50)	S2(t)	N(c)	S2(t)
		EAt (30)	S3(s)	N(c)	S3(s)
		LdC (20)	S2(t)	N(c)	S2(t)
		WRV	0.66		0.66
		SMU	S2	N	S2
2	Ald	Al (50)	S2(t)	S2(t)	S2(t)
		ECh (30)	S2(t)	S2(t)	S2(t)
		Ca (20)	S2(t)	S2(t)	S2(t)
		WRV	0.73	0.73	0.73
		SMU	S2	S2	S2
4	BU	Bu (50)	S3(w)	N(w)	S3(w)
		PdH (30)	S3(w)	N(w)	S3(w)
		EPu (20)	S2(t)	S2(t)	S2(t)
		WRV	0.55	0.15	0.55
		SMU	S3	N	S3
6	EA	EAt (50)	S3(t)	S3(t)	S3(t)
		SdA (30)	S3(t)	S3(t)	S3(t)
		LdC (20)	S3(t)	S3(t)	S3(t)
		WRV	0.50	0.50	0.50
		SMU	S3	S3	S3
7	EC	ECh (50)	S2(t)	S2(t)	S2(t)
		ESu (30)	S2(t)	S2(t)	S2(t)
		SAl (20)	S2(t)	S3(s)	S2(t)
		WRV	0.73	0.68	0.73
		SMU	S2	S2	S2
9	Ga	Ga (50)	S1(w)	S2(w)	S1(w)
		Ra (30)	S3(w)	N(w)	S3(w)
		So (20)	S3(w)	N(w)	S3(w)
		WRV	0.70	0.37	0.70
		SMU	S2	N	S2
10	GPi	GPi (50)	S1(f)	S2(s)	S1(s)
		Ra (30)	S3(w)	N(w)	S3(w)
		So (20)	S3(w)	N(w)	S3(w)
		WRV	0.70	0.37	0.70
		SMU	S2	N	S2
14	LC	LCr (50)	S3(s)	S3(s)	S3(s)
		LRa (30)	S2(t)	S2(t)	S2(t)
		EPo (20)	N(s)	N(s)	N(s)
		WRV	0.47	0.47	0.47
		SMU	S3	S3	S3
15	LEz	LEz (50)	S2(f)	S2(s)	S2(f)
		Ra (30)	S3(w)	N(w)	S3(w)
		Ga (20)	S1(f)	S2(s)	S1(s)
		WRV	0.70	0.51	0.70
		SMU	S2	S3	S2
16	LMo	LMo (50)	N(t)	N(t)	N(t)
		EAt (30)	S3(t)	S3(t)	S3(t)
		LdC (20)	N(t)	N(t)	N(t)
		WRV	0.15	0.15	0.15
		SMU	N	N	N
17	LR	LRa (50)	N(t)	N(t)	N(t)
		CPo (30)	N(t)	N(t)	N(t)
		Stone (20)			
		WRV			
		SMU	N	N	N

Table11.11. Land suitability for irrigated agriculture in Burruyacú district (continued).

Soil map unit			Soybean	Citrus	Sugarcane
Number	Local name	Soil phases (%)			
19	PMo	PMo (50)	N(t)	N(t)	N(t)
		LCa (30)	N(t)	N(t)	N(t)
		Stone (20)			
		WRV			
		SMU	N	N	N
21	Taj	ETa (50)	S3(t)	N(w)	S3(t)
		Vi (30)	S3(t)	S3(t)	S3(t)
		TPo (20)	S3(t)	N(w)	S3(t)
		WRV	0.50	0.15	0.50
		SMU	S3	N	S3
22	TP	TPo (50)	S3(w)	N(w)	S3(w)
		SRo (30)	S3(w)	N(w)	S3(w)
		Vi (20)	S1(f)	S2(s)	S1
		WRV	0.58	0.15	0.58
		SMU	S3	N	S3
23	Vir	Vi (50)	S1(f)	S2(s)	S1
		TPo (30)	S3(w)	N (w)	S3(w)
		ETa (20)	S3(w)	N (w)	S3(w)
		WRV	0.7	0.25	0.74
		SMU	S2	N	S2

Soil map units missing in the list correspond to riverbeds, streams and narrow floodplains that have not been evaluated.
S1 = high suitability; S2 = moderate suitability; S3 = marginal suitability; N = not suitable.
Letters in brackets refer to major limitations: c = climate; t = slope; w = wetness (flooding and/or drainage); s = physical soil characteristics; f = soil fertility characteristics.
WRV = average of the values assigned to each soil phase according to its suitability class.
SMU = suitability class of each map unit for each crop.

Table 11.12. Land suitability for rain-fed agriculture under rainy-year conditions in Burruyacú district.

Soil map unit			Soybean	Soybean-alfalfa	Alfalfa	Maize-alfalfa	Maize	Wheat	Citrus	Safflower
No	Local name	Soil phases (%)								
1	Abr	SdA (50)	S3(w)		S3(w)		S3(w)	S3(s)	N(c)	S2(w)
		EAt (30)	S3(w)		S3(w)		S3(w)	S3(s)	N(c)	S3(s)
		LdC (20)	S3(w)		S3(w)		S3(w)	S2(s)	N(c)	S2(w)
		WRV	0.50	0.50	0.50	0.50	0.50	0.55		0.66
		SMU	S3	S3	S3	S3	S3	S3	N	S2
2	Ald	Al (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		ECh (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		Ca (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		WRV	0.50	0.50	0.50	0.50	0.50	0.73		0.73
		SMU	S3	S3	S3	S3	S3	S2	N	S2
4	BU	Bu (50)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(f)
		PdH (30)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		EPu (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		WRV	0.10	0.10	0.10	0.10	0.10	0.55		0.55
		SMU	N	N	N	N	N	S3	N	S3
6	EA	EAt (50)	S3(s)		S3(s)		S3(s)	S3(s)	N(c)	S3(s)
		SdA (30)	S2(s)		S2(c)		S2(c)	S3(s)	N(c)	S2(f)
		LdC (20)	S2(s)		S2(c)		S2(c)	S2(s)	N(c)	S2(s)
		WRV	0.62	0.62	0.62	0.62	0.62	0.55		0.62
		SMU	S2	S2	S2	S2	S2	S3	N	S2
7	EC	ECh (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		ESu (30)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		SAl (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		WRV	0.50	0.50	0.50	0.50	0.50	0.73		0.73
		SMU	S3	S3	S3	S3	S3	S2	N	S2
9	Ga	Ga (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		Ra (30)	N(w)		N(w)		N(w)	S3(w)	N(c)	S3(w)
		So (20)	N(w)		N(w)		N(w)	S3(w)	N(c)	S3(f)
		WRV	0.25	0.25	0.25	0.25	0.25	0.62		0.62
		SMU	N	N	N	N	N	S2	N	S2
10	GPi	GPi (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		Ra (30)	N(w)		N(w)		N(w)	S3(w)	N(c)	S3(w)
		So (20)	N(w)		N(w)		N(w)	S3(w)	N(c)	S3(f)
		WRV	0.25	0.25	0.25	0.25	0.25	0.62		0.62
		SMU	N	N	N	N	N	S2	N	S2
14	LC	LCr (50)	S3(w)		S3(w)		S3(w)	S3(s)	N(w)	S3(s)
		LRa (30)	S3(w)		S3(w)		S3(w)	S3(s)	N(w)	S2(c)
		EPo (20)	N(s)		N(s)		N(s)	N(s)	N(w)	N(s)
		WRV	0.40	0.40	0.40	0.40	0.40	0.40		0.47
		SMU	S3	S3	S3	S3	S3	S3	N	S3
15	LEz	LEz (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		Ra (30)	N(w)		N(w)		N(w)	S3(w)	N(c)	S3(w)
		Ga (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(c)	S2(w)
		WRV	0.40	0.40	0.40	0.40	0.40	0.65		0.65
		SMU	S3	S3	S3	S3	S3	S2	N	S2
16	LMo	LMo (50)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		EAt (30)	S3(s)		S3(s)		S3(s)	S3(s)	S3(c)	S3(s)
		LdC (20)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		WRV	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
		SMU	S3	S3	S3	S3	S3	S3	S3	S3

Table11.12. Land suitability for rain-fed agriculture under rainy-year conditions in Burruyacú district (continued).

Soil map unit			Soybean	Soybean-alfalfa	Alfalfa	Maize-alfalfa	Maize	Wheat	Citrus	Safflower
No	Local name	Soil phases (%)								
17	LR	LRa (50)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		CPo (30)	S3(t)		S3(t)		S3(t)	S3(t)	S3(c)	S3(t)
		Stone (20)								
		WRV	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
		SMU	S3	S3	S3	S3	S3	S3	S3	S3
19	PMo	PMo (50)	S3(t)		S3(t)		S3(t)	S3(t)	N(s)	N(s)
		LCa (30)	S3(t)		S3(t)		S3(t)	S3(t)	S3(t)	S3(t)
		Stone (20)								
		WRV	0.4	0.4	0.4	0.4	0.4	0.4	0.15	0.15
		SMU	S3	S3	S3	S3	S3	S3	N	N
21	Taj	ETa (50)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		Vi (30)	S3(w)		S3(w)		S3(w)	S2(t)	N(w)	S2(c)
		TPo (20)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		WRV	0.15	0.15	0.15	0.15	0.15	0.57		0.57
		SMU	N	N	N	N	N	S3	N	S3
22	TP	TPo (50)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		SRo (30)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		Vi (20)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		WRV	0.10	0.10	0.10	0.10	0.10	0.55		0.55
		SMU	N	N	N	N	N	S3	N	S3
23	Vir	Vi (50)	S3(w)		S3(w)		S3(w)	S2(w)	N(w)	S2(c)
		TPo (30)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		ETa (20)	N(w)		N(w)		N(w)	S3(w)	N(w)	S3(w)
		WRV	0.25	0.25	0.25	0.25	0.25	0.62		0.62
		SMU	N	N	N	N	N	S2	N	S2

Soil map units missing in the list correspond to riverbeds, streams and narrow floodplains that have not been evaluated.
S1 = high suitability; S2 = moderate suitability; S3 = marginal suitability; N = not suitable.
Letters in brackets refer to major limitations: c = climate; t = slope; w = wetness (flooding and/or drainage); s = physical soil characteristics; f = soil fertility characteristics.
WRV = average of the values assigned to each soil phase according to its suitability class.
SMU = suitability class of each map unit for each crop.

CHAPTER 12

CONCLUSIONS

J.A. Zinck

12.1. LAND USE CHANGES

In the past, the study area was fully covered by Chaco forest and this was used for fodder and timber. After Spanish colonialists introduced cows into the area, cattle browsing became the first step of resources degradation. Starting by the end of the 19th century, timber extraction concentrated on the selective removal of quebracho trees for railway sleepers. The Chaco forest was also a source of tannin. Following cattle expansion, leather production was reported as an important economic activity in the Burruyacú area in the last century, while becoming raw material for handicraft in more recent years. Nowadays, the degraded remnants of the Chaco forest are used for cattle browsing.

The current Chaco forest in the study area has been strongly degraded, resulting from logging, repeated burning, grazing and cutting for fuel wood. The proportion of shrub species is high and a few species (1 to 3) dominate the stands in proportions of 50% or more, indicating relatively low biodiversity. Shrub density increases and biodiversity decreases from west to east and from north to south, reflecting differences in rainfall and site quality. In general, basal area as a measure of biomass is controlled by the occasional presence of a few big trees, such as algarrobo, mistol, quebracho and tala. Basal area values increase from west to east and from north to south, which means that shrubs with small stem diameters play an increasing role in the biomass in southeastern direction.

At present, crop production is the main economic activity. The most important crop is soybean, followed by maize, wheat and vegetables. The first data about soybean production in Tucumán province were recorded in the early 1960s, with high yields in spite of poor management knowledge in those days. Currently, different farming systems are implemented, depending mainly upon the economic wealth of the farmer. No-tillage, direct sowing, irrigation and fertilizers are applied on some large farms, but conventional farming is still practiced on small landholds.

Since the 1970s, there has been an increase in annual rainfall. This, together with attractive market prices for soybean, credit opportunities, easy accessibility to the area, suitable soils and favourable land tenure, led to the expansion of the agricultural production and to an increasing demand for new land. Farmland rapidly expanded at the expense of the forest cover, resulting in a drastic reduction of the Chaco forest. Mechanized deforestation replaced the traditional, less harming hand-clearing. Trees were felled using heavy machinery, usually a set of two bulldozers connected by a chain.

To monitor the conversion of forest to cropland, four different procedures were applied to the available remote sensing data covering five consecutive dates (1971, 1972, 1976, 1985 and 1991). The best approach was a simplified procedure, which took into account all the imagery available and operated with a limited number of six land use change classes, allowing easy interpretation. The extreme-dates procedure, which used only four land use change classes and two images, provided the lowest land use change figure. The color-composite procedure, easy and fast to apply, was suitable to show land use changes over three dates. The non-simplified procedure was the most complicated approach, but also the only one that considered the possibility of forest regeneration. After adding up the changes detected during the four selected periods, each procedure gave a total figure of the magnitude of the land use changes that occurred over the whole time span 1971-1991, such as follows: 49% by the extreme-dates procedure; 54% by the simplified procedure; 55% by the color-composite procedure; and 57% by the non-simplified procedure. From the total forest area in 1971, forest conversion to cropland was 6% in 1971-1972 (3% per year), 20% in 1972-1976 (5% per year), 45% in 1976-1985 (5% per year) and 7% in 1985-1991 (1% per year). In the period 1971-1991, an extent of 57,000 ha has been cleared, representing 78% of the original forest area, at an average deforestation rate of 2850 ha per year.

The most important land use changes took place in the period 1972-1985. Increasing rainfall played an important role in promoting the expansion of the agricultural frontier. Large forest patches survived only in the eastern part of the study region because of less rainfall and unpaved access ways. West of road 304, forest subsisted because of sloping piedmont relief. In the following period (1985-1991), land use changes became less significant, with the incorporation of fewer areas into cropland, mainly along road 34 and in the central part of the study region.

Annual rainfall fluctuated considerably around a long-term regional mean of 867 mm over the largest part of the last century (1916-1989). From the beginning of the 1970s, rainfall consistently increased, especially in the western and southern parts of the study region. However, annual rainfall remains strongly variable not only in the drier east of the area but also in the moister west. Rainfall varies practically from year to year, with large differences per sets of 2-3 years, making crop planning hazardous. Multi-annual periods of lower and higher rainfall succeed each other in cycles of 10-20 years. The development of soybean cultivation in the early 1970s coincided roughly with the beginning of a cycle of relative rainfall abundance, which started declining again in the late 1980s. The lack of data for the decade 1990-2000 does not allow extending the correlation soybean-rainfall into recent years. But rainfall decrease certainly puts at risk soybean cultivation in the drier east of the study area and will very likely slow down the expansion of the agricultural frontier eastwards.

12.2. LAND DEGRADATION

Soils derived from loess are naturally vulnerable to the impact of farming. Their unbalanced particle size distribution, with high silt and low clay contents causing weak structural stability, makes loess soils prone to wind and water erosion and susceptible to sealing and crusting.

The conversion of the forest cover to cropland and the farming practices used in the area, especially for the mono-cropping of soybean, have contributed to land degradation in terms of compaction and fertility depletion. Soil compaction starts with mechanized forest clearing and increases with the use of heavy tillage and harvest machinery. Flooding, deposition of sediments and river overbank flows occur during heavy rainfall periods.

The crossing of six geographic locations, strategically distributed in west-east and north-south directions, with five forest reclamation time ranges constitutes a matrix approach to analyzing and assessing land degradation, which allows highlighting simultaneously spatial and temporal trends. Bulk density, penetration resistance and water infiltration were used to monitor soil compaction, while organic carbon, exchangeable calcium and soluble phosphorus were used to monitor fertility depletion. Changes affecting these attributes over a period of 25-30 years (<1971-1996) reveal a clear tendency to deterioration of soil quality under mechanized mono-cropping of soybean.

(1) Bulk density

The regional mean value of bulk density in the topsoil is 1.09 Mg m^{-3} in the first horizon and 1.23 Mg m^{-3} in the second one, corresponding to an increase of 13%. In all study areas, average bulk density values in agricultural fields are up to 30% higher in the lower topsoil than in the upper one. Thus, while physical conditions of the arable layer are overall good, there is a general tendency of compaction in the second horizon, with plow-pan formation. A regional trend is visible in the northern transect, where bulk density values seem to parallel the displacement of the agricultural frontier from west to east, with the highest values in the oldest reclamation areas in the west.

In general, there is a slight increase in bulk density in both topsoil horizons from the younger to the older fields. Upon reclamation, the physical conditions of the upper topsoil seem to be improved, probably because annual tillage removes the earlier trampling effect of cattle browsing in the Chaco forest. In all land reclamation ranges considered, bulk density is higher in the lower topsoil than in the upper one, reflecting compaction beneath the arable layer through plow-pan formation. In conclusion, soil compaction takes place in all time ranges considered, mainly in the lower topsoil, and increases with time in proportions not yet dramatic. Intensive farming for commercial crop production and the use of heavy machinery are the main factors causing soil compaction.

(2) Penetration resistance

There is a clear difference of penetration resistance between forest and crop sites. The topsoil is more homogeneous in the cropland than under forest, because yearly plowing over two to three decades caused homogenization of the surface soil. The presence of a plow-pan is reflected by the increase of penetration resistance between 10 cm and 20 cm depth, especially at 15 cm depth. In contrast, the dense rooting system in the forest topsoil makes penetration resistance more variable.

The spatial pattern of penetration resistance varies between forest and crop sites. In the crop field, isolines of penetration resistance tend to be concentrical. In the forest, the isolines are elongated between 0 cm and 35 cm depth, corresponding to soil compaction along the pathways repeatedly used by roaming cattle when browsing the Chaco forest.

At both the forest and crop sites, penetration resistance increases from 35-40 cm downwards, indicating the presence of Bt horizons in the subsurface soil. At similar depths, penetration resistance is less variable at the crop site than at the forest site. Under the long-lasting effect of plowing, the arable soil has become more uniform, especially between 15 cm and 40 cm depth. In contrast, the upper forest soil mantle shows short-distance variability because of its dense rooting system and intense biological activity, and the effect of these properties on soil structure and aeration. Thus, the original short-distance pedodiversity, typical of the forest environment, has been significantly impoverished through monocultural farming.

(3) Infiltration

In general, infiltration velocities at 30 minutes into the simulated rain, with splash, are about 1mm/min. Infiltrated volumes during half-hour periods are mostly 50-100 mm. This means that the soil can cope with very heavy rainfall when it is dry, but abundant overland flow and extensive inundation occur in rainy periods when infiltration is lower than rain intensity. Infiltration is greater and soil sealing is less in Chaco forest soils and recently reclaimed land than in older arable land. Under Chaco forest, infiltration varies at short distance because of cattle trails, footpaths and shallow roots.

Test results obtained during the dry season with limited infiltration times and rain volumes did not generate saturation above relatively impermeable subsoil horizons. It is expected, however, that layers such as plow-pans and Bt horizons will affect infiltration in a dominant way during the later part of the rainy season, with frequent rains at close intervals. In this condition, the older arable land may produce strong overland flow. The cross-section of the wetted soil after infiltration frequently shows lateral spreading and thus indicates stagnation of infiltrated water at the depth of a few centimetres. This is caused by the platy structure of the plow-pan. Generally, the eastern part of the study area has lower infiltration than the western part.

(4) Organic carbon

In general, average organic carbon content is higher in the first horizon (2.55%) than in the second (1.53%), corresponding to a difference of 40%. When compared to conventional standards, these contents can be considered medium to high in the upper part of the topsoil and low in its lower part. Organic carbon clearly decreases from west to east in both horizons, paralleling a west-east decrease in annual rainfall. This might reflect the influence of the climate gradient on biomass production and organic matter incorporation into the soil. After accelerated depletion in the first couple of years following deforestation, organic carbon content decreases slowly over time to reach about 60% of the original forest content in the oldest crop fields (from 2.54% to 1.77% over the period <1970-1996). The lower topsoil layer does not show significant variations in organic carbon content over time. In spite of continuous depletion, the organic carbon status at regional level is not yet limiting for agriculture.

