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**CLASSIFYING STRONGLY WEATHERED SOILS FROM  
THE ZAIRIAN BASIN INTO THE REVISED INTERNA-  
TIONAL SOIL CLASSIFICATION SYSTEMS  
(Soil Taxonomy, 1990; FAO-UNESCO legend, 1988)**

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R. LANGOHR

*Abstract*

This study discusses the classification of strongly weathered soils from the Zairian basin according to the USDA Soil Taxonomy and the FAO-Unesco Systems. The recent changes introduced in these soil classifications resulted in a further drift of the systems. The testing of both taxonomies on representative soil profiles of the Zaire basin showed that the newly proposed kandic horizon in the USDA Taxonomy made the classification of deeply weathered soils more difficult. The proposed total silt/clay ratio as an index of soil weathering in the FAO-Unesco legend gave unsatisfactory results and it is proposed to calculate rather the fine silt/clay ratio. The rigorous testing of the classification of the Zaire soils permits to evaluate the adequacy of the pedon data base and to recommend a series of field observations and laboratory data to be checked in the future. This will raise the quality of the data base to the requirement of the present-day taxonomic systems.

*Keywords*

FAO-UNESCO Soil Map legend, silt/clay ratio, strongly weathered soils, USDA Soil Taxonomy, Zaire.

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## 1. INTRODUCTION

Many national and international institutions update their soil classification systems regularly according to the progress made in soil science through field and laboratory investigations. Here we study the changes in the soil classification of strongly weathered tropical soils of the Zaire basin, according to the recent revisions of the FAO-UNESCO (FAO, 1988) and the USDA Soil Taxonomy (Soil Survey Staff, 1990) Systems (abbreviated here as FAO88 and ST90).

Soil classification plays an important role in the communication of information about soils, particularly in agrotechnology transfer. A prerequisite, however is that one soil profile will be classified similarly by different pedologists. Unfortunately this prerequisite is seldom met in soil science. The classification of 6 pedons of well drained red clayey upland soils of Mozambique by an international panel of 12 soil experts showed a large variation (Kauffman, 1985). At the subgroup level of the USDA Soil Taxonomy (1975) system, each pedon received 8 different names on the average. At order level some soils were given up to 4 different names, ranging, for example, from Oxisols to Mollisols, Ultisols and Alfisols. Yet a rather comprehensive data base of these soils had been provided to the scientists. All professionals attending meetings and field excursions about soil classification also know that rarely all colleagues agree on a single name for one soil.

There are three main reasons for this unfortunate situation in soil science.

1. Frequently a particular name is given to a soil largely influenced by a scientist's personal bias, i.e. to his experience, this is just the best name for that soil type without rigorously checking the diagnostic requirements mentioned in the classification system for the particular taxon.

2. The syntax of the classification system handbook is so difficult that the reader will have difficulties in identifying the soil correctly. Poorly defined diagnostic criteria and poor construction of the key for taxonomic determination are additional obstacles for a correct classification of the soil.

3. The absence of important information in the soil data base is another frequent problem. In an evaluation study on the adequacy of pedon data for soil classification, Lopulisa (1986) concluded that of the 172 pedons, selected from 151 soil publications, only 8% provided more than 75% of all the data needed to classify soils down to the subgroup level in the USDA Soil Taxonomy; the highest ranking profile had 85% of information needed. Yet in all these publications the authors had classified the soils according to Soil Taxonomy. Furthermore a subjective decision was made since these pedologists gave only one name to each soil, i.e. the "best fitting" name. It is evident that this procedure will result in a soil profile being given several names by different pedologists.

These three weak aspects in soil classification will be further discussed below for a set of representative pedons of the Zaire basin.

## **2. RECENT CHANGES IN THE USDA SOIL TAXONOMY AND THE FAO SYSTEMS**

We refer to Van Wambeke (1989) for a more theoretical discussion about the rational and the positive and negative aspects of some important changes for the classification of tropical soils in the FAO88 and ST90 systems. The comments made here concern those aspects important for the discussion of the Zaire soils.

### **2.1. Updated soil taxonomy (ST90)**

#### *2.1.1. Kandic horizon*

The original idea for the introduction of the kandic horizon was to upgrade the oxic subgroup of tropical Ultisols and Alfisols to the great group soil level (Moormann, 1975). This would permit to distinguish Ultisols and Alfisols of tropical regions from those of the temperate regions. The kandic horizon is, however, not the expression of a single soil forming process, the clay increase may be the result of clay migration-accumulation, clay destruction, selective erosion, sedimentation or lithological discontinuity (FAO, 1988; Van Wambeke, 1989; Driesen and Dudal, 1991).

Compared with other diagnostic B horizons, the kandic horizon is not mutually exclusive with the argillic horizon. When considered at the same classification level, part of the pedon may meet the requirements of both the argillic and the kandic horizons.

#### *2.1.2. Oxic horizon*

The definition of the oxic horizon changed in ST90 Keys in such a way that the argillic and the oxic horizon are not any more mutually exclusive and the precedence of the argillic horizon over the oxic horizon is now reversed. Consequently, according to the new key, a given horizon may at the same time be argillic and oxic. Examples are soils in which the clay increase requirement is met within a distance of more than 15 cm but less than 30 cm.

### **2.2. Revised FAO-UNESCO legend (FAO88)**

#### *2.2.1. Ferralic horizon*

The name and the definition of the oxic B horizon were modified, it became the ferralic B horizon and three new attributes were introduced:

- the silt/clay ratio should be less or equal to 0.2,
- a low (less than 10%) content of water dispersible clay,
- the qualifier "apparent" in the CEC and ECEC requirement of clay is dropped as the FAO recommends to make a correction in the calculation of the CEC/100 g clay by subtracting the CEC due to the organic mater.

### 2.2.2. *Argic horizon*

The FAO legend removed the name "argillic" and replaced it by the "argic" horizon. It considered that this horizon may be the result of different soil forming processes and not only the illuvation. Other processes such as destruction of clay in the overlying horizon, selective erosion of clay, sedimentation or biological activities may also lead to its formation.

An argic B horizon is exclusive of the ferralitic B horizon as it should lack its set of properties.

### 2.2.3. *Climatic regime*

Except where permafrost is present, the FAO-UNESCO legend has dropped the climatic criteria which in the FAO74 version were only required for desert soils. In the FAO88 system, the soil climatic regime is not a diagnostic characteristic for classifying tropical soils.

## 3. MATERIALS AND METHODS

89 pedons scattered over the Zairian basin have been classified rigorously according to the revised ST90 and the FAO88 systems (Ngongo, 1990). Five of these profiles, representing specific and common problems at the level of classification, are discussed here in two phases. The field and the laboratory data profiles are given at the end of this paper. In a first phase, the quality of the profile data base used for this classification was evaluated following the method proposed by Langohr and described by Ngongo (1990). With this method it was possible to estimate first the adequacy of the data base for soil classification by listing the missing, the vague and the unreliable field and laboratory data.

In the second phase the adequacy of the classification systems for the soils of the region under study was evaluated.

In function of these items, the soil taxon name is followed by a number from 0 to 10, according to the confidence level (table 3), a number less than 10 indicating that an uncertainty remains for the proposed taxon name.

The CEC analysis and the particle size distribution of pedon PED3 were determined by the methods proposed in 1975 by the USDA Soil Conservation Service (Soil Survey Staff, 1975). For the other four pedons the INEAC (Congo Institute for Agricultural Study and Research) methods were followed (Croegaert, 1958). Here the CEC was determined by calcium acetate at pH 7 and the particle size distribution was measured by successive sedimentation. Unpublished studies performed in Zaire have shown that the USDA SCS and the INEAC results of CEC determination are not different for strongly weathered soil (Sys, oral communication).

## 4. RESULTS AND DISCUSSION

### 4.1. Evaluation of the data base

The evaluation of the pedon data base did permit to detect the missing, the vague and the unreliable field descriptive and laboratory data for classifying the soil profiles into FAO88 and ST90. This procedure was followed for the epipedon, the diagnostic subsurface horizons, the diagnostic properties and

**Table 1.**

Evaluation of the data base of pedon PED4 for soil classification purposes in ST90 and FAO88

Requirement of diagnostic B horizon	ST90	FAO88
1 <sup>(1)</sup>	+	+
2	+	+(7)
3	+	+
4	+	+(8)
5	+	+
6	+	+
7	-	+
8	(+)8	+
9	+	+
conclusion: diagnostic B horizon	kandic/ argillic(?)	ferralic
1 = details not specified here (Ngongo, 1990; ST90)		

*Legend of the symbols* foreseen in these tables (not all mentioned in this table):

? = uncertain

+ = fulfils the requirement

- = does not fulfil the requirement

+(n) = available data with vague definition

(+)n = missing data, but based on other data one can consider that the requirement is fulfilled

(-n) = missing data, but based on other data one can consider that the requirement is not fulfilled

n = confidence level (10=100%, 9=90%, 8=80%, etc)

o = missing data, relevant for classification

∅ = missing data, not relevant for classification

the diagnostic criteria mentioned in the keys for taxon determination.

The most important missing, unreliable and vague data in the Zaire soil data base include: amounts of weatherable minerals, vagueness about definition and content of clay coatings, dry soil color, color of "mottling", presence and content of plinthite, gibbsite, water-dispersible clay, thin section data (microscopic observation),  $P_2O_5$  content, bulk density, moisture content at 15 bar.

Table 1 shows an example of the data base evaluation for the diagnostic B horizon determination of pedon PED4.

**Table 2.**

Evaluation of diagnostic features for PED4

Soil unit	Diagnostic horizons and characteristics				
	Epipedon	Subsurface horizon			Humidity regime
		ST85	ST90	FAO88	ST85 & ST90
PED4	ochric	argillic	kandic or argillic (?)	ferralic	perudic
? = uncertain					

#### 4.2. Evaluation of the classification

Pedons **PED1** and **PED2** are classified as Kandiudalfic Eutrudox and Typic Kandiudalf (ST90) respectively. Both are Ferralsols (FAO88). These two pedons are developed on the same parent material, are situated in the same geographic region, have the same topographic position and have a low CEC and weatherable mineral content. Yet they are in different orders in ST90 due to the differences in clay content of the first 18 cm below the soil surface (PED1 = 41%, PED2 = 36%).

We propose that the requirement of more than 40% in the upper 18 cm of the soil for entering the Oxisols for pedons that otherwise meet all the requirements of the kandic horizon should be dropped. We don't see important differences in the management of such soils and in all land evaluation systems both soils will be classified identically. To separate these soils furthermore raises the problem of texture determination, particularly in tropical soils which have frequently high amounts of pseudoparticles. Van Reewijk (1984) showed that in western Europe, where pseudoparticles are much less frequent, the variability of clay content determination in the laboratory is around 11%.