(5) Exchangeable calcium

Exchangeable calcium is high throughout the topsoil, with average values slightly higher in the first horizon (17.5 cmol kg^{-1}) than in the second one (14.9 cmol kg^{-1}). In the southern transect (La Ramada-Piedrabuena), Ca^+ decreases from west to east in the whole topsoil. The long-term tendency is one of declining Ca^+ in both topsoil horizons, with some kind of stabilization in old crop fields at around one third of the original Ca^+ content under forest conditions.

(6) Soluble phosphorus

On average, there is about two times more soluble phosphorus in the first horizon than in the second one (26.2 mg kg^{-1} and 13.4 mg kg^{-1}, respectively). When compared to the other selected topsoil parameters, soluble phosphorus shows a different spatial pattern, with values increasing at the same time from west to east and from south to north. According to conventional standards, soluble phosphorus contents of the study region can be considered low to very low throughout. There is an overall trend of decreasing soluble phosphorus in the upper topsoil with time. After 10-15 years of agricultural use, the content in cultivated land is 40-60% lower than that in soils under forest. The soluble phosphorus left over after 40 years of cropping was only 17% of the original forest content. In the lower topsoil, the soluble phosphorus content is in general half that of the upper topsoil in agricultural fields as well as under forest. The temporal depletion pattern is similar to that shown by organic carbon.

12.3. LAND USE POTENTIALS

It was hypothesized that crop diversification and crop rotation could contribute to improve the tillage conditions and reduce land degradation caused by the mono-cropping of soybean.

According to physical land evaluation, only 16% of the study area has high suitability for most of the selected land utilization types, including soybean, maize, wheat, alfalfa, citrus, safflower and sugarcane. The most promising farming area is located in the southwest, where the physical land conditions are most favourable for cropping on the basis of climate, landscape and soil features, including water surplus during the growing cycle of the crops, good physical and chemical soil characteristics, and flat or smooth topography.

Major limitations for cropping are low rainfall and flooding in the east of the study area, and sloping topography and flooding in the west. On older arable land, the risk of flooding rather than soil loss seems to be the most important land use limitation resulting from soil degradation. Surface storage and flow diversion are probably insufficient to reduce erosion. Water retention could be increased by incorporating plant residues in the topsoil instead of burning them. Periods of drier years may restrict yields and make it difficult to incorporate enough mulch and crop residues. Periods of wetter years may encourage cultivators to extend their activities eastwards and incur greater risk of drought.

Soybean and citrus cultivated under irrigation in areas provided with groundwater would generate yields substantially higher than those obtained under rain-fed conditions. Drip irrigation would be more adequate than furrow irrigation to avoid soil erosion. Rain-fed citrus is the crop least adapted to the area.

Cropping could be hazardous in periods of extreme climatic conditions (rainy or dry years). Wheat and safflower would be the only options, with moderate to marginal potential, under rainy-year conditions, while only safflower would be marginally adapted under dry-year conditions.

Areas with high physical land suitability for most of the crops are exposed to competition between several land utilization types and thus critical for land use allocation. Map units offering competing land use options are mainly located in the southwest of the study area. They are also the most favourable for natural regeneration of the Chaco forest. However, the latter would be successful almost everywhere, as it is the native vegetation of the study area.

Physical land suitability assessment provided results appropriate for formulating land use options to address issues of current and potential land use conflicts in the study area. One main objective was to consider land use alternatives to the soybean mono-cropping. This would lead to crop diversification in a context of climatic and economic uncertainty and contribute to reducing and maybe reverting land degradation. A consensual land use allocation plan was generated from a variety of proposed land use options, respecting the priorities given to each land utilization type by decision-makers and stakeholders in the context of formulating and implementing planning policies.

CHAPTER 13

SOIL DATA

METHODS USED FOR SOIL DESCRIPTION, SAMPLING AND ANALYSIS

Soils were described according to FAO guidelines (FAO, 1990) and classified according to USDA Soil Taxonomy (Soil Survey Staff, 2003) and the World Reference Base for Soil Resources (FAO, 1998).

Soil samples were analyzed in the laboratory of the Faculty of Agronomy and Zootechnique at the National University of Tucuman, Argentina, using the methods mentioned below. Samples with high cation exchange capacity were crosschecked at the laboratory of the International Reference and Information Centre (ISRIC), Wageningen, the Netherlands. Clay mineralogy was determined at ISRIC (Van Reeuwijk, 1993). Carbon-14 determination was carried out at the Laboratory for Isotope Research, University of Groningen, the Netherlands. The resulting radiocarbon ages were calibrated to correct errors due to natural variations of the ^{14}C content in the atmosphere, using the Seattle/Groningen method described by Van der Plicht and Mook (1989).

Methods used for soil sampling and analysis were as follows:

- Particle size analysis: sieving and pipette method (Kilmer & Alexander);
- Moisture equivalent: centrifugation;
- Effective moisture: soil water determination at sampling dates;
- Bulk density: sampling with Uhland equipment;
- Penetration resistance: using the Stiboka penetrograph (Eijkelkamp, 1989);
- Soil reaction: pH in water 1:1 using glass electrode;
- Organic carbon: Walkley & Black method;
- Cation exchange capacity: sodium acetate 1N at pH 8.2 and ammonium acetate 1N at pH 7 (Bower);
- Exchangeable bases: ammonium acetate 1N at pH7;
- Carbonate: titration with hydrochloric acid;
- Soluble phosphorus: extraction solution of ammonium fluoride 0.03N – hydrochloric acid 0.025N (Dickman & Bray and Bray & Kurtz).

References:

Eijkelkamp, 1989. Soil penetrograph catalogue. Giesbeek, The Netherlands.

FAO, 1990. Guidelines for soil profile description. Food and Agriculture Organization of the United Nations. Rome, Italy.

FAO, 1998. World reference base for soil resources. World Soil Resources Reports 84. FAO, ISRIC and ISSS. Rome, Italy.

Soil Survey Staff, 2003. Keys to soil taxonomy. Natural Resources Conservation Service, US Department of Agriculture. Washington DC, USA.

Van der Plicht, J., Mook, W.G., 1989. Calibration of radiocarbon ages by computer. Radiocarbon 31 (3): 805-816.

Van Reeuwijk, L.P., 1993. Procedures for soil analysis. Technical Paper 9. International Soil Reference and Information Centre (ISRIC). Wageningen, The Netherlands.

SOIL DESCRIPTIONS

REFERENCE SOIL PROFILES

Soil profile P1A

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo farm; 300 m northwest of the farm house; road 336
Coordinates: S 26°27'32.0", W 64°44'55.6"
USDA classification (2003): Typic Argiustoll, fine silty, mixed, thermic
WRB classification (1998): Silti-Cutanic Luvisol (Thaptoluvic)
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 640 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: maize residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize since 1994 after eight years fallow
Reclamation date: in the mid-1950s
Human influence: plowing
Described by: A. Zinck, J.M. Sayago, L. Neder
Description date: 30.05.1995 (upper horizons) and 11.09.1995 (lower horizons)

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-13	Very dark gray (10YR 3/1) silt loam, dark grayish brown (10YR 4/2) dry; moderate medium to coarse subangular blocky structure; slightly hard, friable, plastic and sticky; high porosity; few roots; gradual boundary.
Ad	13-13/15	Dark brown (7.5YR 3/3) silty clay loam to silt loam, grayish brown (10YR 5/2) dry; moderate fine to medium platy structure; hard, friable, plastic and sticky; limited porosity; few roots; abrupt and, locally, broken boundary.
Bt	13/15-35	Dark brown (7.5YR 3/2) silty clay loam to silt loam, brown (7.5YR 4.5/3) dry; moderate medium prismatic structure breaking into strong coarse blocks; hard, firm, plastic and sticky; low porosity; very few fine roots; few pedotubules; common to many distinct dark brown clay cutans (7.5YR 3/2 dry); gradual smooth boundary.
BC	35-53	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 5/4) dry; moderate medium prismatic structure breaking into moderate medium to fine subangular blocks; hard, friable, plastic and sticky; few roots; gradual smooth boundary.
C	53-90	Dark yellowish brown (10YR 3/4) silt loam, light brown (7.5YR 6/4) dry; massive; soft, friable, slightly plastic and sticky; very few roots.
2Btb1	90-140	Dark brown to brown (7.5YR 3.5/4) silt loam, brown (7.5YR 5/4) dry; moderate medium subangular blocky structure; slightly hard, friable, plastic and sticky; few clay cutans; few fine roots.
2Btb2	140-165	Yellowish brown (10YR 5/4) silt loam; moderate medium subangular blocky structure; soft, friable, plastic and sticky; few clay cutans; very few very fine roots.
2Cb	165-185	Brown (10YR 4/3) silt loam; massive; soft, friable, plastic and sticky; no roots.

Soil profile P2

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo farm; 500 m west of the farm house; road 336
Coordinates: S 26°27'32.1", W 64°45'05.9"
USDA classification (2003): Pachic Argiustoll, fine silty, mixed, thermic (bordering Typic)
WRB classification (1998): Silti-Luvic Phaeozem (Thaptoluvic)
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 650 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: A. Zinck, J.M. Sayago, L. Neder
Description date: 30.05.1995 (upper horizons) and 11.09.1995 (lower horizons)

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

A	0-28	Very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; moderate medium subangular blocky structure; slightly hard, friable, slightly plastic and sticky; medium porosity; few to common very fine and medium roots; clear smooth boundary.
Bt	28-52	Dark brown (7.5YR 3/3) silty clay loam, brown (10YR 5/3) dry; moderate coarse subangular blocky structure breaking into moderate fine and medium subangular blocks; slightly hard, friable, plastic and sticky; medium porosity; common to many clay cutans; few medium and coarse roots; gradual smooth boundary.
BC	52-74	Brown (7.5YR 4/3) silty clay loam to silt loam, brown (10YR 5/3) dry; weak medium subangular blocky structure breaking into moderate fine subangular blocks; slightly hard, friable, plastic and sticky; few clay cutans; few medium roots.
C	74-91	Brown (10YR 4/3) silt loam to silty clay loam, pale brown (10YR 6/3) dry; massive; soft, friable, slightly plastic and slightly sticky; few fine and medium roots; clear smooth boundary.
2Ab	91-97	Very dark grayish brown (10YR 3/2) silty clay loam, brown (10YR 5/3) dry; weak medium subangular blocky structure; slightly hard, friable, plastic and sticky; very few fine and medium roots; gradual smooth boundary; ^{14}C age 2840 ± 60 BP.
2Btb	97-117	Brown (7.5YR 4/2) silty clay loam, light yellowish brown (10YR 6/4) dry; moderate fine to medium subangular blocky structure; hard, friable, plastic and sticky; few clay cutans; very few fine roots; gradual smooth boundary.
2Cb	117-140	Brown (10YR 4.5/3) silt loam, light brown (7.5YR 6/4) dry; massive; slightly hard, friable, slightly plastic and slightly sticky; moderately calcareous; no roots.
3Ab	140+	Dark brown (10YR 3/3) silt loam, brown (10YR 5/3) dry; weak medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; very few fine and medium roots; gradual smooth boundary; ^{14}C age 3780 ± 40 BP.

Soil profile P3B

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo Farm, 300 m southwest of the farm house; road 336
Coordinates: S 26º27'34.4", W 64º45'04.1"
USDA classification (2003): Pachic Argiustoll, fine silty, mixed, thermic (bordering Typic)
WRB classification (1998): Silti-Cutanic Luvisol (Thaptocambic)
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 650 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: maize residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize
Reclamation date: 1991-1996
Human influence: plowing
Described by: J.M. Sayago, L. Neder, E. Flores
Description date: 20.06.1996 (upper horizons) and 13.02.1997 (lower horizons)

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-9	Very dark brown (10YR 2/2) silt loam, brown (10YR 4/3) dry; weak fine to medium blocky structure; slightly hard, friable, slightly plastic and sticky; high porosity; few to common fine roots; abundant biological activity; clear wavy boundary.
Bt	9-50	Very dark grayish brown (10YR 3/2) silty clay loam, brown (7.5YR 4/3) dry; weak coarse subangular blocky structure breaking into weak medium and fine subangular blocks; slightly hard, friable, plastic and slightly sticky; medium porosity; very few faint clay cutans; very few fine roots; clear smooth boundary.
BC	50-75	Dark brown to brown (7.5YR 3.5/3) silt loam, brown (7.5YR 5/3) dry; moderate coarse subangular blocky structure breaking into moderate medium to fine subangular blocks; slightly hard, friable, plastic and sticky; low to medium porosity; few faint clay cutans; very few very fine roots; abrupt smooth boundary.
C	75-95	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 4.5/4) dry; weak coarse subangular blocky structure breaking into weak medium and fine subangular blocks; slightly hard, very friable, plastic and sticky; abrupt smooth boundary.
2Ab	95-118	Very dark grayish brown (10YR 3/2) silt loam, light brown (7.5YR 6/4) dry; weak coarse subangular blocky structure breaking into weak medium subangular blocks; soft, friable, slightly plastic and slightly sticky; very few fine roots; abrupt smooth boundary.
2Bwb	118-140	Brown (7.5YR 4/3) silt loam, light brown (7.5YR 6/3) dry; moderate coarse subangular blocky structure breaking into medium subangular blocks; soft, friable, plastic and sticky; no roots.

Soil profile P4A

Location: Campo Elías; Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Salim farm, 250 m west of the farm house; road 336
Coordinates: S 26º33'38.9", W 64º35'04.9"
USDA classification (2003): Torrifluventic Haplustept, coarse silty, mixed, thermic (bordering coarse loamy)
WRB classification (1998): Silti-Eutric Cambisol (Thaptocambic) (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 440 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize
Reclamation date: <1970
Human influence: plowing, application of fertilizers
Described by: A. Zinck, J.M. Sayago, L. Neder
Description date: 13.09.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-8/12	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak to moderate fine and medium subangular blocky structure; slightly hard, very friable, slightly plastic and non sticky; common to many medium roots; abrupt wavy boundary.
2A1	8/12-30	Very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; moderate fine and medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; slightly calcareous; gradual smooth boundary.
2A2	30-41	Dark brown (10YR 3/3) silt loam, grayish brown (10YR 5/2) dry; moderate fine and medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; few roots; gradual smooth boundary.
2AC	41-67	Dark brown (7.5YR 3/3) silt loam, brown (10YR 5/3) dry; moderate medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; few roots; clear smooth boundary.
2C	67-90	Dark brown (7.5YR 3/4) silt loam, light brown (7.5YR 6/3) dry; massive; soft, very friable, slightly plastic and slightly sticky; very few roots; clear smooth boundary.
3Bwb1	90-117	Dark brown (7.5YR 3/4) silt loam, light brown (7.5YR 6/4) dry; weak fine subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; few roots; gradual smooth boundary.
3Bwb2	117-150	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak fine subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; strongly calcareous; ^{14}C age 6290 ± 120 BP.

Soil profile P5A

Location: Campo Elías; Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Salim farm; 150 m east of the farm house; road 336
Coordinates: S 26º33’45.2”, W 64º34’34.6”
USDA classification (2003): Pachic (Torriorthentic) Haplustoll, coarse loamy, mixed, thermic (bordering coarse silty)
WRB classification (1998): Silti-Pachic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 435 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: A. Zinck, J.M. Sayago, L. Neder
Description date: 13.09.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Oi	3-0	Litter of undecomposed dry leaves, twigs and branch fragments
A	0-13	Very dark brown (10YR 2/2) silt loam, grayish brown to dark grayish brown (10YR 4.5/2) dry; moderate fine and medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; common fine and medium roots; gradual smooth boundary.
2A	13-31	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/2) dry; moderate fine to medium subangular blocky structure; hard, friable, slightly plastic and slightly sticky; common to many fine and medium roots; gradual smooth boundary.
2AC	31-64	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 5/3) dry; moderate fine to medium subangular blocky structure; hard, friable, slightly plastic and slightly sticky; many medium roots; clear smooth boundary.
2C	64-110	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/3) dry; massive; soft, very friable, slightly plastic and slightly sticky; few fine roots; clear smooth boundary.
3Bwkb	110-160	Strong brown (7.5YR 4/6) silt loam, light brown (7.5YR 6/4) dry; fine to medium subangular blocky structure; friable, slightly plastic and slightly sticky; few fine carbonate nodules; many fine roots.

Soil profile P6B

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 800 m west of the farm house and 300 m north of road 336
Coordinates: S 26º32'15.3", W 64º40'17.7"
USDA classification (2003): Typic Haplustoll, coarse loamy, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 500 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture, maize
Reclamation date: <1970
Human influence: plowing, application of fertilizers, surface compaction
Described by: J.M. Sayago, L. Neder, A. Zinck
Description date: 21.11.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-10	Very dark brown (10YR 2/2) silt loam, grayish brown (10YR 5/2) dry; granular to moderate fine and medium subangular blocky structure; slightly hard, loose, plastic and sticky; few fine and very fine roots; clear smooth boundary.
A2	10-28	Very dark brown (10YR 2/2) silt loam, grayish brown (10YR 5/2) dry; moderate medium subangular blocky structure; hard, friable, slightly plastic and slightly sticky; few very fine and fine roots; clear smooth boundary.
Bw	28-51	Dark grayish brown (10YR 4/2) silt loam, brown (7.5YR 4/3) dry; moderate fine and medium subangular blocky structure; slightly hard, friable, plastic and sticky; few fine and very fine roots; clear smooth boundary.
C	51-70	Brown (7.5YR 4/4) silt loam, brown (7.5YR 5/3.5) dry; weak medium subangular blocky structure; soft, friable, plastic and slightly sticky; few fine and very fine roots; clear wavy boundary.
2Bwb1	70-106	Brown (7.5YR 4/3) silt loam, light brown (7.5YR 6/3) dry; weak medium subangular blocky structure; slightly hard, very friable, plastic and sticky; very few very fine roots; gradual smooth boundary.
2Bwb2	106-138	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; moderate fine and medium subangular blocky structure; soft, very friable, slightly plastic and sticky; no roots; gradual smooth boundary.
2Cb	138-168	Light brown (7.5YR 6/4 dry) silt loam; very weak coarse to medium subangular blocky structure; soft, very friable, plastic and sticky; no roots.

Soil profile P7B

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 700 m west of the farm house and 400 m north of road 336
Coordinates: S 26º32'13.8", W 64º40'13.0"
USDA classification (2003): Entic Haplustoll, coarse loamy, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 495 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: J.M. Sayago, L. Neder, A. Zinck
Description date: 21.11.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Oi	3-0	Litter of undecomposed dry leaves, twigs and branch fragments
A1	0-21	Very dark brown (10YR 2/2) loam, brown (7.5YR 4/2) dry; massive breaking into moderate medium subangular blocky structure; hard, slightly plastic and slightly sticky; few roots; gradual wavy boundary.
A2	21-39	Very dark brown (10YR 2/2) loam, brown (7.5YR 4/2) dry; moderate medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; common roots; gradual boundary.
A3	39-68	Dark brown (7.5YR 3/2) loam, brown (7.5YR 4/2) dry; moderate medium subangular blocky structure; very friable, slightly plastic and slightly sticky; carbonate nodules; few fine roots; wavy boundary.
C	68-90	Dark brown (7.5YR 3/2) silt loam to loam, brown (7.5YR 4/4) dry; massive to subangular blocky structure; slightly hard, slightly plastic and slightly sticky; very few roots.
2Bwb1	90-118	Brown (7.5YR 4/3) loam, light brown (7.5YR 6/3) dry; strong medium subangular blocky structure; slightly hard, firm, slightly plastic and sticky; very few medium roots; abrupt smooth boundary; ^{14}C age 3040 ± 40 BP.
2Bwb2	118-140	Brown (7.5YR 4/4) loam, light brown (7.5YR 6/4) dry; moderate to strong medium subangular blocky structure; hard, firm, plastic and slightly sticky; very few very fine roots; abrupt wavy boundary.
2Cb	140-155	Strong brown (7.5YR 4/6) silt loam, light brown (7.5YR 6/4) dry; weak medium subangular blocky structure; soft, friable; strongly calcareous; very few fine roots.

Soil profile P8B

Location: Campo Elías; Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Salim farm; 450 m south of the farm house; road 336
Coordinates: S 26°34'09.2", W 64°34'54.5"
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 440 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1991-1996
Human influence: application of fertilizers, surface compaction
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 23.11.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-11	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/3) dry; weak medium subangular blocky structure; loose, slightly plastic and slightly sticky; few roots.
Bw1	11-28	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/2) dry; moderate medium subangular blocky structure; slightly hard, firm, slightly plastic and slightly sticky; few roots; clear boundary.
Bw2	28-40	Dark yellowish brown (10YR 3/4) silt loam, strong brown (7.5YR 4/6) dry; moderate medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; few fine roots.
C	40-52	Brown (7.5YR 4/4) silt loam, brown (7.5YR 5/4) dry; massive to weak medium subangular blocky structure; slightly hard, very friable, slightly plastic and slightly sticky; few fine roots.
2Bwb1	52-90	Brown (7.5YR 4/4) silt loam, light brown (7.5 YR 6/4) dry; moderate medium subangular blocky structure; firm, slightly plastic and slightly sticky; few roots; gradual boundary.
2Bwb2	90-107	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; moderate medium subangular blocky structure; friable, slightly plastic and slightly sticky; gradual boundary.
2Bwb3	107-120	Brown (7.5YR 4/4) silt loam, strong brown (7.5YR 5/6) dry; subangular blocky structure; very friable, slightly plastic and slightly sticky; gradual boundary.
3Ckb	120-145	Brown (7.5YR 4/4) silt loam, strong brown (7.5YR 5/6) dry; subangular blocky structure to massive; soft, friable; few carbonate nodules.

Soil profile P9B

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Santiago Garmendia farm; road 336
Coordinates: S 26º32'13.4", W 64º42'21.1"
USDA classification (2003): Typic Haplustoll, fine silty, mixed, thermic (bordering coarse silty)
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: glacis-terrace
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 560 m.a.s.l.
General topography: slightly undulating
Local topography: 0-3% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: N-S strips of burned material; crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; vegetables
Reclamation date: 1991-1996
Human influence: clearing, burning
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 23.11.1995

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-11	Very dark brown (10YR 2/2) silt loam, dark grayish brown (10YR 4/2) dry; granular to subangular blocky structure; common fine to medium and very few coarse roots; clear smooth boundary.
Ad	11-29	Very dark brown (10YR 2/2) silt loam, brown (10YR 4/3) dry; medium subangular blocky structure; friable; common medium and very few coarse roots; clear smooth boundary.
Bw1	29-50	Dark brown (10YR 3/3) silt loam, brown (10YR 4.5/3) dry; moderate medium subangular blocky structure; firm; few clay cutans; common fine and medium roots; gradual smooth boundary.
Bw2	50-72	Dark brown (7.5YR 3/4) silt loam, brown (10YR 4/3) dry; subangular blocky structure; few fine roots; gradual smooth boundary.
C	72-110	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 4.5/4) dry; weak medium subangular blocky structure; firm; few carbonate nodules; few fine roots; gradual smooth boundary.
2Bwb	110-135	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; moderate coarse subangular blocky structure; slightly hard, friable; very few fine and very fine roots.
2Cb	135-150	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; moderate coarse subangular blocky structure; soft, friable; no roots.

Soil profile P10

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: 200 m north of school 369 located on road 317 and 15 km east of road 304
Coordinates: S 26°43'24.2", W 64°52'48.4"
USDA classification (2003): Entic Haplustoll, fine loamy, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptoluvic)
Landscape: plain
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 480 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: slight sheet erosion
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 01.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Oi	1-0	Litter of green and dead leaves, partially decomposed, twigs and branch fragments
A1	0-6	Very dark brown (10YR 2/2) silt loam, grayish brown (10YR 5/2) dry; moderate fine and medium granular structure; soft, very friable, non plastic and slightly sticky; high porosity; common fine and medium roots; clear smooth boundary.
A2	6-21	Very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; moderate medium and fine subangular blocky structure; slightly hard, friable, plastic and sticky; medium porosity; common very fine and few medium to coarse roots; gradual smooth boundary.
A3	21-38	Very dark brown (7.5YR 2.5/2) silt loam, brown (10YR 5/3) dry; moderate medium and fine subangular blocky structure; hard, very friable, plastic and slightly sticky; medium porosity; common very fine and few medium to coarse roots; clear smooth boundary.
C	38-57	Brown (7.5YR 5/4) silt loam, light yellowish brown (10YR 6/4) dry; strong medium and fine subangular blocky structure; slightly hard, friable, plastic and slightly sticky; medium porosity, common very fine and few medium to coarse roots; clear smooth boundary.
2BAb	57-88	Dark brown (7.5YR 3/2) silty clay loam to silty clay, grayish brown (10YR 5/2) dry; weak medium to coarse prismatic structure breaking into strong medium subangular blocks; strong micro-aggregation; hard, firm, plastic and sticky; few dark clay cutans in pores; common pedotubules; medium porosity; few fine and very few coarse roots; gradual smooth boundary; ^{14}C age 4670 ± 60 BP.
2Btb	88-128	Dark brown (7.5YR 3/3) silty clay loam, brown (7.5YR 4/4) dry; weak medium to coarse prismatic structure breaking into strong medium subangular blocks; strong micro-aggregation; hard, friable, plastic and sticky; common dark clay cutans in pores and few on pedfaces; medium porosity; few fine and very few coarse roots; clear smooth boundary.
2Cb	128-150	Strong brown (7.5YR 4/6) silt loam, light brown (7.5YR 6/3) dry; moderate fine to medium subangular blocky structure; very strong micro-aggregation; hard, firm, plastic and slightly sticky; medium porosity; few fine roots.

Soil profile P11

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: 450 m north of school 369 located on road 317 and 15 km east of road 304
Coordinates: S 26°43’21.4”, W 64°52’48.1”
USDA classification (2003): Entic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptoluvic)
Landscape: plain
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 480 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: slight rill erosion
Soil effective depth: no rooting limitation
Surface characteristics: slight to moderate surface crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1991-1996
Human influence: plowing
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 02.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-12	Very dark brown (10YR 2/2) silt loam, grayish brown (10YR 5/2) dry; moderate fine subangular blocky to moderate fine granular structure; soft, very friable, slightly plastic and slightly sticky; high porosity; common fine and very fine roots; clear smooth boundary.
A2	12-32/36	Very dark brown (10YR 2/2) silt loam to silty clay loam, grayish brown (10YR 5/2) dry; moderate fine to medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; medium to high porosity; very few coarse, few fine and very fine roots; gradual wavy boundary.
C	32/36-52	Dark brown (7.5YR 3/4) silt loam, light brown (7.5YR 6/4) dry; weak fine and medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; high porosity; few fine and very fine roots; smooth clear boundary.
2Ab	52-77	Very dark grayish brown (10YR 3/2) silty clay loam to silt loam, pale brown (10YR 6/3) dry; moderate fine and medium subangular blocky structure; hard, firm, plastic and sticky; medium porosity; few fine and very fine roots; gradual smooth boundary.
2BAb	77-100	Dark brown (7.5YR 3/3) silty clay loam, brown (10YR 5/3) dry; weak coarse prismatic structure breaking into strong mediun to coarse subangular blocks; hard, firm, very plastic and sticky; common distinct clay cutans in pores and few faint clay cutans on pedfaces; medium porosity; very few very fine roots; gradual smooth boundary.
2Btb	100-130	Brown (7.5YR 4/4) silt loam to silty clay loam, light brown (7.5YR 6/4) dry; weak medium prismatic structure breaking into moderate medium subangular blocks; slightly hard, firm, very plastic and sticky; common distinct clay cutans in pores and few faint clay cutans on pedfaces; medium porosity; very few very fine roots; clear smooth boundary.
2Cb	130-150	Dark brown (7.5YR 3/3) silt loam, light brown (7.5YR 6/4) dry; moderate fine to medium subangular blocky structure; slightly hard, friable, plastic and sticky; medium porosity; no roots.

Soil profile P12

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: 450 m north of road 317, 15 km east of road 304, approximately 600 m east of profile site P11
Coordinates: S 26°43’28.8”, W 64°52’18.0”
USDA classification (2003): Entic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptoluvic)
Landscape: plain
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 480 m.a.s.l.
General topography: flat
Local topography: 1-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: slight to moderate rill erosion
Soil effective depth: no rooting limitation
Surface characteristics: generalized surface crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: <1970
Human influence: plowing
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 03.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap1	0-8	Very dark gray (10YR 3/1) silt loam, dark grayish brown (10YR 4/2) dry; weak platy structure breaking into moderate fine to very fine subangular blocks; soft, very friable, slightly plastic and slightly sticky; common fine and few medium pores; common fine and very fine roots; clear smooth boundary.
Ap2	8-20	Black (10YR 2/1) silt loam, dark grayish brown (10YR 4/2) dry; moderate fine and very fine subangular blocky structure; slightly hard, very friable, slightly sticky and slightly plastic; common fine and few medium pores; few fine and very fine roots; clear smooth boundary.
Ad	20-35/40	Black (10YR 2/1) silt loam to silty clay loam, dark grayish brown (10YR 4/2) dry; moderate medium to coarse subangular blocky structure; hard, friable, slightly sticky and slightly plastic; few fine pores; few fine and very fine roots, very few medium roots; gradual wavy boundary.
C	35/40-62	Brown (7.5YR 4/3) silt loam, light brown (7.5YR 6/4) dry; weak medium to fine subangular blocky structure; soft, very friable, slightly plastic and slightly sticky; common fine and few medium pores; few fine roots; clear smooth boundary.
2BAb	62-99	Dark brown (7.5YR 3/3) silt loam to silty clay loam, light brown (7.5YR 6/4) dry; weak medium to coarse prismatic structure breaking into strong medium to coarse subangular blocks; strong micro-aggregation; slightly hard, firm, sticky and plastic; common faint dark clay cutans in pores; medium porosity; few very fine roots; clear smooth boundary.
2Btb	99-134/140	Brown (7.5YR 4/4) silt loam to silty clay loam, light brown (7.5YR 6/4) dry; weak medium to coarse prismatic structure breaking into strong medium to coarse subangular blocks; hard, firm, very sticky and plastic; common distinct dark brown (7.5YR 3/3) clay cutans in pores and on pedfaces; medium porosity; few fine and very few very fine roots; gradual wavy boundary.
2Cb	134/140-155	Strong brown (7.5YR 4/6) silt loam, reddish yellow (7.5YR 6/6) dry; weak fine and medium subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; medium porosity; very few fine and very fine roots.

Soil profile P13

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Blasco farm; 1.6 km from La Tuna on road 317
Coordinates: S 26º45'23.8", W 64º40'57.3"
USDA classification (2003): Pachic (Aridic) Haplustoll, coarse silty, mixed, thermic (bordering fine silty)
WRB classification (1998): Silti-Pachic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 410 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: slight sheet erosion
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 03.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Oi	2-0	Litter of green and dead leaves, partially decomposed, twigs and branch fragments; abrupt smooth boundary.
A1	0-8	Very dark brown (10YR 2/2) silt loam, very dark grayish brown to dark grayish brown (10YR 3.5/2) dry; moderate fine to very fine granular structure; slightly hard, friable, non sticky and slightly plastic; very high porosity; common fine and very fine roots; clear smooth boundary.
A2	8-28	Very dark brown (10YR 2/2) silt loam, very dark grayish brown to dark grayish brown (10YR 3.5/2) dry; moderate medium to fine subangular blocky structure; hard, friable, slightly sticky and slightly plastic; medium porosity; common fine and very fine roots, few medium roots; gradual smooth boundary.
A3	28-60	Dark brown (10YR 3/3) silt loam, dark grayish brown to brown (10YR 4/2.5) dry; strong fine to medium subangular blocky structure; soft, friable, slightly sticky and slightly plastic; medium porosity; few fine and very fine roots, few medium roots; clear smooth boundary.
C	60-80	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; moderate fine to medium subangular blocky structure; slightly hard, very friable, plastic and slightly sticky; medium porosity; few fine and very fine roots, very few medium roots; clear smooth boundary.
2Bwb1	80-106	Strong brown (7.5YR 4/6) silt loam, light brown to reddish yellow (7.5YR 6/5) dry; moderate medium and coarse subangular blocky structure; slightly hard, friable, slightly plastic and sticky; medium porosity; few fine and very fine roots; gradual smooth boundary.
2Bwb2	106-128	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak coarse prismatic structure breaking into strong medium and coarse subangular blocks; slightly hard, friable, plastic and slightly sticky; medium porosity; circular structures built by ants; very few fine and very fine roots; gradual smooth boundary.
2Cb	128-153	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; moderate fine to medium subangular blocky structure; slightly hard, friable, slightly plastic and slightly sticky; very few very fine roots.

Soil profile P14

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Close to Blasco farm; 1.2 km east of La Tuna on road 317
Coordinates: S 26°44'49.8", W 64°41'40.3"
USDA classification (2003): Torriorthentic Haplustoll, fine silty, mixed, thermic (bordering coarse silty)
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 415 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1991-1996
Human influence: truncation of surface horizon when clearing the forest cover with heavy machinery
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 04.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap1	0-7	Very dark brown (10YR 2/2) silt loam, brown (7.5YR 5/2) dry; moderate fine and very fine subangular blocky structure; soft, very friable, slightly plastic and slightly sticky; medium porosity; few fine and very fine roots; clear smooth boundary.
Ap2	7-20	Very dark brown (10YR 2/2) silt loam, brown (7.5YR 4/2) dry; moderate fine and medium subangular blocky structure; very hard, very friable, slightly plastic and slightly sticky; medium porosity; few medium, fine and very fine roots; gradual smooth boundary.
A3	20-38	Very dark grayish brown (10YR 3/2) silt loam, brown (7.5YR 4/2) dry; moderate fine and medium subangular blocky structure; very hard, friable, slightly plastic and slightly sticky; medium porosity; few medium, fine and very fine roots; gradual smooth boundary.
C	38-57	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/3) dry; weak to moderate fine and medium subangular blocky structure; hard, very friable, slightly plastic and non sticky; medium porosity; few fine and very fine roots, very few medium roots; clear smooth boundary.
2Ab	57-82	Brown (7.5YR 4/4) silt loam, brown (7.5YR 5/4) dry; strong fine and medium subangular blocky structure; hard, firm, plastic and slightly sticky; common pedotubules; medium porosity; very few medium, fine and very fine roots; gradual smooth boundary; ^{14}C age 2660 ± 50 BP.
2Bwb	82-131	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak medium to coarse prismatic structure breaking into strong medium subangular blocks; hard, firm, plastic and slightly sticky; common pedotubules; medium porosity; very few medium, fine and very fine roots; clear smooth boundary.
2Ckb	131-152	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak to moderate fine and medium subangular blocky structure; soft, very friable, slightly plastic and slightly sticky; medium porosity; moderately calcareous in the matrix; inclusion of brownish (7.5YR 4/4 dry) soil aggregates hard when dry, covered with strongly effervescent white powdery calcium carbonate and filaments in the aggregates (no reaction in matrix), 0.5-1cm diameter, spread over the horizon (5-6%); very few medium, fine and very fine roots.

Soil profile P15

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Blasco farm, at the southern border of Gobernador Piedrabuena, close to the train station
Coordinates: S 26°44'40.4", W 64°39'05.1"
USDA classification (2003): Torriorthentic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 405 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: rill erosion; gully nearby
Soil effective depth: no rooting limitation
Surface characteristics: crop residues; locally, surface crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: <1970
Human influence: plowing, application of fertilizers
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 05.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil slightly moist at description date):

	0-1	Rainsplash crust formed after harvest in areas not covered by crop residues; very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; platy structure in the upper 2-3mm, powdery in the lower part; soft to slightly hard, slightly plastic and slightly sticky; low porosity; clear smooth boundary.
Ap	1-9	Very dark grayish brown (10YR 3/2) silt loam, grayish brown (10YR 5/2) dry; platy to weak very fine subangular blocky structure; soft, loose, slightly plastic and slightly sticky; medium porosity; few fine and medium roots; clear smooth boundary.
Ad	9-20/30	Dark brown (10YR 3/3) silt loam, dark grayish brown to grayish brown (10YR 4.5/2) dry; platy structure breaking into strong angular blocks; soft, friable, slightly plastic and slightly sticky; low porosity; very few fine and medium roots; gradual wavy boundary.
AC	20/30-42	Dark brown (7.5YR 3/3) silt loam, light brown (7.5YR 6/3) dry; moderate fine to medium subangular blocky structure; hard, friable, slightly plastic and slightly sticky; medium to high porosity; incorporation of coarse clods from the upper horizons through deep plowing; very few fine and very fine roots; gradual smooth boundary.
C	42-61	Dark brown (7.5YR 3/4) silt loam, light brown (7.5YR 6/3.5) dry; weak to moderate fine and medium subangular blocky structure; slightly hard, firm, slightly plastic and slightly sticky; medium to high porosity; very few fine and very fine roots; clear smooth boundary.
2Bwb1	61-85	Strong brown (7.5YR 4/6) silt loam, light brown (7.5YR 6/4) dry; weak medium to coarse prismatic structure breaking into moderate fine and medium subangular blocks; slightly hard, friable, plastic and slightly sticky; common pedotubules; some tubular burrows; medium to high porosity; very few fine and very fine roots; gradual smooth boundary.
2Bwb2	85-130	Brown to strong brown (7.5YR 4/5) silt loam, light brown to pink (7.5YR 6.5/4) dry; weak medium to coarse prismatic structure breaking into moderate fine and medium subangular blocks; soft, friable, slightly plastic and slightly sticky; medium to high porosity; slightly calcareous in the lower part; inclusion of brownish (7.5YR 4/4) blocky soil aggregates hard when dry, covered with strongly effervescent white powdery calcium carbonate and filaments in the aggregates (no reaction in matrix), 0.5-1cm diameter, spread over the horizon (5-10%); some spherical insect burrows (insectos estiercoleros); no roots; clear smooth boundary.

2Ckb	130-160	Brown to strong brown (7.5YR 4/5) silt to silt loam, light brown (7.5YR 6/4) dry; weak fine and medium subangular blocky structure; soft, friable, slightly sticky and slightly plastic; medium to high porosity; no roots.

Soil profile P16

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Blasco farm; 1.5 km east of La Tuna on road 317 and 200 m south of profile site P14
Coordinates: S 26º44'53.8", W 64º41'41.7"
USDA classification (2003): Torriorthentic Haplustoll, fine silty, mixed, thermic (bordering coarse silty)
WRB classification (1998): Siltic Phaeozem (Thaptocambic)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 415 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean cropping since three years, after long fallow period
Reclamation date: <1970
Human influence: plowing, application of fertilizers
Described by: A. Zinck, L. Neder, J.M. Sayago, E. Flores
Description date: 05.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil slightly moist at description date):

Ap1	0-14	Very dark brown (10YR 2/2) silt loam; moderate fine and medium subangular blocky structure; few fine and very fine roots; clear smooth boundary.
Ap2	14-30/40	Dark brown (7.5YR 3/3) silt loam; strong medium to coarse subangular blocky structure; few fine and very fine roots; gradual wavy boundary.
C	30/40-50/55	Brown (7.5YR 4/3) silt loam; weak medium to fine subangular blocky structure; friable to very friable; very few very fine roots; clear wavy boundary.
2Bwb1	50/55-82	Dark yellowish brown (10YR 3/4) silt loam; weak coarse prismatic structure breaking into moderate medium and coarse subangular blocks; friable; very few fine and very fine roots; clear smooth boundary.
2Bwb2	82-138	Brown (7.5YR 4/4) silt loam; weak coarse prismatic structure breaking into moderate medium and coarse subangular blocks; friable; very few very fine roots; gradual smooth boundary.
2Cb	138-150	Dark brown to brown (7.5YR 3.5/3) silt loam to silt; weak fine and medium subangular blocky structure; friable to very friable; slightly calcareous; inclusion of brownish (7.5YR 4/4) blocky soil aggregates hard when dry; no roots; clear smooth boundary.