In fact, considering how the kandic horizon is defined and used through ST90, it seems a diagnostic property rather than a diagnostic horizon. Indeed, it does not reflect a particular and well defined type of pedogenetic process and its most important role is to distinguish Ultisols and Alfisols of the tropics from those of the temperate regions.

The classification of **pedon PED3** in ST90 and FAO88 is somewhat difficult as some profile characteristics have values at the limit of the diagnostic criteria. In the tropics, soils with less than 30% clay generally have an apparent CEC higher than 16 meq/100g clay. A small test performed at the University of Ghent has shown that PED3 was classified by different soil specialists as an Oxisol, an Ultisol or an Entisol in ST90 and as an Acrisol or as a Ferralsol in FAO88. The different methods used to calculate the apparent CEC were responsible for these differences. In one method the apparent CEC of each B subhorizon is calculated separately. As one of these values is less than 16 meq/100g clay, the soil was considered an Oxisol. Another method calculates the weighted average value of the apparent CEC of the whole B horizon. This way the B horizon of pedon PED3 has a CEC value higher than 16 meq/100g clay.

The absence, in most if not all soil classification systems, of precise instructions on how to calculate exactly the diagnostic criteria will always be a cause of discrepancies in the taxonomic determination of soils.

**Pedon PED4** illustrates a profile that can have an oxic or an argillic B horizon in ST90. This pedon is classified as an Ultisol in ST85 and, following the key procedure, becomes an Oxisol in ST90. In the FAO74 and FAO88 systems, it remains a Xanthic Ferralsol.

Due to the lack of data on weatherable minerals, **pedon PED5** can be an Inceptisol or an Entisol. This pedon shows some of the problems that are commonly met in the identification of a cambic horizon in the tropical region of the Zaire basin. Indeed very few soil reports provide information about the amount of weatherable minerals. Pedon PED5 can not have an oxic nor a kandic horizon because its CEC is higher than 16 meq/100g clay (the eventual pseudoparticles have been destroyed). Consequently it meets all the requirements of a cambic horizon, except for the missing data of weatherable minerals.

If sufficient weatherable minerals would be present, PED5 will have a cambic horizon and will be classified as an Eutropept.

Otherwise this soil will not meet the criteria for any of the diagnostic B horizons and will come out as a Troporthent.

Soils traditionally considered to be Oxisols but ending up in other orders because of a too high CEC/100g clay is quite frequent. More and more there is a trend to propose a diagnostic limit of 24 meq/100g of clay instead of 16 meq (Sys, 1969). The Zairian soil data supports this proposal.

**Table 3.**

Classification of seven pedons selected from the 89 studied soils, with the confidence level (PED1 to PED5 are discussed in more detail in the text)

PEDON	SOIL CLASSIFICATION		
	ST85	ST90	FAO88
PED1	(7) Typic Eutrorthox, clayey, isohyperthermic	(8) Kandiudalfic eutrudox, clayey, isohyperthermic	(9) Xanthic Ferralsol
PED2	(7) Ultic Haplorthox, clayey, isohyperthermic	(7) Typic Kandiudalf, clayey, isohyperthermic	(9) Haplic Ferralsol
PED3	(7) Typic Haplustox, fine loamy, isohyperthermic	(8) Typic Kandiustult, fine loamy, isohyperthermic	(5) Haplic Acrisol Haplic Ferralsol
PED4	(6) Typic Paleudult, clayey, isohyperthermic	(8) Xanthic Hapludox, clayey, isohyperthermic	(9) Xanthic Ferralsol
PED5	(5) Typic Eutropept, clayey, isohyperthermic	(5) Typic Eutropept, clayey, isohyperthermic	(5) Eutric Cambisol
	(5) Typic Troporthent, clayey, isohyperthermic	(5) Typic Troporthent, clayey, isohyperthermic	(5) Eutric Leptosol
SS1	(7) Typic Haplorthox, fine loamy, isohyperthermic	(8) Typic Kandiudult, fine loamy, isohyperthermic	(9) Haplic Ferralsol
SS2	(S) Quartzipsammentic, Haplorthox, coarse loamy, isohyperthermic	(S) Typic Haplorthox, coarse loamy, isohyperthermic	(S) Xanthic Ferralsol

N.B.: The number in brackets shows the confidence level of the classification (S = 100% of confidence level, 8 = 80%, 7 = 70%, 6 = 60% etc...).  
ST85 and ST90 = USDA Soil Taxonomy.

In Zaire, the introduction of the kandic horizon considerably decreases the extension of the Oxisols in favour for the Ultisols (table 5). This is in conflict with the common idea that Ultisols are less strongly weathered than Oxisols. We conclude here from an agronomic as well as from a soil genetic viewpoint that it is very difficult to accept that extensive areas of Kandiudults of the Zaire basin are sufficiently different from Oxisols to locate them in different taxa from the highest level of classification on.

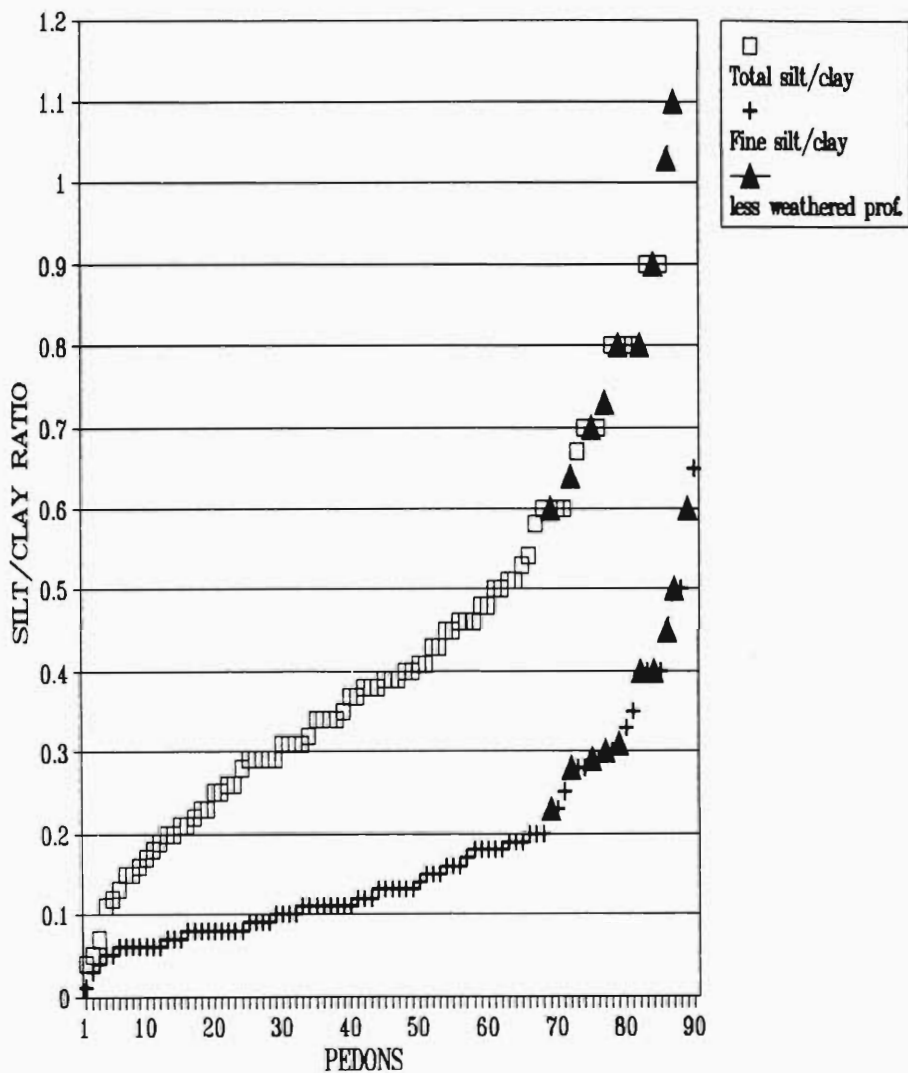
#### 4.3. Silt/clay ratio evaluation

The silt/clay ratio, an index of soil weathering established by Van Wambeke (1959) is now one of the most important criteria of the definition of the ferralic horizon. According to FAO88 this ratio of total silt/clay should be less or equal to 0.2. The adequacy of this weathering index to separate strongly weathered soils from the others was checked here by calculating the silt/clay ratio of 90 representative profiles from a large area, including Australia, Brazil, Cameroon, Costa Rica, Malaysia, New Guinea, Peru, Thailand, Rwanda, Zaire and Zambia. Due to the frequent presence of pseudoparticles in many tropical soils, the degree of removal of cementing agents such as sesquioxides strongly influences the results. As particle size distribution becomes a very important criterion in the classification of these soils, precise recommendations about the analytical procedures should be formulated. For this reason, in this study we selected profiles where complete destruction of sesquioxidic cementing agents is ascertained.

Figure 1 and table 4 show the results. Ten of these 90 profiles are considered to be less weathered (high amounts of weatherable minerals and high

**Table 4.**  
 Repartition of silt/clay ratio of the 90 pedons. (only those pedons showing the same trend in all B sub-horizons are mentioned)

SILT/CLAY RATIO				
Fine silt (FS)/ clay (C)		Total silt (TS)/ clay (C)		
= < 0.2	> 0.2	= < 0.2	0.2-0.5	>0.5
68 pedons	22 pedons	11 pedons	65 pedons	14 pedons
		└─ 10 less weathered (LW)		└─ 6 LW
				└─ 4 LW



**Figure 1.**

The silt/clay ratio of 90 profiles from tropical regions (10 of these pedons represent less weathered soils)

apparent CEC after Lincoln laboratory of soil science, USA). The 10 less weathered pedons have a FS/C > 0.2 and a TS/C > 0.2.

- From table 4 it is evident that a silt/clay ratio = < 0.2 (FAO88) is only efficient if the fine silt (0.002-0.020 mm) is used.

- If the total silt is used, the 0.2 value of the silt/clay ratio does not give satisfactory results and we can conclude that in this case a value = < 0.5 is better since 90% of the studied pedons give satisfactory results when this ratio is accepted.

**Table 5.**

Consequence of implementation of changes in ST90 versus ST85 on the 89 pedons from Zaire

Soil Orders	number of pedons	
	ST85	ST90
Oxisols	58	21
Ultisols	6	41
Alfisols	2	4
Others	23	23

#### 4.4. Soil classification updates

It is evident that correct soil classification systems can only be elaborated by adapting the soil classification criteria continuously to match the advances in soil science through field and laboratory investigations. The revised FAO88 legend, based on a large experience in tropical areas, is already a good try to distinguish different types of tropical soils. Six units, Plinthosols, Nitisols, Alisols, Acrisols, Ferralsols and Lixisols at the highest taxonomic level characterize strongly weathered tropical soils (FAO88, Van Wambeke, 1990), compared with three orders (Oxisols, Ultisols and Alfisols) in ST90.

In ST90, criteria for the characterization of Oxisols, Ultisols and Alfisols have changed by the introduction of the kandic horizon and by the changes in the definition of the oxic horizon. Since the name of oxic horizon was maintained in ST90 version, there is a risk of confusion and in the future the exact reference of the handbook should always be stated when a soil is classified. FAO88 has avoided this particular problem by changing the name of the horizons when the definition changed, i.e. argillic to argic, oxic to ferrallic).

## 5. CONCLUSIONS

Both the FAO and the USDA Soil Conservation Service regularly update their soil classification system. With these successive amendments it is observed that both taxonomies gradually drift apart. Both have now different definitions for horizons they had in common before, e.g. the argillic and the oxic horizons. In the FAO88 system the names of diagnostic horizons have been changed (argic and ferrallic horizons) when some of the diagnostic

criteria were modified. In contrast, in ST90 names remained the same, even when the diagnostic criteria changed (oxic horizon). In addition, the kandic horizon was introduced in the USDA Soil Taxonomy (1987) in order to solve some of the problems of classifying soils with a subsurface horizon where it was difficult to decide between an argillic and an oxic horizon. Unfortunately the definition of the kandic horizon, which is not mutually exclusive from the argillic horizon, is such that the classification of strongly weathered soils of the Zaire basin is far from satisfactory. Indeed, soils which are considered to be very similar being in the same landscape units and having nearly similar morphological, chemical and land management characteristics, are separated from order level on.

At present the FAO88 system appears to be more satisfactory for the classification of strongly weathered soils, at least at the higher taxonomic levels. One important change however is proposed here: the silt/clay ratio, a weathering index, should be calculated on the basis of fine silt (0.002-0.02 mm) instead of the total silt fraction.

In order to avoid confusion an appeal is also made that in the future the handbooks for soil classification should clearly indicate how to calculate the diagnostic criteria exactly.

The evaluation of the Zairian soils data base shows that, when it comes to soil classification procedures, some upgrading would be useful. The most frequent missing or vague data concern the amount of weatherable minerals, the content of clay coatings, dry soil color, color of "mottling", presence and content of plinthite, gibbsite, water-dispersible clay, thin section data,  $P_2O_5$  content, bulk density and moisture content at 15 bar.

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### *Résumé*

Cette étude discute la classification des sols très altérés de la cuvette Zaïroise par la USDA Taxonomie des Sols et par la légende FAO-Unesco de la Carte Mondiale des Sols. Les récents changements introduits ont pour conséquence une plus grande séparation des deux systèmes de classification. L'application de ces deux classifications aux sols de la cuvette Zaïroise a montré que l'introduction de l'horizon kandique dans la USDA Taxonomie des Sols rend la classification des sols profondément altérés plus difficile. L'utilisation du rapport limon total/argile comme critère de classification dans la légende FAO-Unesco n'a pas donné des résultats satisfaisants. Nous recommandons ici l'utilisation du rapport limon fin/argile. La classification rigoureuse des sols du Zaïre a permis d'évaluer la qualité de la base de données et de recommander une série d'observations de terrain et de laboratoire qui doivent être vérifiées dans l'avenir. Ceci permettra d'élever la qualité de la base de données au niveau actuel des exigences des systèmes de classification des sols.

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### PROFILE DESCRIPTIONS

**Profile number:** PED1

**Classification**

- Soil Taxonomy 1990 : Kandiodalfic Eutrudox, clayey, isohyperthermic.
- FAO 1988: Xanthic Ferralsol

**Location:** Ubangi (Kutubongo)

**Elevation:** 550 m

**Vegetation:** tree savanna

**Parent material:** low Ubangi schists

**Physiographic position:** almost flat plateau, slope (0-2%)

**Drainage:** well drained

**Authors**

- Profile description : P. Jongen and M. Van Oosten (1960)
- classification : Ngongo (1989)

A1 0-5 cm: 2.5YR 4/2; clay; medium crumb; friable to firm; abundant roots; diffuse, smooth boundary.

A2 5-18 cm: 2.5YR 4/2; clay; crumb; friable to firm; abundant roots; clear, smooth boundary.



- A3 18-28 cm: 2.5YR 4/2; clay; medium and subangular blocky; friable to firm; low biological activity; abundant roots; diffuse, smooth boundary.  
BA 28-48 cm: 10YR 4/4; clay; moderately well developed subangular blocky, friable to firm; abundant roots; diffuse, smooth boundary.  
B1 48-83 cm: 10YR 4/6; clay; well developed subangular blocky; friable to firm; patchy thin coatings on ped faces; very frequent roots; diffuse boundary.  
B2 83-90 cm: 10YR 4/6; clay; weak subangular blocky; friable to firm; few roots; diffuse boundary.  
B3 90-140 cm: 10YR 4/6; clay; structureless; very few roots; clear boundary.  
B4 140-200 cm: 10YR 4/6; gravelly sheets; ironstones mixed with clay.
- 

**Profile number:** PED2

**Classification**

- Soil Taxonomy 1990: Typic Kandiodalf, clayey, isohyperthermic.
- FAO 1988: Haplic Ferralsol

**Location:** Ubangi (Gemena)

**Elevation:** 446 m

**Vegetation:** tree savanna

**Parent material:** schists

**Physiographic position:** gently sloping plateau slope 2-4%

**Drainage:** well drained

**Autors**

- Profile description: P. Jongen and M. Van Oosten (1960)
- Classification: Ngongo (1989)

- A1 0-10 cm: 5YR 3/2; sandy clay; weak crumb; friable; high biological activity (worm casts); diffuse, smooth boundary.  
A2 10-20 cm: 5YR 3/3; sandy clay loam; weak subangular blocky and crumb; friable to firm; abundant roots; clear boundary.  
BA 20-38 cm: 2.5YR 4/6; clay; weak subangular blocky and crumb; firm; diffuse boundary.  
B1 38-75 cm: 2.5YR 4/6; clay; moderately well developed blocky; firm; abundant roots; diffuse boundary.  
B2 75-108 cm: 2.5YR 4/6; clay; structureless; firm; few roots; diffuse boundary.  
C 108-200 cm: 2.5YR 4/6; clay; structureless; firm.
- 

**Profile number:** PED3

**Classification**

- Soil Taxonomy 1990: Typic Kandiusult, fine loamy, isohyperthermic.
- FAO 1988: Haplic Acrisol(?) or Ferralsol

**Location:** Maniema (Kayembe)

**Vegetation:** grass savanna (*Imperata cylindrica*)

**Parent material:** Karro rocks (schists + sandstone) Lukuga group.

**Physiographic position:** undulating summit

**Elevation:** 685 m

**Climate:** Af (Köppen)

**Drainage:** well drained

**Evidence of erosion:** slight water erosion

**Soil moisture conditions:** moist

**Depth to the ground water table:** unknown, certainly > 2 m

**Author**

- Profile description: NGONGO (1985)

- A1* 0-14 cm: 10YR 2/2; sandy clay loam; moderate crumb; non plastic; friable; low biological activity; clear boundary.
- A2* 12-14 cm: 10YR 2/3; sandy clay loam; moderate crumb; non plastic; friable; frequent roots; gradual boundary.
- B1* 14-54 cm: 10YR 4/4; sandy clay loam; weak subangular blocky; slightly plastic; friable; few roots; diffuse boundary.
- B2* 54-90 cm: 10YR 5/6; sandy clay loam; moderate subangular blocky; slightly plastic; few roots; diffuse boundary.
- B3* 90-130 cm: 10YR 5/6; sandy clay loam; moderate subangular blocky; slightly plastic; friable; very few roots; gradual boundary.
- B4* 130-200 cm: 10YR 5/6; sandy clay loam; moderate subangular blocky; slightly plastic; friable
- 

**Profile number:** PED4

**Classification**

- Soil Taxonomy 1990: Xanthic Hapludox, clayey, isohyperthermic.
- FAO 1988: Xanthic Ferralsol

**Location:** Zairian bassin ("bassin de la Loile"), altitude 370 m

**Vegetation:** secondary forest

**Parent material:** Karroo rocks (shists + sandstone)

**Physiographic position:** undulating summit, slope < 5%

**Drainage:** well drained

**Authors:**

- Profile description: P. Jongen and M. Jamagne (1958)
- Classification: Ngongo (1989)

- A1* 0-4 cm: 10YR 3/4; sandy clay; moderate developed crumb; friable moist; abundant roots; high biological activity (worm casts); clear boundary.
- A2* 4-14 cm: 10YR 4/4; sandy clay; moderate granular; friable; worm casts; abundant roots; artefacts (charcoal); clear boundary.
- B1* 14-27 cm: 10YR 5/4; sandy clay; moderate subangular blocky; friable; frequent roots; patchy clay coating (+/- 20%).
- Bt1* 27-55 cm: 7.5YR 5/6; clay; moderate developed angular blocky; firm; broken clay coatings (+/- 50%); clear boundary.
- Bt2* 55-90 cm: 7.5YR 5/6; clay; moderate subangular blocky; firm; broken clay coatings (30-40%); diffuse boundary.
- Bt3* 90-150 cm: 7.5YR 5/6; clay; moderately developed subangular blocky; friable; patchy coatings (+/- 30%).
- 

**Profile number:** PED5

**Classification**

- Soil Taxonomy 1990: Lithic Eutropept, clayey, isohyperthermic.
- FAO 1988: Eutric cambisol

**Location:** Ubangi (Kutubongo)

**Elevation:** 550 m

**Vegetation:** tree savanna

**Parent material:** schists mixed with shales

**Physiographic position:** summit and convex slope (rolling area)

**Drainage:** well drained

**Authors**

- Profile description: P. Jongen and M. Van Oosten (1960)
- Classification: Ngongo (1989)

*A1* 0-7 cm: 10YR 4/2; clay; moderate blocky; firm; low biological activity; abundant roots; clear boundary.

*A2* 7-13 cm: 10YR 4/3; clay; strong angular blocky; firm; abundant roots; clear boundary.

*Bw* 13-33 cm: 10YR 4/3; clay; strong angular blocky; firm; abundant roots; patchy red colors on the matrix; diffuse boundary.

*BC* 33-45 cm: 10YR 5/4; clay; compact; firm; few roots; clear wavy boundary.

*R* > 45 cm: Rock, schists.