Soil profile P17

Location: La Ramada de Abajo; La Ramada area, southwest of the study region; Burruyacú, Tucumán, Argentina
Site: Zavaleta farm; 2.5 km north of road 317 and 2.5 km east of road 304
Coordinates: S 26°42'09.2", W 64°55'06.9"
USDA classification (2003): Pachic Haplustoll, fine silty, mixed, thermic (bordering Udorthentic)
WRB classification (1998): Silti-Pachic Phaeozem (Thaptoluvic)
Landscape: piedmont (distal sector)
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 530 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: A. Zinck, L. Neder, J.M. Sayago
Description date: 19.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil moist at description date):

A1	0-19	Black (7.5YR 2.5/1) silty clay loam to silt loam, very dark grayish brown (10YR 3/2) dry; moderate medium and fine subangular blocky structure; slightly hard, slightly sticky and slightly plastic; dry; common roots.
A2	19-32	Very dark grayish brown (10YR 3/2) silt loam to silty clay loam; moderate medium subangular blocky structure; hard, sticky and plastic; moderately compact; slightly moist; many roots.
A3	32-50	Very dark brown (7.5YR 2.5/2) silt loam; moderate medium and fine subangular blocky structure; friable, sticky and plastic; many roots.
AC	50-80	Dark brown (7.5YR 3/4) silt loam to silty clay loam; moderate coarse and medium subangular blocky structure; friable, sticky and plastic; common roots.
2Btb1	80-113	Dark brown (7.5YR 3/2) silty clay loam; moderate to weak coarse and medium prismatic structure breaking into subangular blocks; firm, very sticky and plastic; few faint dark clay cutans in pores and on pedfaces; few roots; ^{14}C age 5640 ± 40 BP.
2Btb2	113-125	Dark brown (7.5YR 3/2) silty clay loam; weak prismatic structure breaking into moderate medium and fine subangular blocks; friable, sticky and plastic; common dark clay cutans, faint on pedfaces and distinct in pores.

SOIL DESCRIPTIONS

SUPPORTING SOIL PROFILES

Soil profile M1

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 600 m west of the farm house and 300 m north of road 336
Coordinates: S 26º32'16.7", W 64º40'16.8"
USDA classification (2003): Typic Haplustoll, coarse loamy, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 500 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues on newly threshed field
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean, zero-tillage for three years
Reclamation date: <1970
Human influence: plowing, application of fertilizers, surface compaction
Described by: E. Flores, A. Zinck
Description date: 21.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-4	Very dark brown (10YR 2/2) silt loam, brown (10YR 5/3) dry; coarse subangular blocky structure; slightly hard, loose, plastic and very sticky; high porosity; few fine and medium roots; abrupt smooth boundary.
Ad	4-30/35	Very dark brown (10YR 2/2) silt loam, yellowish brown (10YR 5/4) dry; moderate coarse prismatic structure breaking into moderate medium to fine subangular blocks; hard, firm, plastic and sticky; low porosity; few fine and medium roots; abrupt wavy boundary.
Bw	30/35-49	Dark yellowish brown (10YR 3/4) silt loam, brown (7.5YR 5/3) dry; moderate coarse prismatic structure breaking into weak medium and fine subangular blocks; slightly hard, friable, plastic and sticky; medium porosity; few fine roots; gradual smooth boundary.
C	49-60	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/3) dry; weak medium to fine subangular blocky structure; slightly hard, very friable, plastic and very sticky; medium porosity; no roots.

Soil profile M2

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo farm; road 336
Coordinates: S 26°27'35.2", W 64°45'00.6"
USDA classification (2003): Udic Haplustoll, fine silty, mixed, thermic (bordering Argiustoll)
WRB classification (1998): Silti-Luvic Phaeozem
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 650 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize ready for harvesting
Reclamation date: 1991-1996
Human influence: plowing
Described by: E. Flores, A. Zinck
Description date: 21.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-13/15	Very dark grayish brown (10YR 3/2) silty clay loam to silt loam, grayish brown (10YR 5/2) dry; moderate coarse subangular blocky structure breaking into very fine subangular blocks; hard, friable to firm, plastic and sticky; dry; high porosity on plow ridges and low porosity in furrows; common fine and very fine roots; clear wavy boundary.
AB	13/15-48	Very dark gray (10YR 3/1) silty clay loam, dark grayish brown (10YR 4/2) dry; moderate coarse prismatic structure breaking into moderate coarse blocks; hard, firm, plastic and sticky; common fine and few very fine roots; clear smooth boundary.
Bt	48-73	Brown (7.5YR 4/2) silty clay loam, brown (7.5YR 5/4) dry; moderate to strong coarse blocky structure; hard, friable to firm, plastic and sticky; few fine roots; few pedotubules; common distinct brown (7.5YR 4/3) clay cutans.

Soil profile M3

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo farm; road 336
Coordinates: S 26°27'33.6", W 64°44'50.5"
USDA classification (2003): Typic Argiustoll, fine silty, mixed, thermic (bordering Haplustoll)
WRB classification (1998): Silti-Luvic Phaeozem
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 640 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize ready for harvesting
Reclamation date: <1970
Human influence: plowing
Described by: E. Flores, A. Zinck
Description date: 21.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-23	Very dark grayish brown (10YR 3/2) silty clay loam, grayish brown (10YR 5/2) dry; moderate fine to medium granular structure; hard, friable, slightly plastic and slightly sticky; high porosity; very few medium and fine roots; clear smooth boundary.
AB	23-35	Very dark gray (10YR 3/1) silty clay loam, gray (10YR 5/1) dry; moderate to strong coarse blocky structure; slightly hard, firm, slightly plastic and slightly sticky; low porosity; very few medium and fine roots; common burrows; clear wavy boundary.
Bt	35-60	Dark grayish brown (10YR 4/2) silty clay loam, brown (7.5YR 5/3) dry; strong coarse blocky structure; slightly hard, firm, plastic and sticky; low porosity; very few fine roots; few pedotubules; common distinct clay cutans.

Soil profile M4

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Lobo farm; road 336
Coordinates: S 26°27'29.6", W 64°45'04.7"
USDA classification (2003): Typic Argiustoll, fine silty, mixed, thermic (bordering Haplustoll)
WRB classification (1998): Silti-Cutanic Luvisol (Thaptoluvic)
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 650 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: E. Flores, A. Zinck
Description date: 23.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

A	0-12/18	Black (7.5YR 2.5/1) silt loam, brown (7.5YR 4/3) dry; moderate coarse subangular blocky structure breaking into medium subangular blocks; slightly hard, friable, slightly plastic and slightly sticky; medium porosity; very few coarse and common fine roots, mainly horizontally lying; abrupt smooth boundary.
Bt	12/18-40/44	Very dark brown (10YR 2/2) sily clay loam to silt loam, dark grayish brown (10YR 4/2) dry; weak medium subangular blocky structure breaking into fine subangular blocks; slightly hard, very friable, slightly plastic and slightly sticky; low porosity; very few coarse and fine roots; few faint clay-humus cutans; abrupt wavy boundary.
BC	40/44-50	Very dark grayish brown (10YR 3/2) silty clay loam, dark yellowish brown (10YR 4/4) dry; weak coarse subangular blocky structure breaking into medium subangular blocks; slightly hard, friable, plastic and sticky; low porosity; very few coarse and fine roots; strong micro-aggregation; clear smooth boundary.
2Btb	50-60	Dark brown (7.5YR 3/2) silty clay loam, brown (7.5YR 5/3) dry; moderate medium prismatic structure breaking into moderate medium subangular blocks; slightly hard, firm, plastic and slightly sticky; low porosity; very few coarse and very fine roots; moderate micro-aggregation; common faint clay cutans.

Soil profile M5

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Giordano farm; 1.3 km north of road 336
Coordinates: S 26°31'56.8", W 64°40'12.7"
USDA classification (2003): Cumulic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 500 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues on newly threshed field
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1976-1985
Human influence: plowing, application of fertilizers, surface compaction
Described by: E. Flores, A. Zinck
Description date: 22.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-12	Very dark grayish brown (10YR 3/2) silty clay, brown (10YR 5/3) dry; moderate medium to fine granular structure; soft, friable, plastic and slightly sticky; high porosity; very few fine and few medium roots; abrupt smooth boundary.
Ad	12-23	Very dark grayish brown (10YR 3/2) silty clay, brown (10YR 5/3) dry; moderate coarse blocky structure breaking into moderate medium blocks; hard, firm, plastic and slightly sticky; low porosity; very few fine and few medium roots; abrupt smooth boundary.
2Bt1	23-36/40	Very dark brown (10YR 2/2) silty clay loam, dark grayish brown (10YR 4/2) dry; moderate coarse blocky structure breaking into moderate medium blocks; hard, firm, plastic and sticky; low porosity; very few fine and very fine roots; common faint clay-humus cutans; clear wavy boundary.
2Bt2	36/40-60	Dark brown (7.5YR 3/2) silty clay loam, brown (7.5YR 4/2) dry; moderate coarse blocky structure breaking into moderate fine to medium blocks; hard, firm, plastic and sticky; low porosity; very few fines roots; very few faint clay cutans.

Soil profile M6

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 1.7 km north of road 336
Coordinates: S 26°31'45.7", W 64°40'07.5"
USDA classification (2003): Pachic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 500 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: E. Flores, A. Zinck
Description date: 22.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

A1	0-10	Dark brown (7.5YR 3/2) silty clay loam, dark yellowish brown (10YR 3/4) dry; moderate to strong medium subangular blocky structure; hard, friable, very plastic and sticky; low porosity; very few medium and fine roots; strong micro-aggregation; clear smooth boundary.
A2	10-16	Dark brown (7.5YR 3/2) silty clay loam, dark brown (7.5YR 3/3) dry; moderate to strong medium subangular blocky structure; hard, friable, very plastic and sticky; low porosity; very few coarse, medium and fine roots; moderate micro-aggregation; abrupt smooth boundary.
2AB	16-40	Very dark brown (10YR 2/2) silt loam, brown (10YR 5/3) dry; moderate coarse subangular blocky structure breaking into moderate fine to medium subangular blocks; hard, firm, plastic and sticky; low to medium porosity; very few fine and medium roots; abrupt smooth boundary.
2Bw1	40-59	Very dark gray (10YR 3/1) silt loam, dark brown (7.5YR 3/3) dry; weak coarse subangular blocky structure breaking into moderate fine to medium subangular blocks; hard, firm, plastic and sticky; low porosity; very few coarse, medium and very fine roots; clear smooth boundary.
2Bw2	59-65	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 4/3) dry; moderate coarse subangular blocky structure breaking into weak fine subangular blocks; slightly hard, friable, plastic and sticky; low to medium porosity; no roots.

Soil profile M7

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 1.2 km north of road 336
Coordinates: S 26°31'57.4", W 64°40'14.1"
USDA classification (2003): Pachic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 500 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize stand
Reclamation date: 1985-1991
Human influence: plowing, application of fertilizers, surface compaction
Described by: E. Flores, A. Zinck
Description date: 22.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-18	Dark brown (10YR 3/3) silty clay loam, brown (7.5YR 5/4) dry; weak fine to medium granular structure; hard, firm, very plastic and very sticky; medium porosity; strong micro-aggregation; abrupt smooth boundary.
AB	18-32	Very dark brown (10YR 2/2) silty clay loam, brown (7.5YR 4/4) dry; moderate coarse blocky structure breaking into moderate medium to fine subangular blocks; hard, firm, very plastic and very sticky; medium porosity; few faint clay-humus cutans; abrupt smooth boundary.
Bt	32-50	Dark brown (10YR 3/3) silt loam to silty clay loam, brown (7.5YR 5/3) dry; moderate coarse blocky structure breaking into moderate medium subangular blocks; slightly hard, friable, slightly plastic and slightly sticky; low porosity; common distinct clay cutans; abrupt smooth boundary.
BC	50-60	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 4/3) dry; moderate coarse blocky structure breaking into moderate medium subangular blocks; slightly hard, firm, plastic and sticky; medium porosity; few faint clay cutans.

Soil profile M8

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; 800 m north of road 336
Coordinates: S 26º32'07.8", W 64º40'17.4"
USDA classification (2003): Typic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 495 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; wheat stand
Reclamation date: 1970-1976
Human influence: plowing, application of fertilizers, surface compaction
Described by: E. Flores, A. Zinck
Description date: 22.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-12	Dark brown (10YR 3/3) silt loam, dark yellowish brown (10YR 4/4) dry; weak coarse angular blocky structure breaking into moderate medium subangular blocks; hard, friable, non plastic and non sticky; medium porosity; few very fine and fine roots; gradual smooth boundary.
A2	12-37	Very dark gray (10YR 3/1) silt loam, brown (10YR 4/3) dry; weak coarse angular blocky structure breaking into weak medium subangular blocks; slightly hard, friable, plastic and slightly sticky; low porosity; few very fine and fine roots; gradual smooth boundary.
Bw1	37-49	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; weak coarse angular blocky structure breaking into weak medium subangular blocks; slightly hard, friable, plastic and slightly sticky; low porosity; few very fine and fine roots; strong micro-aggregation; clear smooth boundary.
Bw2	49-60	Brown (7.5YR 4/3) silt loam, strong brown (7.5YR 5/6) dry; moderate coarse blocky structure breaking into moderate fine to medium blocks; slightly hard, friable, very plastic and very sticky; low porosity; strong micro-aggregation; no roots.

Soil profile M9

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Soria farm; 200 m east of road 304
Coordinates: S 26º28'35.0", W 64º43'14.6"
USDA classification (2003): Typic Haplustoll, coarse loamy, mixed, thermic (bordering Pachic)
WRB classification (1998): Siltic Phaeozem
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 595 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: plow furrows
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; blackbean stand
Reclamation date: 1976-1985
Human influence: plowing, fertilizer application
Described by: E. Flores, A. Zinck
Description date: 24.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-8/11	Dark brown (10YR 3/3) silt loam to loam, brown (7.5YR 4/4) dry; moderate medium to coarse granular structure; slightly hard, friable, non plastic and non sticky; very few coarse and few medium and fine roots; clear wavy boundary.
A2	8/11-28	Very dark brown (10YR 2/2) silt loam, brown (10YR 4/3) dry; moderate medium subangular blocky structure; slightly hard, friable, non plastic and non sticky; very few fine roots; many burrows and earthworm channels; few faint humus cutans; clear smooth boundary.
Bw1	28- 45	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/3) dry; moderate coarse subangular blocky structure breaking into moderate medium and fine subangular blocks; slightly hard, friable, slightly plastic and non sticky; very few very fine roots; common burrows; clear smooth boundary.
Bw2	45-52	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 5/3) dry; moderate coarse subangular blocky structure; slightly hard, friable, slightly plastic and non sticky; very few very fine roots; common burrows; clear smooth boundary.
BC	52-60	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; moderate coarse subangular blocky structure breaking into moderate medium subangular blocks; soft, friable, slightly plastic and non sticky; no roots.

Soil profile M10

Location: Campo Elías; Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Salim farm; 250 m south of road 336
Coordinates: S 26°33’44.2”, W 64°35’08.2”
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Silti-Eutric Cambisol (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 440 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues on newly threshed field
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: <1970
Human influence: plowing, application of fertilizers
Described by: E. Flores, A. Zinck
Description date: 24.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-5/8	Dark brown (10YR 3/3) silt loam, brown (10YR 4/3) dry; moderate medium subangular blocky structure breaking into moderate fine subangular blocks; loose, very friable, non plastic and non sticky; many very fine and medium roots; common burrows and earthworm channels; clear wavy boundary.
A2	5/8-18	Dark brown (10YR 3/3) silt loam, brown (10YR 4/3) dry; moderate medium subangular blocky structure breaking into moderate fine subangular blocks; soft, friable, plastic and slightly sticky; many very fine and medium roots; common burrows; clear smooth boundary.
Bw1	18-32	Dark yellowish brown (10YR 3/4) silt loam, yellowish brown to dark yellowish brown (10YR 4.5/5) dry; weak coarse subangular blocky structure; soft, friable, non plastic and non sticky; few medium and many fine roots; clear smooth boundary.
Bw2	32-59	Brown (7.5YR 4/3) silt loam, light yellowish brown to yellowish brown (10YR 5.5/4) dry; weak coarse subangular blocky structure breaking into medium to fine subangular blocks; soft, friable, non plastic and non sticky; few medium and many fine roots; strong micro-aggregation; clear smooth boundary.
BC	59-70	Dark brown (7.5YR 3/2) silt loam, light yellowish brown to yellowish brown (10YR 5.5/4) dry; very weak fine granular structure; loose, very friable, non plastic and non sticky; very few fine roots.

Soil profile M11

Location: Campo Elías; Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Salim farm; 350 m south of road 336
Coordinates: S 26°34'09.8", W 64°34'56.4"
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Silti-Eutric Cambisol (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 440 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion; no evidence
Soil effective depth: no rooting limitation
Surface characteristics: compacted soil surface along roaming-cattle trails
Native vegetation: Chaco forest
Land use: selective tree felling for fence posts and fuel wood; cattle browsing
Reclamation date: none
Human influence: strongly degraded forest vegetation (monte)
Described by: E. Flores, A. Zinck
Description date: 24.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

A1	0-3/7	Dark brown (10YR 3/3) silt loam, dark yellowish brown (10YR 4/4) dry; moderate coarse granular structure; soft to slightly hard, friable, non plastic and non sticky; common very fine and medium roots; clear wavy boundary.
A2	3/7-22	Very dark grayish brown (10YR 3/2) silt loam, dark yellowish brown (10YR 3/4) dry; moderate medium subangular blocky structure; slightly hard, firm, non plastic and non sticky; common fine and very few medium roots; clear smooth boundary.
Bw1	22-37	Very dark grayish brown (10YR 3/2) silt loam, dark yellowish brown (10YR 4/6) dry; moderate coarse to medium subangular blocky structure; slightly hard, friable, non plastic and non sticky; very few medium and few fine roots; clear smooth boundary.
Bw2	37-64	Brown (10YR 4/3) silt loam, yellowish brown (10YR 5/4) dry; weak coarse subangular blocky structure breaking into medium subangular blocks; soft, friable, slightly plastic and slightly sticky; very few medium and few fine roots; clear smooth boundary.
BC	64-79	Dark yellowish brown (10YR 4/4) silt loam, pale brown (10YR 6/3) dry; weak medium subangular blocky structure; soft, very friable, slightly plastic and slightly sticky; very few fine roots.

Soil profile M12

Location: Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Deschamps farm; south of Gobernador Garmendia; 250 m west of road 34
Coordinates: S 26º36'36.6", W 64º35'25.0"
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Silti-Eutric Cambisol (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 435 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand
Reclamation date: 1976-1985
Human influence: plowing, application of fertilizers
Described by: E. Flores, A. Zinck
Description date: 25.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-9/12	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 5/3) dry; weak coarse granular structure breaking into fine granular; soft, friable, non plastic and non sticky; few fine and very fine roots; clear wavy boundary.
A2	9/12-15/19	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 5/3) dry; moderate coarse granular structure breaking into fine granular; slightly hard, friable, non plastic and non sticky; few fine and very fine roots; clear wavy boundary.
Bw1	15/19-25/28	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/3) dry; moderate coarse subangular blocky structure breaking into moderate medium to fine subangular blocks; slightly hard, firm, slightly plastic and slightly sticky; very few very fine roots; clear wavy boundary.
Bw2	25/28-42	Brown (7.5YR 4/3) silt loam, brown (7.5YR 5/3.5) dry; weak coarse subangular blocky structure breaking into fine subangular blocks; soft, friable, plastic and slightly sticky; very few very fine roots; clear smooth boundary.
C	42-60	Brown (7.5YR 4/3.5) silt loam, brown (7.5YR 5/3.5) dry; very weak medium and fine subangular blocky structure; soft, very friable, slightly plastic and slightly sticky.