## PEDON: PED1

Hor.	Sample depth(cm)	Particle size distribution(%)				C(%)	pH H2O	Exch.cations meq/100g soil			CEC soil meq/100g	BS (%)	Iron/ clay (%)
		0-2	2-20	20-50	50-2000			Ca	Mg	K			
A1	0-5	45.8	15.5	6.8	31.9	2.30	6.5	10.5	2.8	0.8	14.1	100	7.5
A2	5-19	39.0	12.4	6.0	42.6	1.84	6.3	7.4	2.1	0.6	9.7	100	8.2
A3	19-28	52.7	5.5	3.3	38.5	0.86	6.2	3.1	1.0	0.4	6.7	67	7.0
BA	28-48	64.8	2.7	2.3	30.4	0.55	6.2	2.5	0.8	0.2	6.1	59	7.8
B1	48-83	71.6	2.4	1.9	24.1	0.29	6.1	2.3	0.8	0.3	5.6	61	5.3
B2	83-90	73.6	2.0	1.8	22.6	0.24	6.1	2.2	0.8	0.3	5.2	63	8.5
B3	90-150	73.6	2.4	1.6	22.6	0.24	6.2	2.2	0.8	0.3	5.1	63	6.1
B4	150-200	69.7	3.2	2.2	24.9	0.24	6.2	1.9	0.6	0.3	4.8	61	11.5

## PEDON: PED2

Hor.	Sample depth(cm)	Particle size distribution(%)				C(%)	pH H2O	Exch.cations meq/100g soil			CEC soil meq/100g	BS (%)	Iron/ clay (%)
		0-2	2-20	20-50	50-2000			Ca	Mg	K			
A1	0-10	39.5	6.7	6.4	47.4	1.61	6.6	5.1	1.5	0.6	10.2	70	3.2
A2	10-20	31.5	2.9	4.5	61.1	0.97	6.2	3.6	1.1	0.3	8.0	63	3.1
BA	20-33	48.6	2.6	4.1	44.7	0.50	5.8	2.5	0.8	0.1	5.9	59	4.0
B1	33-75	57.5	1.8	2.7	38.0	0.27	5.7	2.6	0.9	0.1	5.8	62	4.7
B2	75-108	57.0	1.6	3.0	38.4	0.29	5.8	2.5	0.8	0.1	6.1	57	4.3
C	108-200	57.6	1.5	3.6	37.3	0.16	5.8	2.6	0.9	0.2	5.7	54	4.5

PEDON: PED3

Hor.	Sample depth(cm)	Particle size distribution(%)				C(%)	pH H2O	Exch. cations meq/100g soil			CEC soil meq/100g	Al(exch.) meq/100g	BS (%)	Iron/ clay (%)
		0-2	2-20	20-50	50-2000			Ca	Mg	K				
A1	0-14	15.5	9.4	32.1	43.0	0.72	5.4	1.3	0.6	0.1	6.1	0.7	37	2.5
A2	14-31	22.9	7.1	33.1	36.9	0.41	4.7	0.8	0.4	0.1	4.5	0.9	29	4.4
B1	31-54	29.0	7.5	32.0	31.5	0.21	5.1	0.7	0.4	0.1	4.8	0.8	25	4.1
B2	54-90	29.2	7.9	30.8	32.1	0.20	5.1	0.6	0.4	0.1	4.7	0.8	22	3.8
B3	90-130	31.5	7.1	29.8	31.6	0.16	5.0	0.8	0.3	0.1	5.1	0.8	24	5.2
B4	130-200	28.3	7.2	30.5	34.0	0.12	5.2	0.8	0.3	0.1	4.5	0.7	26	5.4

PEDON: PED4

Hor.	Sample depth(cm)	Particle size distribution(%)				C(%)	pH H2O	Exch.cations meq/100g soil			CEC soil meq/100g	BS (%)	Iron/ clay (%)
		0-2	2-20	20-50	50-2000			Ca	Mg	K			
A1	0-6	41.2	2.7	3.0	53.1	1.89	4.2	0.8	0.4	0.2	6.4	22	11.6
A2	6-20	37.7	2.2	2.3	57.8	0.73	4.2	0.4	0.3	0.1	8.2	10	12.3
BA	20-39	49.3	2.2	3.1	45.4	0.51	4.4	0.6	0.4	0.1	8.3	13	11.9
Bt1	39-55	54.7	1.8	2.9	40.6	0.38	4.7	0.6	0.4	0.1	8.4	14	12.4
Bt2	55-90	52.7	2.0	2.8	42.5	0.28	4.7	0.6	0.4	0.1	8.0	13	12.3
Bt3	90-150	54.6	2.1	2.8	40.5	0.25	4.8	0.7	0.4	0.1	7.4	16	12.1

PEDON: PED5

Hor.	Sample depth(cm)	Particle size distribution(%)				C(%)	pH H2O	Exch.cations meq/100g soil			CEC soil meq/100g	BS (%)	Iron/ clay (%)
		0-2	2-20	20-50	50-2000			Ca	Mg	K			
A1	0-7	55.7	24.2	6.9	13.2	2.38	6.8	10.5	2.9	1.1	14.4	100	8.4
A2	7-13	62.2	21.4	6.1	6.3	1.55	5.9	6.8	1.9	0.3	11.7	77	-
Bw	13-33	65.2	21.2	4.6	9.0	1.00	6.0	6.1	1.7	0.2	11.6	69	8.4
BC	33-45	66.7	20.7	4.3	8.3	0.92	5.9	6.4	1.8	0.1	11.7	71	5.9



## FIELD MEASUREMENT OF AMMONIA VOLATILIZATION UPON APPLICATION OF DIFFERENT $\text{NH}_4^+$ -FERTILIZERS AND UREA

A. VERMOESEN  
P. DEMEYER  
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O. VAN CLEEMPUT

### *Abstract*

During the period fall 1990 - summer 1991, the ammonia volatilization was measured on a loamy Polder soil in Northern Belgium. Therefore, a chamber method was used. First, the volatilization upon application of ammonium sulphate was followed during 14 days. Losses of about 8 to 30% of the applied nitrogen were found. Secondly, a comparison was made between the  $\text{NH}_3$ -volatilization upon application of ammonium sulphate and 3 other fertilizers: ammonium nitrate, a liquid N-fertilizer and urea. Ammonium sulphate showed the highest  $\text{NH}_3$ -loss, followed by urea, the liquid fertilizer and ammonium nitrate.

### *Keywords*

$\text{NH}_3$ -volatilization, N-fertilizers, chamber method.

## 1. INTRODUCTION

To obtain optimal yields for agricultural crops, the use of N-fertilizers is a necessity. However, the efficiency of N-fertilizers is quite poor. Nitrogen recovery from surface-applied N-fertilizers can be as low as 10%, and it rarely exceeds 60% (Dilz, 1988). These low recoveries can be assigned to several processes. The most important are denitrification,  $\text{NO}_3^-$ -N-leaching,  $\text{NH}_3$ -volatilization and to a lesser extent nitrification,  $\text{NH}_4^+$ -immobilization and fixation on clay minerals. In this paper, special attention is given to  $\text{NH}_3$ -

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volatilization. These losses are highly variable, depending on the used N-fertilizer, the mode of application, weather and soil conditions,... (Bouwmeester and Vlek, 1981; Faurie and Bardin, 1979; Fenn and Kissel, 1973).

Volatilization means not only an important economic loss, but also a negative influence on the environment.  $\text{NH}_3$  is known as a major air pollutant with an important role in the process of soil acidification (Bouwman, 1990).

## 2. MATERIALS AND METHODS

A chamber technique (Van den Abbeel et al., 1989) was used to determine the  $\text{NH}_3$ -volatilization upon application of  $\text{NH}_4^+$ -fertilizers and urea. In Fig. 1, a scheme of the experimental setup is given. An air stream was generated by a pump in order to have an airflow of  $20 \text{ L min}^{-1}$  in each chamber ( $50 \times 10 \times 7 \text{ cm}^3$ ). The air was led through two parallel flasks per chamber containing 100

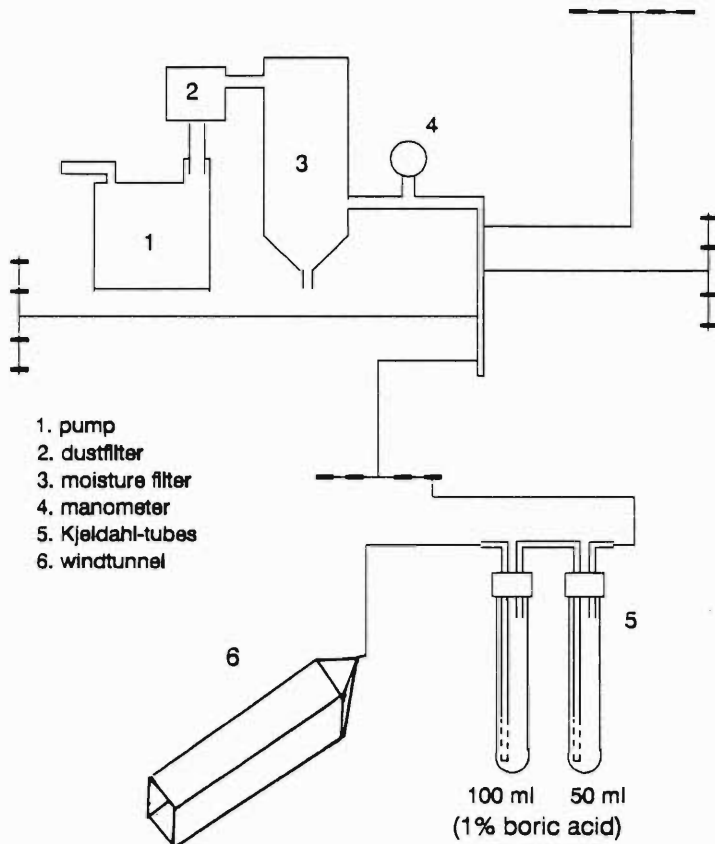


Fig. 1.  
Experimental setup



**Table 1.**

Soil characteristics of the loamy soil (Aquic Udifluent)

granulometrics			humus	CaCO <sub>3</sub>	pH		C.E.C.	C/N
0-2µm	2-50µm	>50µm	(%)	(%)	KCl	H <sub>2</sub> O	(meq/100g)	
18.0	44.2	37.8	1.74	7	7.8	8.0	16.1	8.7

and 50 ml of 1% boric acid. The pump was sucking air through the flasks during only one quarter time of a day; every two hours, half an hour was used to collect emitted NH<sub>3</sub>.

The field experiments were carried out on a loamy Polder soil in Northern Belgium, classified as an Aquic Udifluent. The soil characteristics are given in Table 1. Important in the context of NH<sub>3</sub>-volatilization are the high pH and the presence of free CaCO<sub>3</sub> (Fenn and Miyamoto, 1981).

On a site of 6x6 m<sup>2</sup>, the plants were removed in order to be able to place the equipment and to get information on volatilization without interference of plants. For each experiment, four boxes, of which one was a blank, were placed in 4 wind directions. Two groups of measurements were carried out:

- NH<sub>3</sub>-volatilization measurements after surface-application of ammonium sulphate (AS)
- comparison of this volatilization with volatilization out of ammonium nitrate (AN), liquid nitrogen fertilizer (LF) and urea (U).

*- Ammonia volatilization upon application of AS*

The ammonia volatilization was measured at 5 different times during the period fall 1990-summer 1991. The soil was always fertilized with 100 kg AS-N/ha. During the first 4 days, every day, 16 samples (4 boxes per wind direction) were taken, of which 4 functioned as blanks. After the fourth day, samples were taken at day 7, 10 and 14.

*- Comparison between AS and three other N-fertilizers*

Two series of experiments were carried out. The first series of experiments took 7 days, while the second series took 14 days. The fertilizers used were: ammoniumnitrate (AN), liquid fertilizer (LF) and urea (U). All were applied at a rate of 200 kg N/ha. At each experiment, a part of the plot was always fertilized with AS acting as a reference.

The NH<sub>4</sub><sup>+</sup>-N collected in the boric acid was determined by a Continuous Flow Analyser-system (Beernaert et al., 1987). On the experimental site, a continuous measurement of the temperature and rainfall was executed. Every day, a soil sample of the upper 2 cm layer was taken to determine the moist-

ure content. The amount of collected  $\text{NH}_3$ -gas is given as percentage of applied fertilizer.

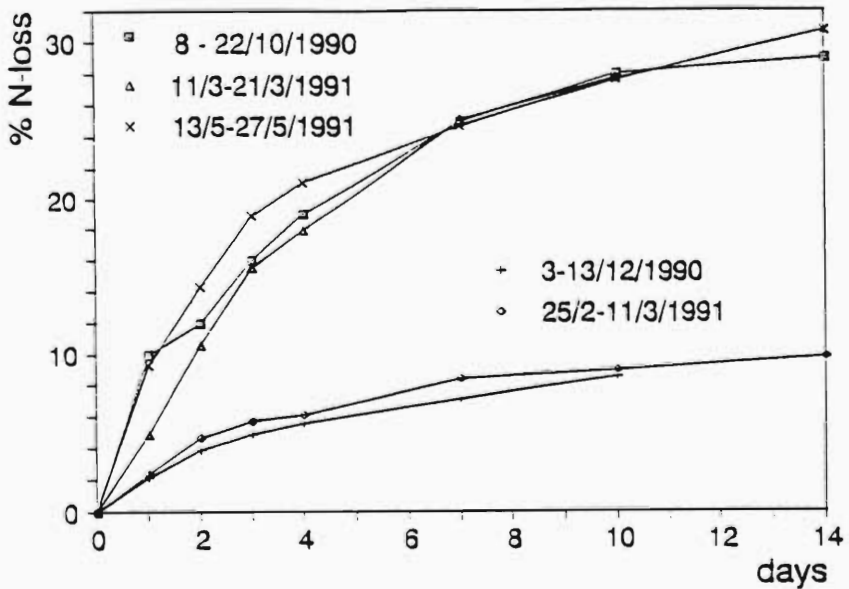
### 3. RESULTS AND DISCUSSION

#### 3.1. Ammonia volatilization upon application of ammonium sulphate (AS)

The total ammonia volatilization was measured after surface-application of AS at 5 different periods (Table 2). The evolution of this volatilization is given in Fig. 2.

**Table 2.**  
Total ammonia volatilization upon application of AS at different periods

	period	% N-loss
1	08 - 22/10/1990	$29 \pm 4$
2	03 - 13/12/1990	$8.5 \pm 1.7$
3	25/2 - 11/03/1991	$9.8 \pm 1.4$
4	11 - 21/03/1991	$27.7 \pm 3$
5	13 - 27/05/1991	$30.7 \pm 3.8$



**Fig. 2.**  
Percent ammonia loss upon application of ammonium sulphate at different periods

During the first measuring period (October 1990), temperatures around 15° C were most common. At the start of the experiment, the soil moisture content was high (21% (w/w)), providing enough water to dissolve the fertilizer. Thereafter, the weather stayed dry till the 10th day of measuring and the moisture content of the surface layer decreased to 7.5% (w/w). It is commonly accepted that, when the fertilizer is dissolved, NH<sub>3</sub> losses rise when the soil moisture content diminishes (Ferguson and Kissel, 1986). During evaporation, the NH<sub>3</sub> which is dissolved in the soil water, moves upwards to the soil surface where it can more easily be volatilized. Besides, when the soil moisture content is low, little NH<sub>3</sub> can dissolve in the soil solution. Also, the nitrification activity diminishes so that more NH<sub>4</sub><sup>+</sup> is available to volatilize. It was clear that in this experiment, both the temperature and the moisture content favoured the ammonia volatilization, which was about 29 ± 4% after 14 days.

In December 1990, on the contrary, temperatures were much lower. The minimum temperature was -1°C and an average temperature of ± 6°C was noted. The moisture content was about 22% during the whole measuring period. Only 8.5 ± 1.7% of the applied N was volatilized.

In the next period (February-March 1991), weather conditions were quite similar to those of December 1990. The average temperature was somewhat higher (± 10°C) and the average moisture content during the first 3 days was 20%. This slightly decreased till 15% but rose up again to 20%. Because of the high initial moisture content, the fertilizer could dissolve easily and NH<sub>3</sub>-volatilization could occur. However, during the entire measuring period, there was a daily rainfall dissolving the NH<sub>3</sub> in the soil H<sub>2</sub>O and transporting it below the soil surface. Besides, temperatures were not high enough to reduce the moisture content and to volatilize large amounts of NH<sub>3</sub>. A loss of 9.8 ± 1.4% of the applied N was measured.

From the 11th of March 1991 on, the weather changed to real spring conditions. The soil was still wet at the time of application of AS (19.6%) but rapidly decreased to 6.8% after 7 days. The last 2 days, it rained again so that the moisture content rose up till 18.1%. The minimum temperature was 6°C and a maximum temperature of 21°C was noted. After 10 days 27.7 ± 3.0% was volatilized.

During the experiment of May 1991, both moisture conditions and temperature favoured the NH<sub>3</sub>-volatilization. A high moisture content at the start of the experiment (17.9%) was followed by dry weather conditions. So, 30.7 ± 3.8% of the applied N volatilized.

Out of these experiments it was concluded that both temperature and moisture content were very important parameters influencing the NH<sub>3</sub>-volatilization.

To minimize the NH<sub>3</sub>-volatilization, it would be recommended to apply the fertilizer when the temperature is not too high, the moisture content is

quite low and when rain is expected. A high temperature favours the  $\text{NH}_3$ -volatilization as well as a high moisture content followed by dry weather conditions.

Because of the high pH (pH = 8.0) and a quite high buffer capacity of the used soil, high amounts of applied AS could volatilize. A high pH means a high concentration of  $\text{NH}_3$  present in the soil solution and soil air, and consequently an easier  $\text{NH}_3$ -volatilization (Freney et al., 1983).

However, the initial pH is only then important when the buffer capacity of the soil is high (Avnimelech and Laher, 1977). When an ammonium salt is added to the soil and  $\text{NH}_3$  volatilizes,  $\text{H}^+$  is formed. This process acidifies the soil and the  $\text{NH}_3$  volatilization would decrease. When the buffer capacity is high, however, the soil pH stays high and the volatilization can continue to occur.

### 3.2. Comparison with ammonia volatilization out of other $\text{NH}_4^+$ -fertilizers and urea

In each experiment, the  $\text{NH}_3$ -loss out of both AS and another  $\text{NH}_4^+$ -fertilizer was measured. Because AS gave the highest amount of loss under all conditions, it was used as a reference. All results of N-losses are expressed in relation to losses out of AS.

Table 3 gives a survey of the different periods of the experiments and the treatments. In series I, the  $\text{NH}_3$ -volatilization was measured during 1 week, while in series II it took 2 weeks.

In Table 4, the total amounts of different  $\text{NH}_3$  losses (%) are given as well as the ratio  $\text{NH}_4^+$ -fertilizer/AS loss. This is the total loss upon 7 days or 14 days.

It was clear that, after AS, urea showed the highest  $\text{NH}_3$ -volatilization,

**Table 3.**  
Survey of the different experiments

Experiment number and series	Fertilizer treatments	Period
1 Series I (7 days)	AS/LF	11-18/6/1990
2	AS/AN	18-25/6/1990
3	AS/U	25/6 - 2/7/1990
4 Series II (14 days)	AS/U	13-27/5/1991
5	AS/AN	27/5 - 10/6/1991
6	AS/LF	10-24/6/1991

**Table 4a.**

Ammonia losses out of urea and AS

	NH <sub>3</sub> -loss (%) after application of U	Corresponding NH <sub>3</sub> -loss (%) out of AS	U/AS
experiment 3 (7 days)	23.9	58.2	<b>0.41</b>
experiment 4 (7 days)	7.8	18.3	<b>0.43</b>
experiment 4 (14 days)	13.9	23.0	<b>0.60</b>

**Table 4b.**

Ammonia losses out of AN and AS

	NH <sub>3</sub> -loss (%) after application of AN	Corresponding NH <sub>3</sub> -loss (%) out of AS	AN/AS
experiment 2 (7 days)	8.7	46.5	<b>0.19</b>
experiment 5 (7 days)	3.9	25.7	<b>0.15</b>
experiment 5 (14 days)	6.3	34.9	<b>0.18</b>

**Table 4c.**

Ammonia losses out of LF and AS

	NH <sub>3</sub> -loss (%) after application of LF	Corresponding NH <sub>3</sub> -loss (%) out of AS	LF/AS
experiment 1 (7 days)	12.0	63.3	<b>0.19</b>
experiment 6 (7 days)	5.7	24.0	<b>0.24</b>
experiment 6 (14 days)	9.9	27.5	<b>0.36</b>

followed by the liquid fertilizer and AN. It is quite evident that the LF showed losses between those of urea and AN because the LF is a mixture of them.