Soil profile M13

Location: Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Deschamps farm; south of Gobernador Garmendia; 1.2 km west of road 34
Coordinates: S 26^{o}36’19.7”, W 64^{o}36’45.8”
USDA classification (2003): Torrifluventic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 450 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize stand
Reclamation date: 1985-1991
Human influence: plowing, application of fertilizers
Described by: E. Flores, A. Zinck
Description date: 25.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-16	Very dark grayish brown (10YR 3/2) silt loam, brown (7.5YR 4/4) dry; moderate medium subangular blocky structure breaking into fine granular; soft, friable, slightly plastic and slightly sticky; very few fine and medium roots; clear smooth boundary.
A2	16-23/26	Very dark grayish brown (10YR 3/2) silt loam, brown (7.5YR 4/3) dry; moderate medium subangular blocky structure breaking into fine subangular blocks; slightly hard, friable, plastic and sticky; very few fine and medium roots; clear wavy boundary.
Bt1	23/26-38/40	Brown (7.5YR 4/3) silt loam, light brown (7.5YR 6/4) dry; weak medium and fine subangular blocky structure; slightly hard, friable, plastic and sticky; very few medium roots; very few faint clay cutans; clear wavy boundary.
Bt2	38/40-51/57	Strong brown (7.5YR 4/6) silt loam, strong brown (7.5YR 5/6) dry; moderate coarse and medium subangular blocky structure; soft, very friable, slightly plastic and slightly sticky; very few very fine roots; very few faint clay cutans; clear wavy boundary.
BC	51/57-70	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 4/4) dry; moderate medium subangular blocky structure; soft, friable, plastic and sticky; very few very fine roots.

Soil profile M14

Location: Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Rodriguez farm; south of Gobernador Garmendia; 1.3 km west of road 34
Coordinates: S 26º36'20.6", W 64º36'46.4"
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 450 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand
Reclamation date: 1991-1996
Human influence: plowing, application of fertilizers
Described by: E. Flores, A. Zinck
Description date: 25.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-14	Dark brown (7.5YR 3/3) silt loam, brown (7.5YR 4/4) dry; weak coarse granular structure; soft, friable, slightly plastic and slightly sticky; few fine and medium, very few coarse roots; clear smooth boundary.
A2	14-25	Very dark brown (7.5YR 2.5/2) silt loam, brown (7.5YR 4/4) dry; weak medium subangular blocky structure; slightly hard, friable, plastic and sticky; few fine and medium, very few coarse roots; clear smooth boundary.
Bw1	25-33	Dark brown (7.5YR 3/4) silt loam, brown (7.5YR 5/4) dry; weak medium subangular blocky structure breaking into fine subangular blocks; slightly hard, friable, plastic and sticky; very few fine and medium roots; clear smooth boundary.
Bw2	33-47	Brown (7.5YR 4/3) silt loam, light brown to brown (7.5YR 5.5/4) dry; moderate medium subangular blocky structure; soft, friable, slightly plastic and slightly sticky; very few very fine roots; clear smooth boundary.
C	47-60	Brown (7.5 YR 4.5/4) silt loam, reddish yellow (7.5YR 6/6) dry; weak coarse to medium subangular blocky structure; slightly hard, friable, plastic and sticky; very few very fine roots.

Soil profile M15

Location: El Puestito; Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Ro farm; 250 m east of road 304
Coordinates: S 26°28'52.9", W 64°43'26.4"
USDA classification (2003): Udic Argiustoll, fine silty, mixed, thermic (bordering Pachic)
WRB classification (1998): Silti-Cutanic Luvisol
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 595 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; wheat newly sown after harvesting soybean
Reclamation date: 1985-1991
Human influence: plowing, fertilizer application
Described by: E. Flores, A. Zinck
Description date: 26.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-10/12	Very dark grayish brown (10YR 3/2) silt loam, brown (10YR 4/3) dry; moderate coarse subangular blocky structure breaking into moderate coarse granular; slightly hard, firm, plastic and slightly sticky; very few very fine roots; clear wavy boundary.
Bt1	10/12-38	Very dark brown (10YR 2/2) silty clay loam, brown (10YR 4/3) dry; moderate coarse subangular blocky structure breaking into moderate medium and fine subangular blocks; slightly hard, firm, plastic and slightly sticky; very few fine roots; very few faint clay-humus cutans; clear smooth boundary.
Bt2	38-50	Dark brown (7.5YR 3/2) silty clay loam, brown (7.5YR 4/2) dry; moderate to strong coarse subangular blocky structure breaking into moderate medium and fine subangular blocks; hard, friable, plastic and slightly sticky; no roots; very few faint clay cutans; clear smooth boundary.
BC	50-60	Dark brown (7.5YR 3/3) silty clay loam, brown (7.5YR 5/2) dry; weak fine subangular blocky structure; hard, friable, plastic and sticky; no roots; strong micro-aggregation.

Soil profile M16

Location: La Argentina area, center-north of the study region; Burruyacú, Tucumán, Argentina
Site: Heguy farm; north of road 336
Coordinates: not recorded
USDA classification (2003): Typic Haplustoll, fine silty, mixed, thermic (bordering Pachic)
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, slightly undulating, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 495 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; cárcamo
Reclamation date: 1991-1996
Human influence: plowing, application of fertilizers, surface compaction
Described by: E. Flores, A. Zinck
Description date: 26.06.1996

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap	0-12	Very dark brown (10YR 2/2) silt loam, brown (10YR 4/3) dry; moderate coarse granular structure; slightly hard, friable, slightly plastic and slightly sticky; common fine and medium roots; clear wavy boundary.
A2	12-32	Very dark brown (10YR 2/2) silt loam, dark grayish brown (10YR 4/2) dry; moderate coarse subangular blocky structure; hard, firm, plastic and sticky; common fine and medium roots; clear smooth boundary.
Bt	32-42	Dark brown (7.5YR 3/2) silt loam, brown (7.5YR 4/4) dry; moderate coarse subangular blocky structure; slightly hard, friable, plastic and sticky; very few fine, medium and coarse roots; very few faint clay cutans; common earthworm channels and burrows; clear smooth boundary.
BC	42-59	Dark brown (10YR 3/3) silt loam, brown (10YR 5/3) dry; moderate medium subangular blocky structure breaking into weak fine subangular blocks; slightly hard, friable, plastic and sticky; very few fine, medium and coarse roots; very few faint clay cutans; clear smooth boundary.
C	59-65	Brown (7.5YR 4/4) silt loam, light brown (7.5YR 6/4) dry; weak medium subangular blocky structure; hard, very friable, plastic and sticky; very few very fine roots; moderate micro-aggregation.

Soil profile M17

Location: La Ramada de Abajo; La Ramada area, southwest of the study region; Burruyacú, Tucumán, Argentina
Site: Argüello farm; 5 km east of road 304 and 300 m north of road 317
Coordinates: S 26°42'54.6", W 64°56'26.1"
USDA classification (2003): Udic Argiustoll, clayey, mixed, thermic
WRB classification (1998): Silti-Luvic Phaeozem
Landscape: plain
Relief type: fluvio-denudational depression, inactive
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: loess cover
Parent material: loess
Elevation: 550 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid over slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand
Reclamation date: <1970
Human influence: plowing, application of fertilizers, surface compaction
Described by: A. Zinck, L. Neder, J.M. Sayago
Description date: 18.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil moist at description date):

Ap	0-10	Very dark grayish brown (10YR 3/2) silt loam; moderate to weak medium subangular blocky structure; slightly sticky and slightly plastic; few to common roots; gradual smooth boundary.
Ad	10-26	Very dark brown (10YR 2/2) silt loam; moderate medium angular and subangular blocky structure; firm, sticky and plastic; compact; few roots; gradual smooth boundary.
A3	26-37	Very dark brown (10YR 2/2) silt loam; moderate medium subangular blocky structure; slightly sticky and slightly plastic; compact; few roots; clear smooth boundary.
A4	37-51/54	Very dark grayish brown (10YR 3/2) silt loam; locally, pockets of darker material (10YR 2/2); medium and fine subangular and angular blocky structure; firm to friable, slightly sticky and slightly plastic; medium porosity (10-15%), pores irregularly distributed; few roots; clear wavy boundary.
2Bt	51/54-80	Very dark grayish brown (10YR 3/2) silty clay; medium prismatic structure breaking into moderate subangular blocks; friable to firm, sticky and plastic; many prominent very dark brown (10YR 2/2) clay-humus cutans in pores and on pedfaces; clear smooth boundary.

Soil profile M18

Location: La Ramada de Abajo; La Ramada area, southwest of the study region; Burruyacú, Tucumán, Argentina
Site: Argüello farm; 6.4 km east of road 304 and 700 m north of road 317
Coordinates: S 26^{o}42'45.9", W 64^{o}55'36.1"
USDA classification (2003): Udic Argiustoll, fine silty, mixed, thermic
WRB classification (1998): Silti-Pachi-Luvic Phaeozem
Landscape: piedmont (distal sector)
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: loess cover
Parent material: loess
Elevation: 540 m.a.s.l.
General topography: flat to slightly undulating
Local topography: 1-2% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crop residues on newly threshed field
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1970-1976
Human influence: plowing, application of fertilizers, surface compaction
Described by: A. Zinck, L. Neder, J.M. Sayago
Description date: 18.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil moist at description date):

Ap1	0-11	Very dark brown (10YR 2/2) silt loam; moderate to weak medium subangular blocky structure; friable, slighly sticky and slightly plastic; few roots; slightly moist; clear smooth boundary.
Ap2	11-31	Very dark brown (7.5YR 2.5/2) silt loam; moderate medium angular and subangular blocky structure; friable, sticky and plastic; gradual smooth boundary.
A3	31-57	Very dark brown (7.5YR 2.5/2) silt loam; moderate to weak medium and fine subangular blocky structure; friable, slightly sticky and slightly plastic; clear smooth boundary.
Bt	57-80	Very dark brown (7.5YR 2.5/2) silty clay loam; medium prismatic structure breaking into moderate subangular blocks; friable, slightly sticky and slightly plastic; common distinct clay cutans.

Soil profile M19

Location: La Ramada; La Ramada area, southwest of the study region; Burruyacú, Tucumán, Argentina
Site: Zavaleta farm; 600 m east of road 304 and 2.5 km north of road 317
Coordinates: S 26°41'46.6", W 64°56'36.0"
USDA classification (2003): Pachic (Udic) Haplustoll, clayey, mixed, thermic
WRB classification (1998): Silti-Pachic Phaeozem
Landscape: piedmont (distal sector)
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: loess cover
Parent material: loess
Elevation: 600 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow to slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand ready to harvest
Reclamation date: 1985-1991
Human influence: plowing, application of fertilizers, surface compaction
Described by: A. Zinck, L. Neder, J.M. Sayago
Description date: 18.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil moist at description date):

Ap1	0-17	Very dark brown (10YR 2/2) silty clay loam; moderate medium subangular blocky structure; friable to firm, slightly sticky and slightly plastic; common roots; clear smooth boundary.
2Ap2	17-36	Black (10YR 2/1) silty clay loam; moderate fine prismatic structure; friable, sticky and plastic; few roots; gradual smooth boundary.
2AB	36-53/56	Black (10YR 2/1) silty clay loam; medium prismatic structure breaking into medium subangular blocks; friable, slightly sticky and slightly plastic; clear wavy boundary.
2Bt	53/56-70	Very dark brown (7.5YR 2.5/3) silty clay loam; few mottles; medium prismatic structure breaking into moderate medium subangular blocks; firm, very sticky and plastic; common faint clay cutans; few mica.

Soil profile M20

Location: La Ramada de Abajo; La Ramada area, southwest of the study region; Burruyacú, Tucumán, Argentina
Site: Zavaleta farm; 2 km north of road 317 and 2.5 km east of road 304
Coordinates: S 26°42'09.5", W 64°55'06.3"
USDA classification (2003): Pachic (Udic) Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Silti-Pachic Phaeozem
Landscape: piedmont (distal sector)
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: loess cover
Parent material: loess
Elevation: 530 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; maize stand
Reclamation date: 1976-1985
Human influence: plowing, application of fertilizers, surface compaction
Described by: A. Zinck, L. Neder, J.M. Sayago
Description date: 19.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil moist at description date):

Ap	0-18	Black (10YR 2/1) silty clay loam to silt loam; moderate medium subangular blocky structure; firm to friable, sticky and plastic; many roots in the ridge and few in the furrow; gradual smooth boundary.
A2	18-37	Black (10YR 2/1) silty clay loam; medium prismatic structure breaking into moderate medium subangular blocks; friable, slightly sticky and slightly plastic; few roots; gradual smooth boundary.
A3	37-50	Black (10YR 2/1) silty clay loam; moderate medium prismatic structure breaking into subangular blocks; friable, sticky and plastic; few roots; clear smooth boundary.
A4	50-75	Dark brown (7.5YR 3/2) silty clay loam; few mottles; moderate medium and fine subangular blocky structure; friable, sticky and plastic; few roots; common dark-coloured pedotubules; clear smooth boundary.
Bt	75-85	Dark brown (7.5YR 3/3) silty clay loam to silt loam; medium and fine prismatic structure; friable, very sticky and plastic; few faint clay cutans in pores.

Soil profile M21

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: 200 m northwest of school 369, located on road 317, and 15 km east of road 304
Coordinates: S 26º43'34.5", W 64º52'33.3"
USDA classification (2003): Typic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 470 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand ready to harvest
Reclamation date: 1976-1985
Human influence: plowing, application of fertilizers, surface compaction
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 07 and 21.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap	0-18	Very dark brown (10YR 2/2) silt loam; moderate medium and fine subangular blocky structure; common medium and fine roots; clear smooth boundary.
A2	18-42	Very dark gray (10YR 3/1) silt loam to silty clay loam; strong coarse and medium angular and subangular blocky structure; few roots; clear smooth boundary.
Bw	42-60	Dark brown (10YR 3/3) silt loam to silty clay loam; moderate medium subangular and angular blocky structure; few roots.

Soil profile M22

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: 7.5 km north and 5 km west of junction between road 317 and dirt road of Arcos La Virginia
Coordinates: S 26°42'59.8", W 64°51'53.6"
USDA classification (2003): Typic Haplustalf, clayey, mixed, thermic
WRB classification (1998): Silti-Cutanic Luvisol
Landscape: plain
Relief type: fluvio-eolian flat
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 480 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow to slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand ready to harvest
Reclamation date: 1985-1991
Human influence: plowing, application of fertilizers, surface compaction
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 07 and 21.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap	0-12/15	Dark brown (10YR 3/3) silt loam; moderate to weak medium and fine subangular blocky structure; common roots; clear wavy boundary.
A2	12/15-33	Brown (7.5YR 4/2) silt loam; moderate to strong medium subangular blocky structure; moderately compact; few roots; clear smooth boundary.
2Bt	33-60	Dark brown (7.5YR 3/2) silty clay loam to silty clay; moderate medium and fine prismatic structure; many distinct clay cutans; few roots.

Soil profile M23

Location: Colonia La Virginia area, center-south of the study region; Burruyacú, Tucumán, Argentina
Site: Zavaleta farm; 5 km north and 5 km west of junction between road 317 and dirt road of Arcos La Virginia
Coordinates: S 26°42'45.6", W 64°50'59.0"
USDA classification (2003): Pachic Argiustoll, fine silty, mixed, thermic
WRB classification (1998): Silti-Luvic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 475 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately slow
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: crust (1.5-2 cm thick)
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand ready to harvest
Reclamation date: 1970-1976
Human influence: plowing, application of fertilizers, surface compaction
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 21.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap1	0-11	Very dark brown (10YR 2/2) silt loam; weak fine subangular blocky structure; friable, slightly sticky and slightly plastic; many roots; clear smooth boundary.
Ap2	11-21	Very dark brown (10YR 2/2) silt loam; weak medium subangular blocky structure; friable, slightly sticky and slightly plastic; many roots; clear smooth boundary.
A3	21-34	Black (10YR 2/1) silt loam; prismatic structure breaking into moderate medium subangular blocks; firm, sticky and plastic; compact; few roots; clear smooth boundary.
Bt	34-63	Very dark brown (7.5YR 2.5/2) silty clay loam; moderate medium prismatic structure breaking into medium subangular blocks; friable, sticky and plastic; common pores; common distinct clay cutans in pores and few faint clay cutans on pedfaces; gradual smooth boundary.
C	63-73	Dark brown (7.5YR 3/3) silt loam to silty clay loam; weak subangular blocky structure; very sticky and plastic.

Soil profile M24

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Vece farm; at the western border of Gobernador Piedrabuena; 0.5 km west of the train station
Coordinates: S 26°44'18.7", W 64°39'43.2"
USDA classification (2003): Torriorthentic Haplustoll, coarse silty, mixed, thermic (bordering coarse loamy)
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 415 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: no special feature
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: surface compaction through animal trampling (ponies and horses)
Native vegetation: none; originally, Chaco forest
Land use: pasture
Reclamation date: 1970-1976
Human influence: poor pasture management
Described by: J.M. Sayago, L. Neder, A. Zinck
Description date: 07 and 21.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-8	Dark brown (10YR 3/3) silt loam; moderate medium subangular blocky structure; many roots; clear smooth boundary.
A2	8-23	Dark brown (7.5YR 3/2) silt loam; moderate medium subangular blocky structure; common roots; gradual smooth boundary.
AC	23-40	Brown (10YR 4/3) silt loam; weak fine subangular blocky structure; gradual smooth boundary.
C	40-60	Brown (10YR 4/3) silt loam; weak fine blocky structure.

Soil profile M25

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: Vece farm; at the western border of Gobernador Piedrabuena; 1.5 km west and 0.5 km south of the train station
Coordinates: S 26°44'22.9", W 64°40'18.7"
USDA classification (2003): Aridic Haplustept, coarse silty, mixed, thermic (bordering coarse loamy)
WRB classification (1998): Silti-Eutric Cambisol
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 415 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: surface compaction
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; beans (poroto)
Reclamation date: 1976-1985
Human influence: plowing, application of fertilizers
Described by: J.M. Sayago, L. Neder, A. Zinck
Description date: 07 and 21.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap	0-8/12	Dark brown (10YR 3/3) silt loam; weak to moderate fine and medium subangular blocky structure; common roots; clear wavy boundary.
Bw	8/12-25	Brown (7.5YR 4/2) silt loam; moderate fine angular and subangular blocky structure; common roots; clear smooth boundary.
BC	25-42	Dark yellowish brown (10YR 3/4) silt loam; weak medium subangular blocky structure; gradual smooth boundary.
C	42-60	Dark yellowish brown (10YR 4/4) silt loam.

Soil profile M26

Location: Gobernador Piedrabuena area, southeast of the study region; Burruyacú, Tucumán, Argentina
Site: 2.3 km north of Gobernador Piedrabuena on road 34; 50 m east of cemetery
Coordinates: S 26°43'05.7", W 64°38'13.5"
USDA classification (2003): Torriorthentic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Silti-Eutric Cambisol (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 415 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: surface compaction
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean
Reclamation date: 1985-1991
Human influence: plowing, application of fertilizers
Described by: J.M. Sayago, L. Neder, A. Zinck
Description date: 07 and 23.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap	0-15	Very dark brown (7.5YR 2.5/2) silt loam; weak medium subangular blocky structure; slightly hard, slightly sticky and slightly plastic; few roots; gradual smooth boundary.
A2	15-23	Very dark grayish brown (10YR 3/2) silt loam; moderate to weak fine and medium subangular blocky structure; friable, sticky and plastic; few roots; gradual smooth boundary.
AC	23-47	Very dark grayish brown (10YR 3/2) silt loam; weak to moderate medium subangular blocky structure; sticky and plastic; few roots; gradual smooth boundary.
C	47-75	Dark brown (7.5YR 3/4) silt loam; moderate medium subangular blocky structure; friable, slightly sticky and slightly plastic.