In Fig. 3 and 4, the evolution of the ratio fertilizer/AS loss is given. All ratios were lower than 1, indicating a lower loss in relation to the loss from AS. Out of these figures, it is clear that upon 1 week of urea application the ratio of the % of NH<sub>3</sub>-N-loss out of urea to the % of NH<sub>3</sub>-N-loss out of AS

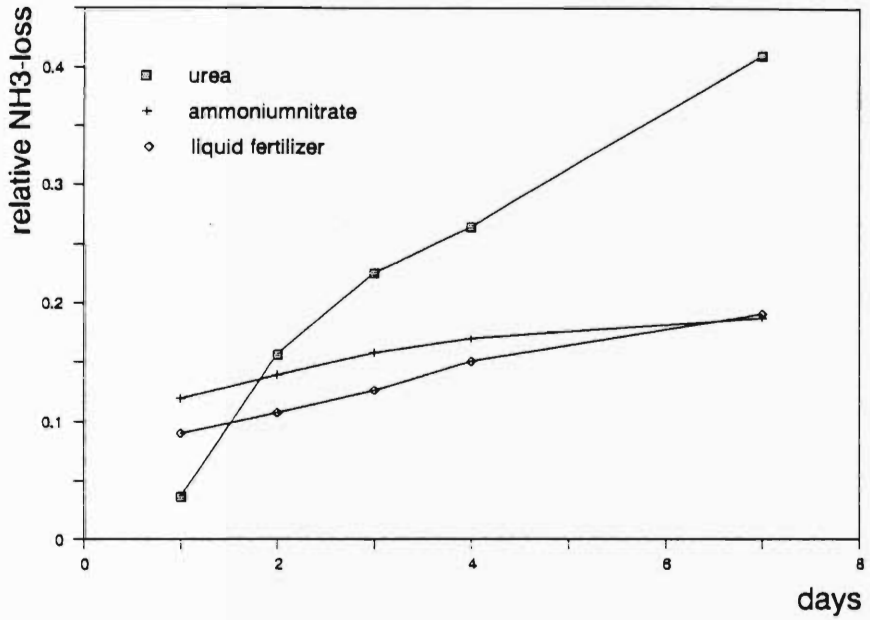


Fig. 3. Ammonia volatilization after application of different fertilizers in relation to AS after 1 week of measurement

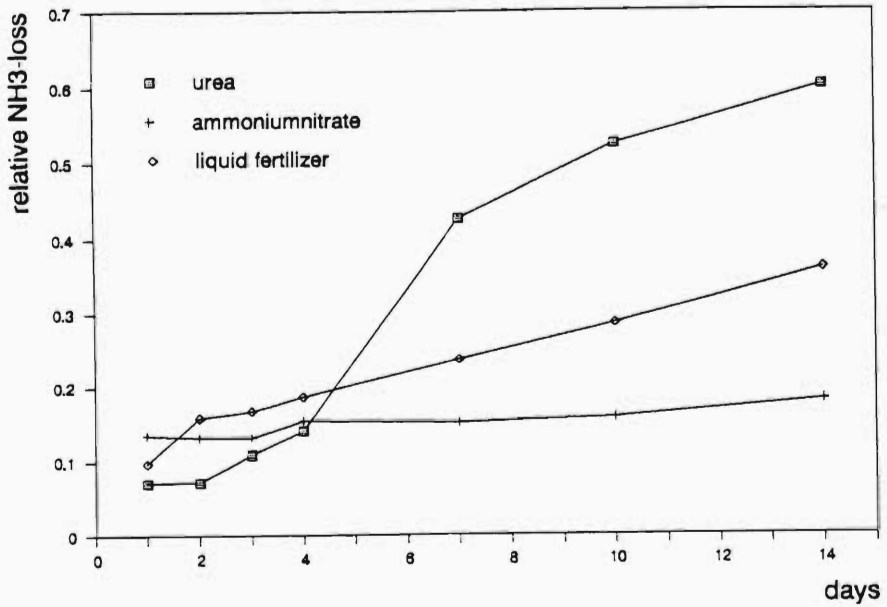


Fig. 4. Ammonia volatilization after application of different fertilizers in relation to AS after 2 weeks of measurement

was about 0.42. After 14 days, this ratio was increased to 0.60. It is not to be expected that this ratio would further increase because the urea hydrolysis is finished and the hydrolysed  $\text{NH}_4^+\text{-N}$  is mostly nitrified. It is evident that the volatilization after application of urea started later than for the other fertilizers, because urea first needs to be hydrolysed.

The ratio of the % AN loss to the % AS loss was about 0.17 after 7 days as well as after 14 days. This indicated that the loss out of AN was much lower than the loss out of AS and a large proportion of the total loss was already volatilized within 2 days.

The liquid fertilizer gave intermediate results. Upon 7 days, the % LF loss/ the % of AS loss was about 0.21. After 14 days it increased to 0.36.

Because all experiments were carried out within a period of 6 weeks, not much time influence was noted. Because of the more or less horizontal shape of the line for AN/AS, it can be concluded that both N-fertilizers volatilize at a similar rate. Urea and the LF show increasing ratios, indicating that, in relation to AS, the volatilization process starts at a slower rate but the more urea is hydrolysed, the faster  $\text{NH}_3$  is volatilized.

#### 4. CONCLUSION

Under the experimental conditions (loamy soil, pH = 8.0, 7%  $\text{CaCO}_3$ ), the  $\text{NH}_3$  volatilization strongly depended on temperature and moisture content. From the fertilizers,  $(\text{NH}_4)_2\text{SO}_4$ , showed the highest losses, going up to more than 50% in extremely favourable conditions, i.e. high temperatures and a high moisture content followed by dry weather. Comparing the different  $\text{NH}_4^+$ -fertilizers, the following ranking was established: AS > urea > LF > AN.

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## TESTING OF FUZZY SET THEORY IN LAND SUITABILITY ASSESSMENT FOR RAINFED GRAIN MAIZE PRODUCTION

TANG HUAJUN  
E. VAN RANST

### *Abstract*

This paper aims at determining land indices and suitability classes for maize using the fuzzy set theory. This theory is applied here in a land suitability assessment for rainfed grain maize production in Aitai County (China). The accuracy of this approach has been tested by comparing the land indices calculated by the fuzzy set theory with those obtained by two other evaluation procedures: the multiplicative parametric and the maximum limitation methods. The respective land indices were then correlated with the crop yields observed in the area: the best relationship is given by the fuzzy set approach. This result illustrates the promising use of this theory in land evaluation.

### *Keywords*

Land suitability, fuzzy set, membership function, maize, China.

## 1. INTRODUCTION

The aim of land evaluation is providing information on the opportunity and constraints for the use of land as a basis for making decisions on its use and management. The unique feature of land evaluation is that it deals with the full complex of land resources and their use potential, based on functional relationships between land and its uses (Van Diepen et al., 1991).

The evaluation framework used by soil scientists deals mainly with the ecological aspects of procedures in which the data of the physical resource surveys represented by land characteristics and / or land qualities, are

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matched with the land use requirements. The advantage of land characteristics (information available in the land resources inventory) is that they can be used directly in the matching procedure without their conversion into land qualities.

There are several ways to estimate potential crop production from land characteristics or land qualities. One of the usual procedures is to rank land units to the lowest single rating or to the most severe limitation only. Examples of this approach are the maximum limitation method (Zheng et al., 1989) and the simple limitation method (Sys, 1978, 1985; Sys et al., 1991). Other procedures attach to each characteristic or each quality a fraction which reduces the expected yield by a certain amount (Van Wambeke, 1986). Examples of such an approach are the Storie index (Storie, 1976), the square root method (Strezemski, 1972; Samir, 1986) and the Sys' parametric method (Sys, 1978, 1985; Sys et al., 1991).

Disadvantages of the above mentioned methodologies are misleading accuracy, arbitrariness in the choice of factors, poor definition of land productivity factors and experience-dependable. The quality of land evaluation depends on the quality of the weighing of the land characteristics (or land qualities) with respect to their effects on crop production (Tang et al., 1991).

This paper proposes another approach to determine land indices and hence suitability classes, using the fuzzy set theory.

The efficiency of this approach will be tested by comparing the results obtained by the multiplicative parametric approach of Sys (Sys et al., 1991), the maximum limitation method (Zheng et al., 1989) and the fuzzy set method, in a land suitability assessment for rainfed grain maize production in Aitai County, China.

## **2. MATERIALS AND METHODS**

### **2.1. Materials**

The studied area, Aitai County, is situated in the southwestern part of the Liao Ning Province in China and is bounded by the latitudes of 41°38' and 42°04' N and by the longitudes of 123°16' and 123°44' E. The total area surveyed covers approximately 100,000 hectares and consists of a large plain and a hilly region with an average elevation of about 34 m above sea level for the plain and of about 94 m above sea level for the hilly region (Jiang, 1984).

A total of 20 soil units representative for the study area is considered in this study. Most of the soils belongs to the order of Inceptisols; some are classified as Entisols (Soil Survey Staff, 1990). The mean monthly air temperature ranges between -11.1°C and 25.3°C. The mean annual rainfall is 713 mm in the north and 656 mm in the southern part of the area. The most important climatic characteristics and the properties of the soils are summarized in table 1.

Table 1.

Climatic and soil data of representative soil units in Aitai County, China

Soil units	Rainfall (growing cycle, mm)	Temperature (mean, growing cycle, °C)	Radiation (mean, growing cycle, %)	Drainage class (FAO, 1977)	Texture class (USDA, 1975)	% Organic carbon (mean 0 - 20 cm)	Soil depth (cm)	Coarse fragment (Vol. %)	Apparent CEC [cmol(+) kg <sup>-1</sup> clay]	Base Saturation (%)	Soil classification (Soil Survey Staff, 1990)	Observed yield (kg/ha)
A-1	560	21	54	imperfect	clay loam	0.88	120	0	38	66	Ochrept	4250
A-2	560	21	54	good	loam	1.67	150	0	40	76	Ochrept	6415
A-3	560	21	54	good	silt loam	1.23	120	1	31	93	Ochrept	6340
A-4	560	21	54	moderately good	clay loam	1.34	95	0	33	100	Orthent	5900
A-5	560	21	54	moderately good	silty clay loam	1.58	120	0	36	82	Ochrept	6240
A-6	560	21	54	good	silt loam	2.21	150	0	32	86	Ochrept	5440
A-7	560	21	54	moderately good	silty clay loam	1.24	150	0	48	78	Ochrept	5850
A-8	560	21	54	good	silt loam	1.80	120	1	45	84	Ochrept	5735
A-9	560	21	54	poor	silt clay	1.27	85	0	35	85	Aquent	2820
A-10	560	21	54	good	silt	1.39	100	0	42	92	Ochrept	4580
A-11	510	22	55	good	fine sand	0.59	75	6	27	100	Orthent	2470
A-12	510	22	55	imperfect	silt clay	1.22	90	0	39	69	Ochrept	3420
A-13	510	22	55	imperfect	silty clay loam	0.85	110	0	48	64	Ochrept	3100
A-14	510	22	55	poor	silt clay	1.43	80	0	34	87	Aquent	2200
A-15	510	22	55	imperfect	clay loam	1.36	150	0	31	88	Ochrept	4470
A-16	510	22	55	good	sand loam	0.96	120	2	44	100	Ochrept	3645
A-17	510	22	55	good	loam sand	0.67	120	2	41	85	Ochrept	3280
A-18	510	22	55	imperfect	clay loam	1.00	100	0	36	78	Ochrept	4320
A-19	510	22	55	poor	silt clay	1.41	75	1	28	95	Aquent	2665
A-20	510	22	55	good	silt loam	1.54	150	0	37	84	Ochrept	5170

Grain maize, grown as a rainfed crop on a sustained subsistence management level, is one of the most important food crops. Actual average yield data (from 1986 to 1988) of grain maize on the different soil units have been collected in the field (table 1).

## 2.2. Methods

### 2.2.1. Multiplicative parametric approach

In the multiplicative parametric approach (Sys, 1978, 1985; Sys et al., 1991), climatic and soil characteristics having an influence on maize perfor-

**Table 2.**

Climatic and soil requirements for rainfed grain maize (Sys, 1985) adapted to the conditions of the study area

Climatic and soil characteristics		Suitability class and rating scale				
		S1 1.0	S2 0.85	S3 0.6	N1 0.4	N2 0.25
Rainfall (growing cycle, in mm)		> 560	500	350	< 250	-
Mean temperature (growing cycle, °C)		18 >26	16 >32	14	-	<14
Insolation (growing cycle, n/N)		0.4 >0.65	< 0.40 > 0.75	-	-	-
Drainage condition	Coarse texture	imperfect moderate	good	poor aeric	poor drainable	very poor non-drain.
	Fine texture	good moderate	imperfect	poor aeric	poor drainable	very poor non-drain.
Soil texture / structure * $\bar{f}$		CL, SiCs, Cs, SiCL, SiL, SCL Si, SC, L	SL, LfS, LS	LcS, fS	-	Cm, S, Cs
Actual soil depth (in cm)		> 90	80	50	-	< 20
Coarse fragment (volume %) $\bar{f}$		< 6	20	40	-	> 40
Apparent CEC [cmol(+)/kg clay] $\bar{\pi}$		21	16 (-)	16 (+)	-	-
Base saturation (%) $\bar{f}$		> 35	20	< 20	-	-
Organic carbon (mean upper 20 cm, %)		> 1.1	1	< 0.5	-	-

\* Symbols used for soil texture and structure are defined as follows:

Cs: structured clay; Cm: massive clay; SiCs: Silty clay, blocky structure; SiCL: Silty clay loam; CL: Clay loam; Si: Silt; SiL: Silt loam; SC: Sandy clay; L: Loam; SCL: Sandy clay loam; SL: Sandy loam; LfS: Loamy fine sand; LS: loamy sand; LcS: loamy coarse sand; fS: fine sand; S: sand; Cs: Coarse sand.

$\bar{f}$  Weighted values over crop rooting depth by using weight factors suggested by Sys (1985)

$\bar{\pi}$  Value at 50 cm depth is used.

mance, are matched with the crop requirements, which are adapted to the conditions of the studied area (table 2). These land characteristics or factors are weighed a priori and are rated on a scale ranging from 1.0 to 0.25 for important factors and from 1.0 to 0.85 or to 0.6 for less important factors. A land index, which is a combined soil-climate index, is calculated as the product of the individual rating values of all characteristics, multiplied by 100. The suitability classes are defined by the value of the land index:

<i>Suitability classes</i>	<i>Land index</i>
S1: Very suitable land	75-100
S2: Moderately suitable land	50- 75
S3: Marginally suitable land	25- 50
N1: Currently unsuitable land	12- 25
N2: Permanently unsuitable land	0- 12

### 2.2.2. Maximum limitation method

The maximum limitation method (Zheng et al., 1989) is based on the assumption that crop performance is determined by the most limiting factor or characteristic. In this method, the rating procedure is the same as in the parametric approach, but the land index is given by the lowest single rating, multiplied by 100. The land suitability class is determined by the land index using the same limits as in the parametric approach.

### 2.2.3. Fuzzy set method

The theory of fuzzy sets, originally proposed by Zadeh (1965), was developed to deal with vaguely defined expressions, classes or categories; like "important" and "less important" land characteristics, "moderately" and "marginally" suitability classes. Although each of these expressions conveys a useful semantic meaning obvious for a certain community, quantification of the degree of importance of characteristics is usually a difficult task. In order to deal with such cases, Zadeh proposed that the membership in a set be measured not as a 0 or a 1 as in the traditional set theory, but as a value ranging between 0 and 1 (fuzzy set theory). This concept of "the degree of belonging" can be represented in a characteristic function called the "membership function". In this way, the degree of importance of land characteristics can be expressed by values between 0 and 1; 1 for the most important characteristic and 0 for the least important one.

Membership functions for the different suitability classes (S1 to N2) have to be established for each of the land characteristics and for the different observed yields. These membership functions express the degree to which a value of a land characteristic or a value of the observed yield belongs to a suitability class.

If a value of a land characteristic or the observed yield does entirely or absolutely not belong to the considered class, the membership value is 1 or 0 respectively. If the value of a land characteristic or the value of observed yield belongs to some extent to the considered class an intermediate membership value will be determined by smooth quadratic interpolation which gives the S-membership function (Ruan, 1990; Tang et al., 1991). The S-membership function is defined as

$$S(x; \alpha, \beta, \gamma) = \begin{cases} 0; & x \in ]-\infty, \alpha[ \\ 2[(x-\alpha)/(\gamma-\alpha)]^2; & x \in [\alpha, \beta] \\ 1-2[(x-\gamma)/(\gamma-\alpha)]^2; & x \in [\beta, \gamma] \\ 1; & x \in [\gamma, +\infty[ \end{cases}$$

where  $\beta = (\alpha+\gamma)/2$

and is represented graphically in figure 1.

This function will be used to describe the increasing belonging to a suitability class and its complement represents the decreasing membership.

Evaluation of land characteristics and classification of observed yield per land unit imply a determination of the degree of membership to the different suitability classes. The result of the evaluation of all land characteristics per land unit is a *characteristic matrix (R)* (Tang et al., 1991) of membership

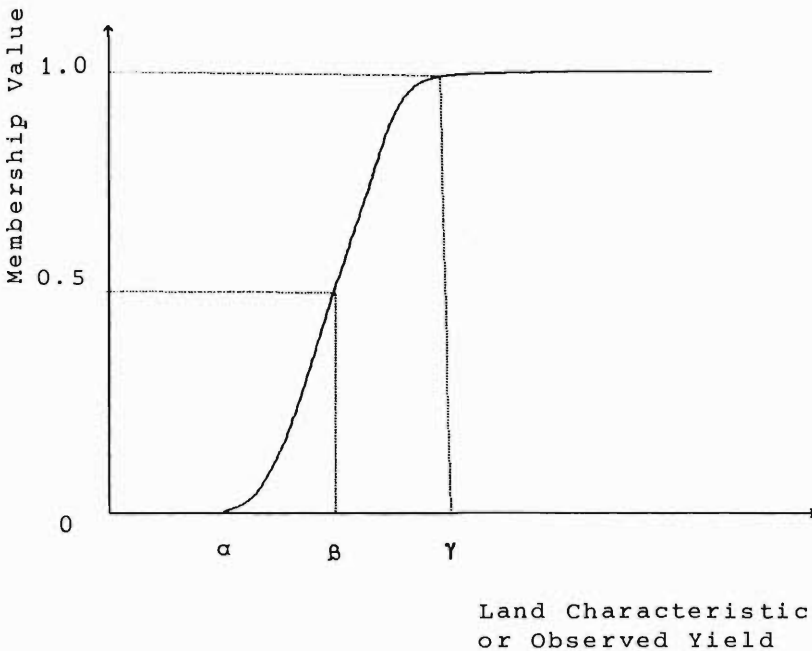


Fig. 1.  
The S-membership function (Tang et al., 1991)

values and the result of the evaluation of an observed yield for each land unit is a *standard suitability matrix (P)* of membership values for all the considered suitability classes.

According to Tang et al. (1991), the degree of importance of a land characteristic on land suitability can be expressed by a weight factor. The weight values for all considered characteristics form a *weight matrix (W)*.

The final land suitability is obtained by the 'multiplication' of the weight matrix (W) with the characteristic matrix (R) of membership values. This final suitability is again a matrix, of which the elements include the membership to each of the suitability classes, from S1 to N2.

### 3. RESULTS AND DISCUSSION

#### 3.1. Application of fuzzy set theory in land suitability assessment

The application of the fuzzy set theory to compare land characteristics with maize production is performed in following successive steps:

##### 1) Determination of membership functions

##### - Membership functions for land characteristics

For each characteristic, membership functions are established for the different suitability classes using figure 1. For the characteristic "organic carbon" the following membership functions can be suggested:

$$S1 = S(x; 0.3, 0.75, 1.2) = \begin{cases} 0; & x \in [0, 0.3] \\ 2[(x-0.5)/0.6]^2; & x \in [0.3, 0.75] \\ 1-2[(x-1.1)/0.6]^2; & x \in [0.75, 1.2] \\ 1; & x \in [1.2, m] \end{cases}$$

where x: organic carbon content (%);

m: possible maximum value of the organic carbon content (%; this value is arbitrarily determined)

$x \in [0, 0.3]$  means that x takes any value between 0 and 0.3.

Therefore membership functions for S2, S3, N1 and N2 can be established based on the same principles as for S1.

Similar S-membership functions are established for the other land characteristics considered in the study.

##### - Membership functions for the observed yield

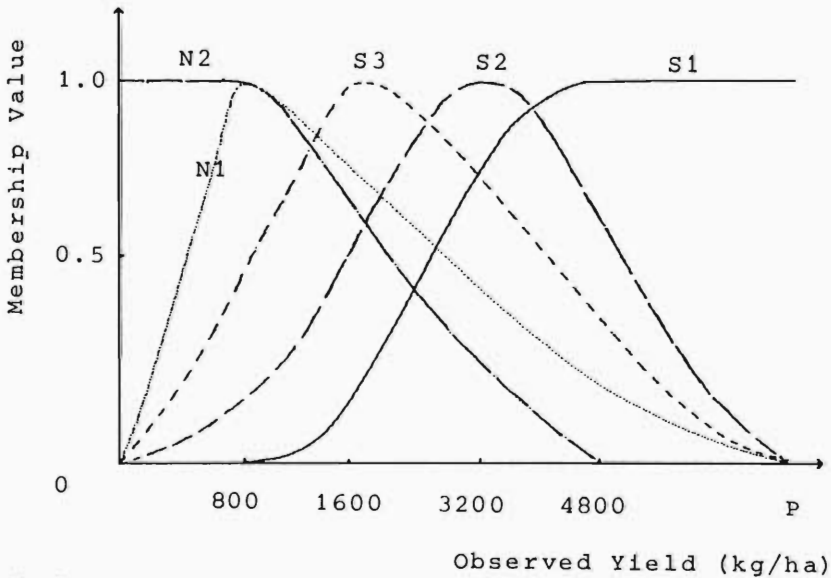
The establishment of the membership functions for the observed yields (table 1) is obtained by using the S-membership function:

$$\begin{aligned}
 S1 &= S(y; 800, 2800, 4800) \\
 &S(y; 0, 1600, 3200) \\
 S2 &= \{ \\
 &1 - S(y; 3200, (3200+p)/2, p) \\
 &S(y; 0, 800, 1600) \\
 S3 &= \{ \\
 &1 - S(y; 1600, (1600+p)/2, p) \\
 &S(y; 0, 400, 800) \\
 N1 &= \{ \\
 &1 - S(y; 800, (800+p)/2, p) \\
 N2 &= 1 - S(y; 800, 2800, 4800)
 \end{aligned}$$

where y: observed yield (kg/ha);

p: possible maximum value of the observed yield (kg/ha, this value is arbitrarily determined)

The membership functions for the classes, S1, S2, S3, N1 and N2, are graphically represented in figure 2.