Soil profile M27

Location: Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Deschamps farm; south of Gobernador Garmendia; 3 km west of Estancia San Benito on road 34
Coordinates: S 26º36'23.0", W 64º36'29.0"
USDA classification (2003): Aridic Haplustoll, coarse silty, mixed, thermic (bordering fine silty)
WRB classification (1998): Siltic Phaeozem
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 450 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: surface compaction and crusting (1 cm thick)
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand
Reclamation date: 1970-1976
Human influence: plowing, application of fertilizers
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 23.04.1997

Profile description (depth in cm; colors for moist soil unless otherwise stated; soil slightly moist at description date):

Ap1	0-9	Very dark brown (10YR 2/2) silt loam; moderate medium and fine subangular blocky structure; hard, slightly sticky and slightly plastic; few roots; dry; clear smooth boundary.
Ap2	9-20	Black (10YR 2/1) silt loam; medium and fine angular and subangular blocky structure; extremely firm, slightly sticky and slightly plastic; few roots; clear smooth boundary.
A3	20-30	Very dark brown (7.5YR 2.5/2) silt loam; moderate medium subangular blocky structure; sticky and plastic; very compact; clear smooth boundary.
Bw	30-56	Dark brown (7.5YR 3/3) silt loam; weak prismatic structure breaking into moderate subangular blocks; friable, slightly sticky and slightly plastic; gradual smooth boundary.
C	56-80	Brown (7.5YR 4/3) silt loam; weak subangular blocky structure; slightly sticky and slightly plastic.

Soil profile M28

Location: Burruyacú area, northwest of the study region; Burruyacú, Tucumán, Argentina
Site: Between Burruyacú and La Argentina on road 336; 4 km east of junction between road 336 and road 304
Coordinates: S 26º32'05.7", W 64º43'12.3"
USDA classification (2003): Udic Haplustoll, fine silty, mixed, thermic
WRB classification (1998): Siltic Phaeozem
Landscape: plain at piedmont foot
Relief type: glacis
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 585 m.a.s.l.
General topography: east-facing slope, gently undulating
Local topography: 0-2% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: no special feature
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; wheat stand
Reclamation date: 1970-1976
Human influence: plowing, fertilizer application
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 23.04.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was moist at description date):

Ap1	0-9/12	Very dark brown (10YR 2/2) silt loam; moderate medium subangular blocky structure; friable to firm, slightly sticky and slightly plastic; few roots; slightly moist to dry; clear wavy boundary.
Ap2	9/12-22	Black (10YR 2/1) silt loam; moderate to strong medium subangular blocky structure; very firm, slightly sticky and slightly plastic; moderately compact; few roots; gradual smooth boundary.
A3	22-33	Very dark brown (10YR 2/2) silt loam; moderate to weak medium and fine subangular blocky structure; friable, sticky and plastic; few roots; gradual smooth boundary.
AB	33-55	Very dark brown (7.5YR 2.5/2) silt loam; weak prismatic structure breaking into moderate medium subangular blocks; friable, sticky and plastic; few roots; gradual smooth boundary.
Bt	55-70	Dark brown (7.5YR 3/2) silt loam; weak prismatic structure breaking into medium subangular blocks; friable, sticky and plastic; few faint clay cutans on pedfaces and in pores; few roots.

Soil profile M29

Location: Gobernador Garmendia area, northeast of the study region; Burruyacú, Tucumán, Argentina
Site: Rodríguez farm; south of Gobernador Garmendia; 2.5 km west of Estancia San Benito on road 34
Coordinates: S 26°36'27.4", W 64°36'09.7"
USDA classification (2003): Torriorthentic Haplustoll, coarse silty, mixed, thermic
WRB classification (1998): Silti-Eutric Cambisol (bordering Phaeozem)
Landscape: plain
Relief type: fluvio-eolian flat, inactive to semi-active
Lithology/facies: loess layers with intercalated paleosoils (Holocene)
Landform: eolian cover
Parent material: loess
Elevation: 445 m.a.s.l.
General topography: flat
Local topography: 0-1% slope
Micro-topography: furrows-ridges
Drainage: well drained
Permeability: moderately rapid
Salts and alkali: no evidence
Erosion: no evidence
Soil effective depth: no rooting limitation
Surface characteristics: surface compaction and crusting
Native vegetation: none; originally, Chaco forest
Land use: rain-fed agriculture; soybean stand
Reclamation date: 1991-1996
Human influence: plowing, application of fertilizers
Described by: L. Neder, J.M. Sayago, A. Zinck
Description date: 30.05.1997

Profile description (depth in cm; colors are for moist soil unless otherwise stated; soil was dry at description date):

Ap	0-10/13	Very dark brown (10YR 2/2) silt loam; weak medium and fine subangular blocky structure; soft, non sticky and non plastic; common roots; clear wavy boundary.
A2	10/13-30	Very dark grayish brown (10YR 3/2) silt loam; medium and fine subangular blocky structure; very hard, slightly sticky and slightly plastic; compact (plow pan); few roots; clear smooth boundary.
AC	30-49	Dark brown (7.5YR 3/3) silt loam; moderate medium and fine subangular blocky structure; friable, non sticky and non plastic; common roots; slightly moist; clear smooth boundary.
C	49-68	Dark brown (7.5YR 3/4) silt loam; moderate to weak medium and fine subangular blocky structure; non sticky and non plastic; few roots.

LABORATORY DATA

Table 13.1. Laboratory data of reference soil profiles (1).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	Sand	Silt	Clay	Texture	M Eq	Bd	Carb	OC	pH	Ex Ca	Ex Mg	Ex
P1A	Ap	0-13	0.29	0.21	0.62	5.10	4.78	11.00	67.37	21.63	SiL	23.21	1.09	0	2.07	7.5	10.81	3.29	1
	Ad	13-15	0.09	0.11	0.22	3.67	4.10	8.19	64.63	27.18	SiCL-SiL	29.24	1.36	0	1.56	6.7	13.93		
	Bt	15-35	0.28	0.10	0.31	3.85	3.85	8.39	64.08	27.53	SiCL-SiL	23.87	1.35	0	1.08	7.3	10.39	3.71	1
	BC	35-53	0.26	0.10	0.31	4.73	3.60	9.00	69.61	21.39	SiL	21.91	1.26	0	0.50	7.2	8.69	4.24	0
	C	53-90	0.16	0.20	0.41	10.15	7.31	18.23	67.71	14.06	SiL	18.78	1.09	0	0.23	7.3	5.83	2.33	0
	2Btb1	90-140	0.21	0.00	0.21	3.43	2.70	6.55	70.26	23.19	SiL	24.85	1.17	0	0.32	7.2	10.49	6.15	0
P2	A	0-28	0.50	0.33	0.44	2.19	2.08	5.54	70.68	23.78	SiL	37.77	1.22	0	4.87	7.4	26.50	4.45	1
	Bt	28-52	0.17	0.21	0.10	0.21	0.42	1.11	63.69	35.20	SiCL	28.92	1.42	0	1.02	7.6	10.40	4.24	0
	BC	52-74	0.10	0.21	0.10	0.10	0.52	1.03	71.25	27.72	SiCL-SiL	27.35	1.42	0	0.66	7.3	9.43	5.09	0
	C	74-91	0.08	0.10	0.10	0.21	1.03	1.52	71.97	26.51	SiL-SiCL	29.21	1.46	0	0.43	7.2	9.01	4.77	0
	2Ab	91-97	0.10	0.00	0.10	0.63	1.05	1.88	65.11	33.06	SiCL	32.56	1.27	0	0.64	7.1	10.28	7.84	0
	2Btb	97-117	0.00	0.10	0.00	0.63	0.73	1.45	62.22	36.32	SiCL	31.57	1.49	0	0.50	7.1	9.01	4.24	0
	2Cb	117-140	0.00	0.10	0.00	0.82	1.03	1.95	73.87	24.18	SiL		1.28	0	0.31		8.64		
	3Ab	140+	0.21	0.10	0.31	4.00	3.18	7.80	69.34	22.86	SiL			0	0.43		11.83		
P3A	Ap	0-17	0.37	0.32	1.05	4.53	3.79	10.06	72.08	17.86	SiL	30.11	0.94	0	3.43	6.6	18.23	3.18	1
	A2	17-28	0.37	0.42	0.73	3.96	3.23	8.71	68.44	22.85	SiL	28.44	1.27	0	1.92	7.0	16.54	3.39	1
	Bw1	28-50	0.31	0.10	0.52	2.28	1.35	4.56	70.72	24.72	SiL	26.91	1.34	0	0.98	7.1	13.14	2.76	1
	Bw2	50-75	0.47	0.21	0.52	2.80	2.17	6.17	72.66	21.17	SiL	27.38	1.21	0	0.64	7.1	12.40	3.29	1
	C	75-120	0.48	0.52	1.34	8.47	6.20	17.01	64.97	18.02	SiL	23.24	1.22	0	0.94	7.3	10.39	4.24	1

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sar %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); OC = organic carbon (%); pH (wat calcium; Ex Mg = exchangeable magnesium; Ex K = exchangeable potassium; Ex Na = exchangeable sodium; CECs = cation exchang CEC = cation exchange capacity (all cations in cmol (+) kg^{-1} soil); P Sol = soluble phosphorus (mg kg^{-1}).

Table 13.1. Laboratory data of reference soil profiles (2).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Text	M Eq	Bd	Carb	OC
P3B	Ap	0-9	0.19	0.40	0.97	4.18	4.44	21.54	14.26	10.18	65.49	24.33	SiL	30.08	1.15	0	2.39
	Bt	9-50	0.16	0.26	0.50	1.97	2.25	32.88	16.18	5.14	64.45	30.41	SiCL	26.82	1.38	0	0.88
	BC	50-75	0.22	0.56	1.03	4.07	3.91	31.58	12.70	9.79	64.59	25.62	SiL	26.76	1.43	0	0.58
	C	75-95	1.04	1.27	3.84	10.82	7.22	24.54	11.35	24.19	57.45	18.36	SiL	23.27	1.44	0	0.35
	2Ab	95-118	0.18	0.23	0.49	2.49	2.27	38.28	20.11	5.66	71.94	22.40	SiL	35.93	1.23	1.59	0.31
	2Bwb	118-140	0.19	0.00	0.22	6.08	4.72	32.12	18.87	11.21	71.52	17.27	SiL	33.16		3.14	0.41
P4A	Ap	0-8/12	0.41	0.52	1.55	10.78	11.61			24.87	62.47	12.39	SiL		1.29	0.52	0.96
	2A1	8/12-30	0.41	0.62	2.48	9.94	7.25			20.70	65.74	13.56	SiL		1.20	0.77	0.78
	2A2	30-41	0.41	0.72	2.48	9.91	7.53			21.05	68.59	10.36	SiL		1.14	0.74	0.70
	2AC	41-67	0.41	0.51	2.16	10.81	7.10			20.99	68.25	10.76	SiL		1.21	0.69	0.50
	2C	67-90	0.31	0.51	2.05	11.58	8.40			22.85	66.60	10.55	SiL		1.24		0.29
	3Bwb1	90-117	0.52	0.62	2.47	8.97	6.49			19.07	68.15	12.78	SiL		1.26	0.77	0.22
	3Bwb2	117-150	0.72	0.62	2.78	8.66	6.39			19.17	68.62	12.21	SiL			7.89	0.20
P5A	A	0-13	0.43	0.65	2.59	11.56	8.86			24.09	60.57	15.34	SiL		1.06	0	2.75
	2A	13-31	0.42	0.63	2.42	12.01	8.75			24.23	60.39	15.38	SiL		1.05	0	1.52
	2AC	31-64	0.31	0.52	2.19	11.76	8.53			23.31	62.80	13.89	SiL		1.14	0.89	0.64
	2C	64-110	0.41	0.41	1.95	13.06	9.26			25.09	63.91	11.00	SiL		1.21	0.72	0.37
	3Bwkb	110-160	0.41	0.62	2.99	13.21	9.91			27.14	65.22	7.64	SiL			4.38	0.16
P6B	Ap	0-10	1.81	1.70	5.00	12.01	6.80			27.32	55.90	16.78	SiL		1.13	0	1.57
	A2	10-28	1.15	1.36	4.30	11.22	7.44			25.47	58.34	16.19	SiL		1.36	0	1.04
	Bw	28-51	0.93	1.03	3.82	12.91	7.95			26.64	67.37	5.99	SiL		1.23	0	0.42
	C	51-70	1.04	0.93	3.63	10.48	5.71			21.79	68.04	10.17	SiL		1.23	1.06	0.22
	2Bwb1	70-106	1.15	1.77	4.17	8.44	5.94			21.47	69.83	8.70	SiL		1.27	2.44	0.23
	2Bwb2	106-138	0.83	0.73	2.59	4.98	3.53			12.66	66.79	20.55	SiL			1.92	0.10
	2Cb	138-168														3.27	

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); (water 1:1); Ex Ca = exchangeable calcium; Ex Ca = Ca soluble in ammonium acetate 1N; CEC = cation exchange capacity (all catio = soluble phosphorus (mg kg^{-1}).*

Table 13.1. Laboratory data of reference soil profiles (3).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Text	M Eq	Bd	Carb	OC
P7B	A1(Ad)	0-21	3.28	4.37	11.26	14.97	6.23			40.11	44.92	14.97	L		1.41	0	2.55
	A2	21-39	3.94	4.15	10.68	13.27	6.43			38.47	45.92	15.71	L		1.15	0	1.04
	A3	39-68	3.61	3.92	9.29	14.14	6.81			37.77	47.16	15.07	L		1.21	0	0.52
	C	68-90	2.57	3.49	8.83	14.37	6.98			36.24	50.78	12.98	SiL-L		1.45	1.10	0.35
	2Bwb1	90-118	3.78	3.48	10.63	15.23	5.83			38.95	46.38	14.67	L		1.43	0.75	0.20
	2Bwb2	118-140	3.38	3.49	10.25	13.33	6.46			36.91	48.53	14.56	L			0.58	0.18
	2Cb	140-155														1.06	
P8B	Ap	0-11	0.21	0.11	0.43	4.91	5.01			10.67	68.53	20.80	SiL		1.07	0	2.43
	Bw1	11-28	0.11	0.11	0.32	4.46	5.42			10.42	66.96	22.62	SiL		1.08	0	1.52
	Bw2	28-40	0.10	0.10	0.42	5.96	6.48			13.06	67.59	19.35	SiL		1.13	0	0.66
	C	40-52	0.11	0.08	0.50	6.32	7.35	23.47	9.32	14.36	71.02	14.62	SiL	22.06	1.21	0.77	0.46
	2Bwb1	52-90	0.10	0.10	0.41	7.36	7.68			15.65	69.05	15.30	SiL		1.34	0.88	0.34
	2Bwb2	90-107	0.06	0.17	0.75	6.98	8.03	23.14	8.87	15.99	73.58	10.43	SiL	21.32	1.33	0.90	0.26
	2Bwb3	107-120	0.12	0.23	0.96	5.70	6.89	22.78	8.88	13.90	75.46	10.64	SiL	21.12		0.91	0.21
	3Ckb	120-145	0.21	0.10	0.72	5.75	6.87			13.65	75.58	10.77	SiL			2.87	0.17
P9B	Ap	0-11	0.54	0.87	1.41	4.99	5.53			13.34	65.56	21.10	SiL		0.99	0	3.03
	Ad	11-29	0.54	0.75	1.39	5.58	6.11			14.37	63.97	21.66	SiL		1.04	0	1.48
	Bw1	29-50	0.52	0.63	1.47	5.97	6.08			14.67	63.79	21.54	SiL		1.09	0	0.88
	Bw2	50-72	0.74	0.53	1.37	6.43	5.58			14.85	64.51	20.64	SiL		1.18	0.75	0.66
	C	72-110	0.83	0.63	1.46	7.72	5.84			16.48	66.67	16.85	SiL		1.29	0.66	0.32
	2Bwb	110-135	2.84	2.63	3.26	4.53	4.53			17.79	74.63	7.58	SiL		1.29	0.60	0.04
	2Cb	135-150	0.56	0.74	1.82	4.37	5.95	25.79	8.97	13.44	77.47	9.09	SiL	20.47	1.33	0.66	0.10

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); (water 1:1); Ex Ca = exchangeable calcium; Ex Ca = Ca soluble in ammonium acetate 1N; CEC = cation exchange capacity (all catio = soluble phosphorus (mg kg^{-1}).*

Table 13.1. Laboratory data of reference soil profiles (4).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Texture	Eff M	M Eq	Bd	Carb
P10	A1	0-6	1.43	0.66	1.77	7.39	7.39	18.85	8.93	18.64	59.34	22.02	SiL	28.24	28.41	1.09	0
	A2	6-21	1.05	0.63	1.47	6.91	8.90	22.27	9.16	18.96	58.00	23.04	SiL	13.12	25.61	1.15	0
	A3	21-38	0.52	0.73	1.25	8.12	8.64	20.10	8.59	19.26	55.38	25.36	SiL	11.85	23.43	1.06	0
	C	38-57	0.61	0.51	1.23	12.39	9.52	22.37	8.29	24.26	56.96	18.78	SiL	8.27	21.12	1.12	0
	2BAb	57-88	1.46	0.94	2.08	4.16	4.16	20.43	0.36	12.80	48.32	38.88	SiCL-SiC	11.55	23.63	1.55	0
	2Btb	88-128	0.84	0.73	1.67	3.82	3.65	19.21	10.33	10.71	58.44	30.85	SiCL	11.65	24.66	1.24	0
	2Cb	128-150	1.24	0.83	2.07	3.32	5.29	24.83	12.60	12.75	73.61	13.64	SiL	10.07	22.11		0
P11	Ap	0-12	0.75	0.43	0.86	5.79	7.29	24.24	10.51	15.12	60.65	24.23	SiL	33.10	28.38	0.99	0
	A2	12-32/36	0.63	0.52	0.73	5.86	8.16	24.36	6.58	15.90	58.27	25.83	SiL-SiCL	27.08	24.77	1.15	0
	C	32/36-52	0.31	0.51	0.61	11.78	9.83	19.97	5.53	23.04	56.38	20.58	SiL	20.54	19.80	1.15	0
	2Ab	52-77	0.62	0.73	1.35	4.77	4.36	21.64	9.75	11.83	60.82	27.35	SiCL-SiL	17.51	23.37	1.33	0
	2BAb	77-100	0.83	0.73	1.15	3.23	3.54	21.03	9.84	9.48	59.70	30.82	SiCL	15.79	24.12	1.36	0
	2Btb	100-130	0.93	0.72	1.24	3.31	3.83	21.82	8.74	10.03	64.33	25.64	SiL-SiCL	15.52	23.76	1.35	0
	2Cb	130-150	0.93	0.62	1.35	3.11	4.05	22.88	10.12	10.06	66.80	23.14	SiL	16.89	23.50	1.35	0
P12	Ap1	0-8	0.53	0.53	0.96	5.11	7.46	25.62	9.37	14.59	62.24	23.17	SiL	28.73	26.08	1.04	0
	Ap2	8-20	0.53	0.64	0.85	5.30	7.64	24.30	9.07	14.96	61.75	23.29	SiL	27.67	25.37	1.22	0
	Ad	20-35/40	0.32	0.53	0.95	6.41	8.09	19.49	11.62	16.30	57.47	26.23	SiL-SiCL	24.35	22.50	1.24	0
	C	35/40-62	0.31	0.41	0.92	11.75	10.32	23.65	8.12	23.71	61.01	15.28	SiL	18.89	19.11	1.15	0
	2BAb	62-99	0.72	0.82	1.34	4.12	3.92	18.15	11.44	10.92	62.12	26.96	SiL-SiCL	16.76	21.37	1.44	0
	2Btb	99-134/140	1.46	0.62	1.04	2.49	3.01	21.93	11.85	8.62	63.10	28.28	SiL-SiCL	17.05	23.96	1.49	0
	2Cb	134/140-155	1.04	0.73	1.35	2.80	4.15	6.95	15.30	10.07	74.63	15.30	SiL	16.41	21.52	1.50	0
P13	A1	0-8	0.34	0.45	1.13	7.46	9.49	23.72	8.70	18.87	58.25	22.88	SiL	13.68	24.97	0.89	0
	A2	8-28	0.53	0.21	0.74	5.39	6.77	23.59	10.69	13.64	65.16	21.20	SiL	10.34	23.12	0.99	0
	A3	28-60	0.31	0.21	0.62	6.43	7.78	22.76	9.95	15.35	64.95	19.70	SiL	9.33	21.14	1.09	0
	C	60-80	0.31	0.20	0.72	9.30	8.69	25.70	9.71	19.22	67.40	13.38	SiL	6.66	17.64	1.13	0
	2Bwb1	80-106	0.72	0.21	1.14	5.68	5.48	23.67	10.95	13.23	69.25	17.52	SiL	8.95	20.60	1.29	0
	2Bwb2	106-128	0.31	0.21	1.03	5.76	6.27	22.47	11.47	13.58	72.74	13.68	SiL	8.53	19.99	1.31	trace
	2Cb	128-153	0.51	0.62	2.16	7.22	6.80	22.83	7.63	17.31	72.28	10.41	SiL	8.78	20.61	1.33	0.50

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); Eff M = effective moisture (%); M Eq = moisture equivalent (%); Bd = bulk density (Mg m (%); OC = organic carbon (%); pH (water 1:1); Ex Ca = exchangeable calcium; CEC = cation exchange capacity (all cations in cmol phosphorus (mg kg^{-1}).

Table 13.1. Laboratory data of reference soil profiles (5).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Texture	Eff M	M Eq	Bd	Carb
P14	Ap1	0-7	0.63	0.31	0.44	5.66	7.45	24.86	7.35	14.49	67.31	18.20	SiL	15.70	21.82	0.94	0
	Ap2	7-20	0.42	0.32	0.53	5.68	8.21	4.10	6.58	15.16	64.44	20.40	SiL	18.22	21.70	1.21	0
	A3	20-38	0.21	0.21	0.52	6.05	7.51	24.13	7.35	14.50	64.49	21.01	SiL	16.06	20.95	1.09	0
	C	38-57	0.31	0.10	0.51	8.55	9.89	25.18	6.95	19.36	63.90	16.74	SiL	10.87	18.35	1.18	0
	2Ab	57-82	0.31	0.20	0.51	5.84	6.97	23.66	7.10	13.83	67.06	19.11	SiL	11.80	21.55	1.32	0
	2Bwb	82-131	0.41	0.31	0.72	4.22	5.67	24.98	8.66	11.33	72.86	15.81	SiL	11.91	22.08	1.37	trace
	2Ckb	131-152	0.31	0.72	2.58	6.60	7.53	26.41	7.53	17.74	73.65	8.61	SiL	13.65	21.57	1.36	1.86
P15	Ap	1-9	0.21	0.62	2.06	9.58	10.20	14.37	9.17	22.67	62.70	14.63	SiL	14.10	19.05	1.13	0
	Ad	9-20/30	0.31	0.52	2.17	9.38	10.31	17.27	9.65	22.69	62.98	14.33	SiL	14.81	19.87	1.33	0
	AC	20/30-42	0.10	0.51	1.64	10.64	9.42	23.49	9.42	22.31	63.21	14.48	SiL	12.19	20.16	1.25	0
	C	42-61	0.21	0.41	2.26	7.92	7.20	21.86	11.36	18.00	66.52	15.48	SiL	10.79	20.48	1.30	0
	2Bwb1	61-85	0.21	0.41	2.16	6.58	6.68	20.86	12.18	16.04	69.63	14.33	SiL	11.20	20.66	1.34	0
	2Bwb2	85-130	0.21	0.31	2.46	8.01	7.70	21.40	10.57	18.69	71.66	9.65	SiL	10.96	20.85	1.29	0.92
	2Ckb	130-160	0.41	0.62	2.06	4.95	3.30	25.67	11.34	11.34	81.44	7.22	Si-SiL	12.18	21.86	1.34	2.70
P16	Ap1	0-14	0.64	0.21	0.64	3.28	4.13	32.25	16.36	8.90	66.42	24.68	SiL	26.51	29.16	1.11	0
	Ap2	14-30/40	0.57	0.33	0.74	4.01	5.49	16.01	5.86	11.14	74.49	14.37	SiL	20.25	22.66	1.41	0
	C	30/40 - 50/55	0.31	0.31	0.92	11.32	10.70	22.02	7.34	23.56	62.57	13.87	SiL	18.59	21.32	1.51	0
	2Bwb1	50/55 -82	0.31	0.31	1.14	6.00	6.20	22.43	9.09	13.96	65.83	20.21	SiL	17.77	22.90		0
	2Bwb2	82-138	0.31	0.21	1.24	5.17	5.38	26.69	5.58	12.31	69.90	17.79	SiL	17.09	21.85		0
	2Cb	138-150	0.42	0.62	1.66	3.12	5.51	26.76	10.64	11.33	78.95	9.72	SiL-Si	18.75	20.67		0
P17	A1	0-19	0.46	0.34	0.46	7.20	7.66	21.49	11.08	16.12	56.51	27.37	SiCL-SiL	18.74	32.51	0.96	0
	A2	19-32	0.53	0.21	0.53	7.02	8.20	19.60	9.15	16.49	56.85	26.66	SiL-SiCL	18.77	27.21	1.13	0
	A3	32-50	0.53	0.21	0.53	8.35	9.09	22.09	9.83	18.71	56.31	24.98	SiL	24.38	26.62	1.04	0
	AC	50-80	0.53	0.32	0.63	7.46	7.25	20.92	8.88	16.19	58.14	25.67	SiL-SiCL		25.21		0
	2Btb1	80-113	0.32	0.21	0.53	3.07	3.18	21.36	8.64	7.31	54.52	38.17	SiCL		27.81		0
	2Btb2	113-125	0.42	0.21	0.63	3.04	3.57	25.20	5.98	7.87	59.53	32.60	SiCL		25.81		0

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); Eff M = effective moisture (%); M Eq = moisture equivalent (%); Bd = bulk density (Mg m (%); OC = organic carbon (%); pH (water 1:1); Ex Ca = exchangeable calcium; CEC = cation exchange capacity (all cations in cmol phosphorus (mg kg^{-1}).

Table 13.2. Laboratory data of supporting soil profiles (1).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Texture	M Eq	Bd	Carb
M1	Ap	0-4	0.59	0.88	3.10	9.91	6.89	14.49	10.14	21.37	64.29	14.39	SiL	21.12	1.19	(
	Ad	4-30/35	0.72	1.15	3.06	9.72	7.05	19.32	4.96	21.70	59.71	18.59	SiL	21.19	1.43	(
	Bw	30/35-49	0.44	0.99	2.86	10.86	7.30	19.94	6.85	22.45	61.71	15.84	SiL	20.04	1.23	(
	C	49-60	1.25	1.30	3.43	10.10	7.42	18.36	5.56	23.50	60.87	15.63	SiL	19.68	1.31	(
M2	Ap	0-13/15	0.11	0.16	0.28	1.59	2.12	34.01	16.26	4.26	68.40	27.34	SiCL-SiL	34.38	0.94	(
	AB	13/15-48	0.09	0.13	0.26	1.42	1.90	32.28	15.29	3.80	63.75	32.45	SiCL	31.84	1.72	(
	Bt	48-73	0.03	0.03	0.08	0.28	0.64	45.75	18.39	1.06	69.22	29.72	SiCL	27.92	1.36	(
M3	Ap	0-23	0.02	0.06	0.12	1.29	1.82	34.65	17.89	3.31	66.28	30.41	SiCL	35.19	1.03	(
	AB	23-35	0.03	0.03	0.07	0.80	1.15	32.29	17.92	2.08	61.12	36.80	SiCL	33.07	1.24	(
	Bt	35-60	0.02	0.03	0.03	0.14	0.21	37.89	19.98	0.43	65.52	34.05	SiCL	29.40	1.38	(
M4	A	0-12/18	0.11	0.11	0.22	1.95	2.81	33.21	14.43	5.20	71.04	23.76	SiL	38.50	0.91	(
	Bt	12/18-40/44	0.03	0.06	0.14	2.18	3.49	36.68	10.50	5.90	66.32	27.78	SiCL-SiL	34.79	1.07	(
	BC	40/44-50	0.02	0.01	0.07	1.62	2.48	35.11	14.08	4.20	66.01	29.79	SiCL	29.86	1.40	(
	2Btb	50-60	0.02	0.01	0.06	1.48	2.12	31.56	16.22	3.69	66.03	30.28	SiCL	28.74	1.43	(
M5	Ap	0-12	0.37	0.24	0.44	1.07	0.91	23.04	20.07	3.03	49.72	47.25	SiC	34.75		(
	Ad	12-23	0.21	0.20	0.25	0.71	0.58	27.16	22.48	1.91	55.86	42.23	SiC	34.65		(
	2Bt1	23-36/40	0.11	0.15	0.55	4.37	4.57	23.41	14.95	9.75	58.75	31.50	SiCL	31.97		(
	2Bt2	36/40-60	0.11	0.14	0.53	4.61	4.93	22.73	14.00	10.32	58.60	31.08	SiCL	31.76		(
M6	A1	0-10	0.06	0.17	0.54	2.30	2.67	24.69	17.17	5.74	60.53	33.73	SiCL	33.36	1.22	(
	A2	10-16	0.04	0.08	0.31	1.34	1.31	32.52	19.07	3.08	62.26	34.66	SiCL	32.40	1.05	(
	2AB	16-40	0.16	0.31	1.18	7.67	6.93	24.74	12.36	16.25	61.71	22.04	SiL	27.61	1.07	(
	2Bw1	40-59	0.15	0.21	0.97	7.26	6.41	25.48	13.13	15.00	62.90	22.10	SiL	28.64	1.00	(
	2Bw2	59-65	0.17	0.34	1.08	11.29	8.05	27.16	10.18	20.93	61.36	17.71	SiL	24.77		(
M7	Ap	0-18	0.10	0.14	0.49	3.66	3.64	25.52	14.50	8.03	60.06	31.91	SiCL	28.59	1.31	(
	AB	18-32	0.18	0.18	0.71	5.42	5.09	23.85	12.24	11.58	59.37	29.05	SiCL	26.71	1.32	(
	Bt	32-50	0.23	0.23	0.83	7.12	7.16	22.88	10.21	15.57	58.31	26.12	SiL-SiCL	24.81	1.21	(
	BC	50-60	0.21	0.27	0.80	8.92	8.70	23.67	8.98	18.90	60.91	20.19	SiL	22.66		(

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); (water 1:1); Ex Ca = exchangeable calcium; CEC = cation exchange capacity (all cations in cmol (+) kg^{-1} soil); P Sol = soluble phosph

Table 13.2. Laboratory data of supporting soil profiles (2).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Texture	M Eq	Bd	Carb
M8	Ap	0-12	0.39	0.65	1.96	7.12	7.41	14.88	10.87	17.53	64.44	18.03	SiL	20.15	1.37	0
	A2	12-37	0.34	0.65	1.66	6.71	6.93	23.33	8.57	16.29	64.70	19.01	SiL	21.49	1.28	0
	Bw1	37-49	0.29	0.50	1.52	7.48	7.29	24.12	3.45	17.08	58.81	24.11	SiL	20.61	1.11	0
	Bw2	49-60	0.21	0.46	1.38	6.92	7.39	25.35	7.64	13.36	70.68	15.96	SiL	21.14		0
M9	Ap	0-8/11	0.85	1.03	3.30	11.96	10.32	22.04	2.92	27.46	50.46	22.08	SiL-L	22.19	1.19	0
	A2	8/11-28	0.57	1.00	3.03	11.67	10.10	21.06	9.74	26.37	55.89	17.74	SiL	24.02	1.32	0
	Bw1	28-45	0.71	0.93	2.85	11.83	10.16	20.66	9.44	26.48	55.53	17.99	SiL	23.25	1.27	0
	Bw2	45-52	0.46	0.74	2.27	10.31	8.78	24.51	11.35	22.56	59.64	17.80	SiL	24.54	1.30	0
	BC	52-60	0.68	0.94	3.07	12.25	9.54	22.14	10.16	26.48	59.45	14.07	SiL	22.90		0
M10	Ap	0-5/8	0.17	0.26	1.16	8.53	9.35	17.65	7.60	19.47	67.67	12.86	SiL	21.60	1.12	0
	A2	5/8-18	0.13	0.32	1.09	9.47	8.81	22.84	7.76	19.82	67.83	12.35	SiL	21.30	1.21	0
	Bw1	18-32	0.24	0.39	1.53	9.47	10.09	23.99	8.57	21.72	67.77	10.51	SiL	20.75	1.21	0
	Bw2	32-59	0.08	0.19	0.92	9.47	11.19	26.25	6.89	21.85	71.47	6.68	SiL	20.22	1.15	0.79
	BC	59-70	0.18	0.18	0.90	9.84	9.02	26.90	9.15	20.12	71.74	8.13	SiL	19.82		0.93
M11	A1	0-3/7	0.15	0.15	0.57	6.57	7.64	24.00	6.99	15.08	73.05	11.87	SiL	19.84	1.27	0
	A2	3/7-22	0.12	0.11	0.46	6.70	8.56	24.32	7.51	15.95	70.87	13.18	SiL	20.34	1.12	0
	Bw1	22-37	0.07	0.09	0.41	6.27	8.60	24.62	8.63	15.44	71.55	13.01	SiL	20.76	1.04	0
	Bw2	37-64	0.08	0.13	0.47	6.91	8.29	23.63	6.77	15.88	72.30	11.82	SiL	21.93	1.14	0
	BC	64-79	0.11	0.17	0.48	7.99	8.43	28.01	8.24	17.18	73.19	9.63	SiL	21.86		3.67
M12	Ap	0-9/12	0.31	0.62	1.72	6.79	6.00	24.43	6.90	15.44	69.75	14.81	SiL	21.10	1.02	0
	A2	9/12-15/19	0.17	0.52	1.46	6.70	6.52	24.55	6.67	15.37	70.24	14.39	SiL	21.65	1.03	0
	Bw1	15/19-25/28	0.29	0.49	1.48	7.07	8.37	20.66	7.44	17.70	66.54	15.76	SiL	22.29	1.18	0
	Bw2	25/28-42	0.32	0.55	1.48	7.59	8.03	22.57	7.26	17.97	67.19	14.84	SiL	21.58	1.21	0
	C	42-60	0.30	0.46	1.42	8.85	9.32	23.06	6.23	20.35	67.35	12.30	SiL	20.45	1.16	0

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); (water 1:1); Ex Ca = exchangeable calcium; Ex Ca = Ca soluble in ammonium acetate 1N; CEC = cation exchange capacity (all catio = soluble phosphorus (mg kg^{-1}).*

Table 13.2. Laboratory data of supporting soil profiles (3).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Text	M Eq	Bd	Car
M13	Ap	0-16	0.06	0.21	0.91	7.47	7.02	21.99	8.77	15.67	65.26	19.07	SiL	24.16	1.17	
	A2	16-23/26	0.08	0.19	0.92	7.46	7.61	19.58	8.25	16.26	61.47	22.27	SiL	24.12	1.28	
	Bt1	23/26-38/40	0.15	0.15	0.79	7.68	7.74	22.24	8.92	16.51	61.82	21.67	SiL	23.70	1.22	
	Bt2	38/40-51/57	0.13	0.18	0.77	9.60	8.18	26.14	8.22	18.86	65.44	15.70	SiL	22.49	1.18	
	BC	51/57-70	0.09	0.32	1.06	6.89	6.28	21.21	11.04	14.64	64.55	20.81	SiL	23.57		
M14	Ap	0-14	0.64	0.45	1.21	8.22	9.37	20.42	6.53	19.89	65.91	14.20	SiL	21.56	1.10	
	A2	14-25	0.21	0.30	0.92	6.93	7.48	22.13	8.57	15.84	68.10	16.06	SiL	22.26	1.09	
	Bw1	25-33	0.14	0.27	0.89	7.51	7.12	21.41	6.90	15.93	67.10	16.97	SiL	21.55	1.08	
	Bw2	33-47	0.21	0.33	0.87	8.04	7.99	22.28	6.57	17.44	68.55	14.01	SiL	20.55	1.12	
	C	47-60	0.37	0.35	1.07	8.47	9.01	21.45	6.92	19.27	70.28	10.45	SiL	19.23		
M15	Ap	0-10/12	0.24	0.44	1.11	3.16	2.23	28.29	27.43	7.18	76.01	16.81	SiL	35.48	1.13	
	Bt1	10/12-38	0.17	0.17	0.37	3.56	3.75	23.77	11.68	8.02	61.58	30.40	SiCL	32.71	0.93	
	Bt2	38-50	0.10	0.12	0.32	4.30	4.30	26.40	13.77	9.14	60.67	30.19	SiCL	32.05	1.03	
	BC	50-60	0.06	0.11	0.32	4.12	4.41	28.89	10.23	9.02	61.67	29.31	SiCL	31.84		
M16	Ap	0-12	1.09	1.43	2.72	7.04	8.11	20.00	6.25	20.39	60.75	18.86	SiL	25.10	1.17	
	A2	12-32	1.52	1.81	2.84	6.86	7.27	19.12	5.89	20.30	59.55	20.45	SiL	23.58	1.52	
	Bt	32-42	1.17	1.35	2.30	6.94	7.78	19.17	5.88	19.54	60.83	19.63	SiL	22.75	1.28	
	BC	42-59	0.96	1.16	2.19	8.60	7.82	21.30	5.16	20.73	62.19	17.08	SiL	21.60	1.25	
	C	59-65	2.00	1.41	2.76	6.92	6.64	20.84	4.89	19.73	61.72	18.55	SiL	21.49		

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = calcium carbonate (%); (water 1:1); Ex Ca = exchangeable calcium; CEC = cation exchange capacity (all cations in cmol (+) kg^{-1} soil); P Sol = soluble phosph

Table 13.2. Laboratory data of supporting soil profiles (4).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Text	Eff M	M Eq	Bd
M17	Ap	0-10	0.84	0.73	1.36	8.37	9.52	4.03	5.12	20.82	59.93	19.25	SiL	16.77	24.78	1.03
	Ad	10-26	0.52	0.63	1.15	8.08	9.24	23.77	6.82	19.62	58.39	21.99	SiL	19.00	24.20	1.37
	A4	37-51/54	0.41	0.52	1.03	9.98	8.35	26.58	4.38	20.29	56.26	23.45	SiL	23.31	22.90	1.16
	2Bt	51/54-80	0.32	0.53	1.06	4.46	3.29	17.22	5.57	9.66	42.95	47.39	SiC		32.13	
M18	Ap1	0-11	0.95	1.37	2.11	8.45	9.50	18.95	5.02	22.38	56.66	20.96	SiL	17.85	22.40	1.16
	Ap2	11-31	0.85	1.27	1.80	7.72	8.99	22.62	5.49	20.63	56.06	23.31	SiL	22.03	23.37	1.27
	A3	31-57	0.73	0.83	1.45	9.66	9.04	23.74	4.88	21.71	57.09	21.20	SiL	22.72	21.81	1.18
	Bt	57-80+	1.27	1.06	1.80	5.29	4.97	19.42	6.98	14.39	56.20	29.41	SiCL		23.52	
M19	Ap1	0-17	1.34	0.45	1.34	4.01	4.01	28.85	10.36	11.15	51.24	37.26	SiCL	29.40	36.69	0.91
	2Ap2	17-36	0.77	0.44	1.10	3.84	4.83	26.50	10.53	10.98	51.94	37.08	SiCL	32.51	34.19	1.17
	2AB	36-53/56	0.53	1.18	2.35	6.74	5.78	22.09	9.89	16.58	47.79	35.63	SiCL	30.07	31.04	1.22
	2Bt	53/56-70+	0.54	0.76	2.71	7.79	6.50	21.81	8.44	18.30	45.00	36.70	SiCL		30.09	
M20	Ap	0-18	1.34	0.33	1.34	6.36	6.14	27.05	9.60	15.51	56.38	28.11	SiCL-SiL	32.35	32.12	1.16
	A2	18-37	0.64	0.11	0.75	5.25	6.43	25.32	9.41	13.18	57.29	29.53	SiCL	28.42	30.60	1.16
	A3	37-50	0.43	0.21	1.07	7.15	7.04	26.46	7.79	15.90	51.78	32.32	SiCL	27.32	27.33	1.09
	A4	50-75	0.21	0.11	1.06	8.69	7.95	26.33	7.15	18.02	53.43	28.55	SiCL		26.41	
	Bt	75-85+	0.21	0.21	0.62	6.13	8.72	25.43	8.10	15.89	57.60	27.05	SiCL-SiL		25.71	
M21	Ap	0-18	0.63	0.42	0.63	5.81	8.44	22.80	8.28	15.93	62.11	21.96	SiL	15.32	25.81	1.09
	Ap	13-18												21.32		1.22
	A2	18-42	0.53	0.64	0.64	5.62	8.06	23.33	8.17	15.49	58.48	26.03	SiL-SiCL	20.87	27.21	1.21
	Bw	42-60+	0.31	0.52	0.63	7.84	9.83	20.03	8.10	19.13	55.40	25.47	SiL-SiCL	14.62	24.72	1.13
M22	Ap	0-12/15	0.42	0.52	0.31	7.96	10.06	24.20	5.50	19.27	57.68	23.05	SiL	14.41	23.82	0.93
	A2	12/15-33	0.41	0.21	0.52	10.92	10.51	27.25	4.18	22.57	56.98	20.45	SiL	17.23	22.59	1.14
	2Bt	33-60+	0.43	0.11	0.21	3.41	3.62	42.73	13.25	7.78	52.84	39.38	SiCL-SiC	19.46	56.20	1.44
M23	Ap1	0-11	0.43	0.32	1.39	8.79	9.75	24.80	8.08	20.68	57.42	21.90	SiL	19.22	26.29	0.92
	Ap2	11-21	0.21	0.32	1.28	7.23	10.10	25.26	6.91	19.14	57.78	23.08	SiL	19.88	27.08	1.13
	A3	21-34	0.21	0.42	1.66	11.84	10.49	24.15	6.38	24.62	52.48	22.90	SiL	22.66	24.16	1.11
	Bt	34-63	0.11	0.21	1.38	6.60	10.22	23.16	7.23	18.52	51.67	29.81	SiCL	21.98	27.23	1.13
	C	63-73+	0.21	0.21	0.42	8.21	6.44	24.00	10.49	15.49	58.75	25.76	SiL-SiCL		24.24	

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); Eff M = effective moisture; M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = organic carbon (%); pH (water 1:1); CEC = cation exchange capacity (all cations in cmol (+) kg^{-1} soil); P Sol = soluble phosphorus (

Table 13.2. Laboratory data of supporting soil profiles (5).

Site	Horiz	Depth	VCoS	CoS	MS	FS	VFS	MSi	FSi	Sand	Silt	Clay	Texture	Eff M	M Eq	Bd	Ca
M24	Ap	0-8	1.07	0.43	1.28	8.00	9.28	22.18	6.34	20.06	64.79	15.15	SiL	7.94	24.38	1.18	
	A2	8-23	0.53	0.32	1.28	7.24	8.73	20.13	6.60	18.10	65.34	16.56	SiL	9.60	23.01	1.22	
	AC	23-40	0.83	0.42	1.14	7.58	9.03	21.44	9.13	19.00	65.79	15.21	SiL	10.00	22.29	0.99	
	C	40-60	0.41	0.21	2.06	11.34	11.75	21.49	6.90	25.77	65.83	8.40	SiL		20.34		
M25	Ap	0-8/12	0.74	0.42	1.16	8.23	10.14	18.95	6.87	20.95	62.05	17.00	SiL	7.78	21.13	1.10	
	Bw	8/12-25	0.63	0.21	0.95	7.25	9.56	21.42	7.09	18.60	63.60	17.80	SiL	10.80	20.96	1.23	
	BC	25-42	0.31	0.31	1.55	9.82	11.27	20.93	7.09	23.26	64.08	12.66	SiL		19.65		
	C	42-60+	0.21	0.51	2.16	11.31	11.93	18.47	6.48	26.12	65.45	8.43	SiL	12.52	20.10	1.05	
M26	Ap	0-15	0.53	0.32	1.26	7.26	8.73	20.09	4.94	18.10	64.33	17.57	SiL	14.25	21.57	1.02	
	A2	15-23	0.32	0.53	1.47	7.67	8.51	24.04	6.04	18.50	63.75	17.75	SiL	16.27	21.57	1.04	
	AC	23-47	0.31	0.42	1.36	7.95	8.58	23.48	4.19	18.62	62.29	19.09	SiL	19.13	21.23	1.04	
	C	47-75+	0.31	0.41	1.55	7.85	11.77	21.58	8.00	21.89	64.43	13.68	SiL		20.32		
M27	Ap1	0-9	0.42	0.74	2.11	7.92	8.55	25.33	5.28	19.74	61.05	19.21	SiL	19.64	23.15	1.18	
	Ap2	9-20	0.32	0.33	1.69	6.64	7.91	25.25	6.43	17.09	61.56	21.35	SiL	20.12	23.41	1.24	
	A3	20-30	0.52	0.42	1.68	6.29	8.18	24.80	8.18	17.09	60.67	22.24	SiL	19.74	22.80	1.55	
	Bw	30-56	0.52	0.42	1.56	7.07	8.32	22.88	8.26	17.89	62.51	19.60	SiL		21.36		
	C	56-80+	0.41	0.21	1.55	8.04	8.97	24.03	9.75	19.18	64.58	16.24	SiL		19.20		
M28	Ap1	0-9/12	2.05	2.37	3.88	5.83	7.55	16.88	6.47	21.68	55.50	22.82	SiL	24.93	23.09	1.23	
	Ap2	9/12-22	1.94	2.04	3.33	5.91	7.10	19.57	7.04	20.32	54.73	24.95	SiL	22.68	21.99	1.40	
	A3	22-33	1.80	1.69	2.96	6.87	7.29	20.87	6.97	20.61	55.50	23.87	SiL	27.86	21.14	1.26	
	AB	33-55	1.67	1.67	2.82	6.88	9.91	19.86	6.99	22.95	57.87	19.18	SiL		20.40		
	Bt	55-70+	2.19	1.88	3.65	5.74	5.84	20.96	3.65	19.30	57.65	23.05	SiL		19.78		
M29	Ap	0-10/13	0.64	0.75	1.92	8.00	9.82	22.51	3.84	21.13	62.70	16.17	SiL		19.66	1.00	
	A2	10/13-30	0.74	0.63	1.79	7.60	9.50	22.42	5.70	20.26	62.12	17.62	SiL		19.65	1.13	
	AC	30-49	1.04	0.42	1.77	8.01	9.05	23.29	6.24	20.29	63.80	15.91	SiL		19.13	1.14	
	C	49-68+	1.13	0.72	1.64	8.94	10.17	24.46	5.91	22.60	65.79	11.61	SiL		18.01		

Horiz = horizon; Depth (cm); VCoS = very coarse sand; CoS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sa fine silt (all particle size fractions in %); Eff M = effective moisture; M Eq = moisture equivalent (%); Bd = bulk density (Mg m^{-3}); Carb = organic carbon (%); pH (water 1:1); CEC = cation exchange capacity (all cations in cmol (+) kg^{-1} soil); P Sol = soluble phosphorus (

PICTURES

Photo 1.
Chaco forest with 15-20 m high quebracho trees (*Aspidosperma* and *Schinopsis*), remnants of the original forest upper story, and dense shrub forming the lower story. In the foreground, mature soybean. (AZ)

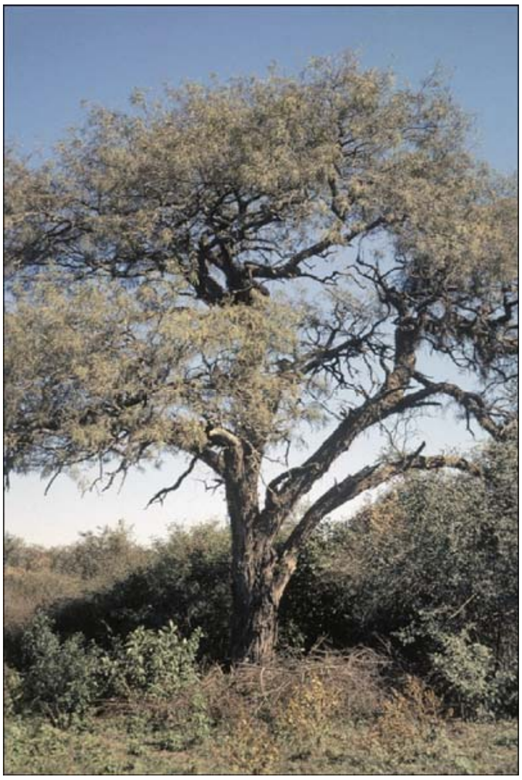


Photo 2.
Algarrobo tree (*Prosopis nigra*), a remnant of the original upper story of the Chaco forest. (AZ)

Photo 3.
Aspect of the Chaco forest during the dry winter season (April-October). Palo borracho tree (*Chorisia insignis*), with a characteristic bottle-shaped stem. (AZ)

Photo 4.
Degraded Chaco forest during the moist summer season (November-March). In the foreground, mature soybean. (AZ)

Photo 5.
Degraded Chaco forest with multi-stem shrubs during the dry winter season (April-October). (AZ)

Photo 6.
Areas reclaimed using mechanized clearing with bulldozer for large soybean fields, in contrast to residual patches of degraded Chaco forest. Area of Gobernador Garmendia. (AZ)

Photo 7.
Chaco forest clearing with bulldozer. Burruyacú area (Sanchez Toranzo farm). (AZ)

Photo 8.
Edge of area reclaimed from Chaco forest. Area of La Ramada. (EB)

Photo 9.
Removed and heaped vegetation from original degraded Chaco forest. (EB)

Photo 10.
Ridge of forest clearing residues heaped up by bulldozer for burning. (AZ)

Photo 11.
Ridge of burned forest residues. (AZ)

Photo 12.
Lines of ashes and burned vegetation after recent reclamation of Chaco forest. (EB)

Photo 13.
Loess cover in the fluvio-eolian plain with a paleosol at mid-height of the outcropping profile along the Tajamar river. (AZ)

Photo 14.
Subparallel pattern of paleochannels buried under the loess cover and recent gully incision. (EB)

Photo 15.
Fine-silty Typic Argiustoll (Silti-Cutanic Luvisol) developed from loess in the western sub-humid to humid strip; compact plow-pan with laminar structure beneath the plowed arable surface horizon. Profile P1A under rain-fed agriculture in the Lobo farm, Burruyacú area. (AZ)

Photo 16.
Fine-silty Entic Haplustoll (Siltic Phaeozem), with a moderately thick mollic epipedon and a buried paleosol, developed from loess in the sub-humid to semiarid central part of the study region (knife = 20 cm). Profile P11 under rain-fed agriculture in La Virginia area. (AZ)

Photo 17.
Coarse-silty Torrifluventic Haplustept (Silti-Eutric Cambisol) showing a light-coloured cover phase of reworked eolian material, a mollic horizon, and the loess parent material. Underneath, a buried paleosol. Plow-pan formation at the bottom of the arable layer with platy structure. Profile P4A under rain-fed agriculture in the eastern semiarid strip in the Gobernador Garmendia area. (AZ)

Photo 18.
Large soybean field in the fluvio-eolian plain. In the background, sub-Andean mountain ranges. (AZ)

Photo 19.
Parallel yellow stripes in a soybean field, corresponding presumably to the location of burned forest residues. In the background, sub-Andean mountain ranges fringed by piedmont glacis. (AZ)

Photo 20.
Sugarcane field bordering a patch of Chaco forest in La Ramada. (EB)

Photo 21.
Sugarcane, citrus and soybean fields from foreground to background. (AZ)

Photo 22.
Strip cropping in the foreground and contour cropping in the background in the piedmont landscape. Burruyacú area. (AZ)

Photo 23.
Contour plowing in the piedmont area. (AZ)

Photo 24.
Conventional farming with traditional horse-powered moldboard plow in a small parcel being prepared for maize cultivation. Lobo farm in the Burruyacú area. (AZ)

Photo 25.
Combine used for harvesting soybean in La Virginia. (AZ)

Photo 26.
Soil surface sealed by rain splash after harvesting soybean. Area of Gobernador Piedrabuena. (AZ)

Photo 27.
Soil crust formed by sealing of the soil surface in a field reclaimed before 1970, in the area of Gobernador Garmendia. (EB)

Photo 28.
Small depression, frequent in soybean fields on flat land. (EB)

Photo 29.
Sealed and cracked soil surface that forms in water ponding places of soybean fields, in the area of Gobernador Piedrabuena. (AZ)

Photo 30.
Field infiltration test in the area of La Ramada (1997). At upper right, rain receiving cylinder; in the centre, sealed soil surface that was subjected to infiltration test; at lower left, rain producing cup with red volume scale. (EB)

Photo 31.
Wetted soil cross-section in a field reclaimed before 1970. The soil is friable till 20 cm depth, but compact underneath. Burruyacú area (Lobo farm). (EB)

Photo 32.
Stiboka penetrograph used for determining and recording soil resistance to penetration. (AZ)

Photo 33.
Local farmer and soil scientist discussing soil management issues. (AZ)

Photo 34.
Central buildings and facilities (house, silos, storage sheds, orchard) of a large mechanized soybean farm in the area of La Argentina. (AZ)

Photo 35.
Regional settlement of Gobernador Garmendia in the northeast corner of the study region that developed around a railroad station, now out of use. (AZ)

Mapa Geomorfológico de la región de Burruyacú, Provincia de Tucumán, Argentina

Leyenda

E: Unidades estructural-denudativas:

- E.1 Espinazo/pendiente fuerte estructural; Formación Pirgua
- E.2 Espinazo/pendiente fuerte estructural; Formación Medina
- E.3 Pendiente fuerte estructural; Formación Río Salí
- E.4 Complejo de espinazos pequeños
- E.5 Faceta
- E.6 Plataforma estructural-denudativa, remanente, alta

D: Unidades denudativas:

- D.1 Glacis inicial/plataforma estructural-denudativa, medio alta
- D.2 Glacis inicial/plataforma estructural-denudativa, medio baja
- D.3 Glacis-cono/raña
- D.4 Glacis mixto degradado/rañizo
- D.5 Colina residual/pendiente fuerte, alta
- D.6 Colina residual/pendiente suave, baja
- D.7 Glacis de piedemonte/glacis de frente, ondulado, alto, durmiente

P: Unidades fluvio-denudativas/eólicas:

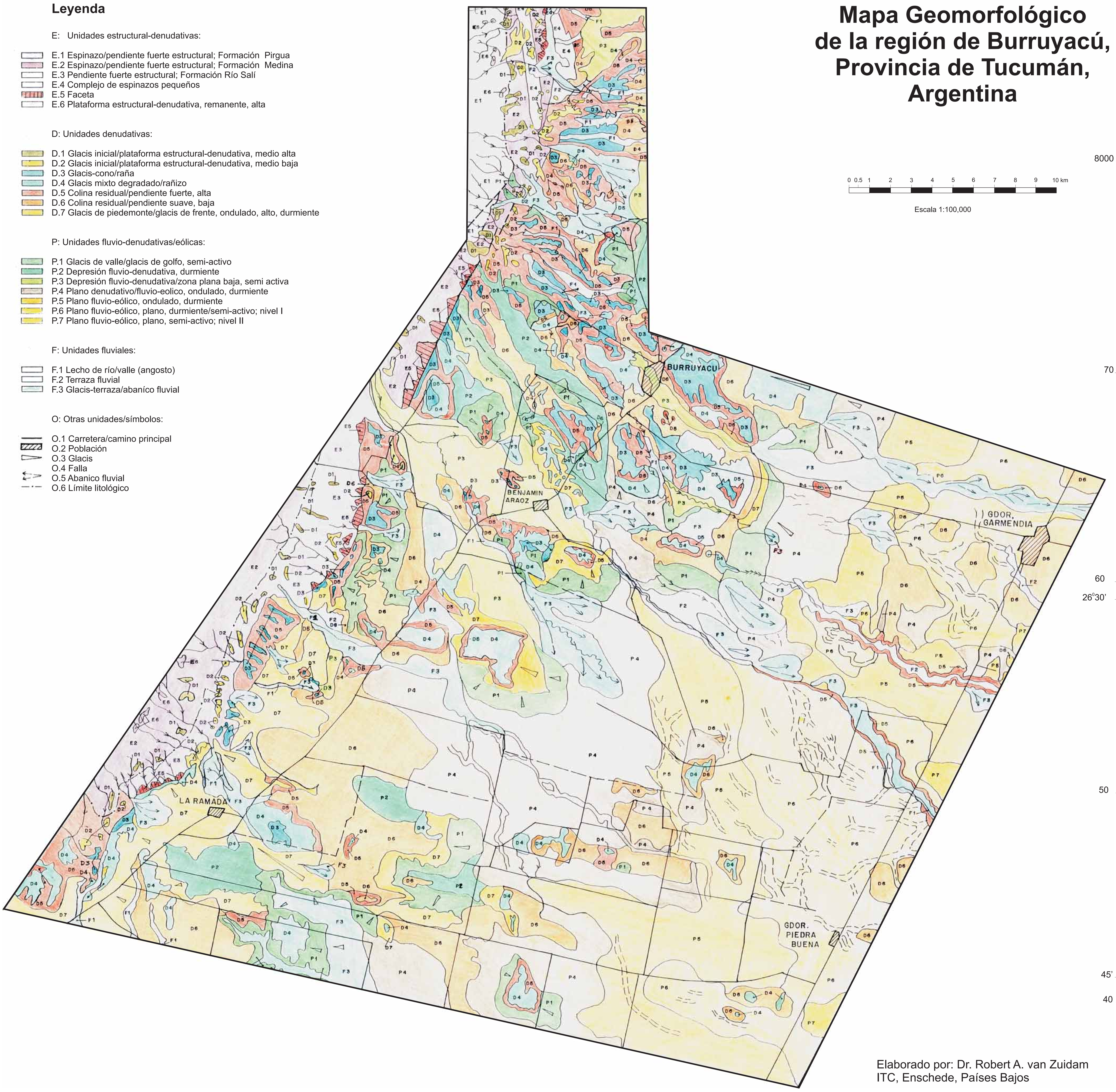
- P.1 Glacis de valle/glacis de golfo, semi-activo
- P.2 Depresión fluvio-denudativa, durmiente
- P.3 Depresión fluvio-denudativa/zona plana baja, semi activa
- P.4 Plano denudativo/fluvio-eolico, ondulado, durmiente
- P.5 Plano fluvio-eólico, ondulado, durmiente
- P.6 Plano fluvio-eólico, plano, durmiente/semi-activo; nivel I
- P.7 Plano fluvio-eólico, plano, semi-activo; nivel II

F: Unidades fluviales:

- F.1 Lecho de río/valle (angosto)
- F.2 Terraza fluvial
- F.3 Glacis-terraza/abanico fluvial

O: Otras unidades/símbolos:

- O.1 Carretera/camino principal
- O.2 Población
- O.3 Glacis
- O.4 Falla
- O.5 Abanico fluvial
- O.6 Límite litológico



0 0.5 1 2 3 4 5 6 7 8 9 10 km

Escala 1:100,000

Elaborado por: Dr. Robert A. van Zuidam
ITC, Enschede, Países Bajos