**Fig. 2.** Graphical presentation of membership functions S1—, S2— — — —, S3 -----, N1 ..... and N2 — . — . — . — for observed yield

## 2) Determination of membership values

### - Membership values for land characteristics

For a given land unit, the membership values for the different land characteristics and suitability classes are determined using the membership



functions established. The membership values are subsequently arranged in a matrix (R) of land characteristics. Using the data of soil unit A-1, the following matrix is obtained:

	S1	S2	S3	N1	N2	
R =	RF	1	0.84	0.44	0.13	0
	MT	1	0.91	0.62	0	0
	IN	1	0.75	0.34	0	0
	DR	0.11	1	0.28	0	0
	TX	1	0.22	0	0	0
	DP	1	0.87	0.42	0.08	0
	CF	1	0.85	0.37	0	0
	AC	1	0.96	0.66	0	0
	BS	1	0.94	0.81	0	0
	OC	0.73	1	0.95	0.47	0

with RF, MT, IN represent rainfall, mean temperature, insolation within crop cycle respectively;

DR: drainage; TX: texture and structure; DP: effective soil depth; CF: coarse fragment;

AC: apparent CEC; BS: base saturation, OC: organic carbon.

The element  $r_{ij}$  of R denotes the membership value for the  $i^{\text{th}}$  land characteristic under  $j^{\text{th}}$  suitability class ( $i=1, 2, 3... 10$ ;  $j=S1, S2, S3, N1$  and  $N2$ ). The element  $r_{10,1} = 0.73$ , for instance, indicates that for an organic carbon content of 0.88 percent (soil unit A-1) in the topsoil (0-20 cm) the membership value of the organic carbon within class S1, based on the formula of the membership functions for S1 is equal to 0.73.

#### - Membership values for observed yields

The membership values for the observed yields are determined using the membership functions for observed yield established earlier. The membership values are subsequently arranged in a standard suitability matrix (P). Using the data of soil unit A-1, the matrix (P) is obtained:

	S1	S2	S3	N1	N2
P =	[0.85	0.96	0.52	0.39	0.04]

The element  $p_j$  of P denotes the membership value for soil unit A-1 under  $j^{\text{th}}$  suitability class ( $j = S1, S2, S3, N1$  and  $N2$ ). The element  $p_2 = 0.96$ , for instance, indicates that for an observed yield of 4250 kg/ha (soil unit A-1), the membership value of the observed yield within class S2, based on the formula of the membership functions for S2 [ $S2 = 1 - S(y; 3200, (3200+p)/2, p)$ ], is equal to 0.96.

3) *Determination of reference weight and reference suitability matrices*  
 - *Determination of reference weight matrix*

Ten land characteristics having an influence on grain maize production in the study area were selected for the evaluation: rainfall (RF), mean temperature (MT), and isolation (IN) within crop cycle; and drainage (DR); texture and structure (TX); effective soil depth (DP); coarse fragment content (CF); organic carbon (OC); apparent CEC (AC) and base saturation (BS). For the evaluation of each characteristic, a large number (50000 in this study) of weight values ranging between 0 and 1 are randomly selected. The combination of the weight values for the different considered characteristics will give *reference weight matrices* ( $M_t, t \in \{1, 2, \dots, 50000\}$ ). e.g., the reference weight matrix at the 100<sup>th</sup> ( $t=100$ ) calculation is:

$$M_{100} = [ \text{RF} \quad \text{MT} \quad \text{IN} \quad \text{DR} \quad \text{TX} \quad \text{DP} \quad \text{CF} \quad \text{AC} \quad \text{BS} \quad \text{OC} ] \\ = [ 0.82 \quad 0.12 \quad 0.63 \quad 0.31 \quad 0.30 \quad 0.17 \quad 0.24 \quad 0.39 \quad 0.53 \quad 0.29 ]$$

- *Calculation of reference suitability matrix*

The *reference suitability matrix* ( $S_t, t \in \{1, 2, \dots, 50000\}$ ) is defined by:

$$S_t = M_t \circ R$$

where "o" is an operator, such that for each element of S and for the  $t^{\text{th}}$  reference weight matrix

$$S_{ij} = \max_i \min (m_{tj}, r_{ij})$$

where  $t \in \{1, 2, \dots, 50000\}$

$j = S1, S2, S3, N1, N2$

$i$  denotes  $i^{\text{th}}$  land characteristic

$r_{ij}$  denotes an element of R the membership value.

i.e. for the  $i^{\text{th}}$  land characteristic under  $j^{\text{th}}$  suitability class.

This operator works as the multiplication of two matrices in algebra. The multiplication of two matrix elements is however replaced by the determination of the lower of the two matrix elements; the addition of products of elements is replaced by the determination of the maximal value of all 'products'. The operator "o" can be generalized as a *Triangular Norm* instead of the minimum and a *Triangular Conorm* instead of the maximum (Ruan, 1990; Tang et al., 1991).

4) *Determination of weight values for different land characteristics*

Based on the *standard suitability matrix* ( $P$ ) and the *reference suitability matrix* ( $S_t$ ), a fuzzy set G of suitable weight matrix ( $W$ ) can be established for the considered characteristics. For each of the reference weight matrices ( $M_t$ ), the membership value  $V_G(M_t)$  is given by (Ruan, 1990):

$$V_G(M_t) = 1 - d(S_t, P)$$

where  $d$  is a normalized distance,

$$d(S_t, P) = \sqrt{\frac{5}{\sum_{j=1}^5 (S_{tj} - p_j)^2}}/5$$

It is obvious from the membership function  $V_G(M_t)$  that the closer the distance between  $S_t$  and  $P$ , the higher value for  $V_G(M_t)$ . Hence we select the weight matrix, which corresponds to the highest membership value of  $V_G(M_t)$ , as the best weight values for the different characteristics. For instance, the best weight values of different characteristics for soil unit A-1 are calculated and presented as follows:

$$M_{15702} = \begin{bmatrix} \text{RF} & \text{MT} & \text{IN} & \text{DR} & \text{TX} & \text{DP} & \text{CF} & \text{AC} & \text{BS} & \text{OC} \\ 0.36 & 0.11 & 0.10 & 0.94 & 0.26 & 0.45 & 0.04 & 0.02 & 0.03 & 0.48 \end{bmatrix}$$

where  $M_{15702}$  means at the 15702<sup>th</sup> calculation, the reference weight matrix ( $M_t, t=15702$ ) corresponds to the highest membership value of  $V_G(M_t)$

This indicates that the drainage condition ( $DR = 0.94$ ) for soil unit A-1 is the most important and apparent CEC ( $AC = 0.02$ ) is the least important land characteristics for grain maize production.

Therefore the average values of those reference weight matrices corresponding to the highest membership values of  $V_G(M_t)$  for all soil units studied, are subsequently considered as the weight values for different land characteristics in the whole study area and are presented as a weight matrix ( $W$ ):

$$W_a = \frac{\sum_{i=1}^n (M_i^a)}{n}$$

whereby:  $W_a$  = mean weight value for  $a^{\text{th}}$  land characteristic,  $a \in \{\text{RF}, \text{MT}, \text{IN}, \text{DR}, \text{TX}, \text{DP}, \text{CF}, \text{AC}, \text{BS}, \text{OC}\}$

$i$  denotes  $i^{\text{th}}$  soil unit

$n$  denotes number of soil units

$M_i^a$  denotes weight value of  $a^{\text{th}}$  land characteristic for  $i^{\text{th}}$  land unit

For example, the final weight value for drainage condition in the study area is calculated as following:

$$W_{DR} = [(0.94 + 0.49 + 0.64 + 0.86 + 0.86 + 0.62 + 0.86 + 0.68 + 0.98 + 0.64 + 0.83 + 0.94 + 0.96 + 0.98 + 0.92 + 0.88 + 0.78 + 0.96 + 0.98 + 0.56)]/20 = 0.82$$

5) *Accuracy test of the fuzzy set method*

The final suitability classification using the fuzzy set method is obtained by multiplying the two fuzzy matrices (W and R) established previously:

$$E = W \circ R$$

The operator "o" has the same significance as in the determination of the reference suitability matrix (S<sub>r</sub>).

The elements of the evaluation matrix (E) express the degree of membership of the land unit to the suitability classes from S1 to N2. The suitability class for the considered land unit coincides with the element of the matrix (E) that has the highest value.

In the evaluation of soil unit A-1, the evaluation matrix (E), defined as E = W o R, is equal to:

$$E = [0.59 \ 0.12 \ 0.10 \ 0.82 \ 0.39 \ 0.48 \ 0.08 \ 0.02 \ 0.03 \ 0.31] \circ \begin{matrix} \boxed{1} & \boxed{0.84} & \boxed{0.44} & \boxed{0.13} & \boxed{0} \\ \boxed{1} & \boxed{0.91} & \boxed{0.62} & \boxed{0} & \boxed{0} \\ \boxed{1} & \boxed{0.75} & \boxed{0.34} & \boxed{0} & \boxed{0} \\ \boxed{0.11} & \boxed{1} & \boxed{0.28} & \boxed{0} & \boxed{0} \\ \boxed{1} & \boxed{0.22} & \boxed{0} & \boxed{0} & \boxed{0} \\ \boxed{1} & \boxed{0.87} & \boxed{0.42} & \boxed{0.08} & \boxed{0} \\ \boxed{1} & \boxed{0.85} & \boxed{0.37} & \boxed{0} & \boxed{0} \\ \boxed{1} & \boxed{0.96} & \boxed{0.66} & \boxed{0} & \boxed{0} \\ \boxed{1} & \boxed{0.94} & \boxed{0.81} & \boxed{0} & \boxed{0} \\ \boxed{0.73} & \boxed{1} & \boxed{0.95} & \boxed{0.47} & \boxed{0} \end{matrix}$$

$$= [0.59 \ 0.82 \ 0.44 \ 0.31 \ 0]$$

The result indicates that soil unit A-1 belongs to suitability class S2 (moderately suitable) since the matrix element with the highest value (0.82) indicates the degree of belonging to class S2.

If the sum of elements of the evaluation matrix (E) is set equal to 1, an index can be calculated as the product of the elements of the evaluation matrix (membership weight factors) and the average suitability class ratings resulting in a weighted index.

The application procedure is graphically presented in figure 3.

3.2. **Evaluation of representative mapping units**

The importance of the climatic characteristics of two meteorological

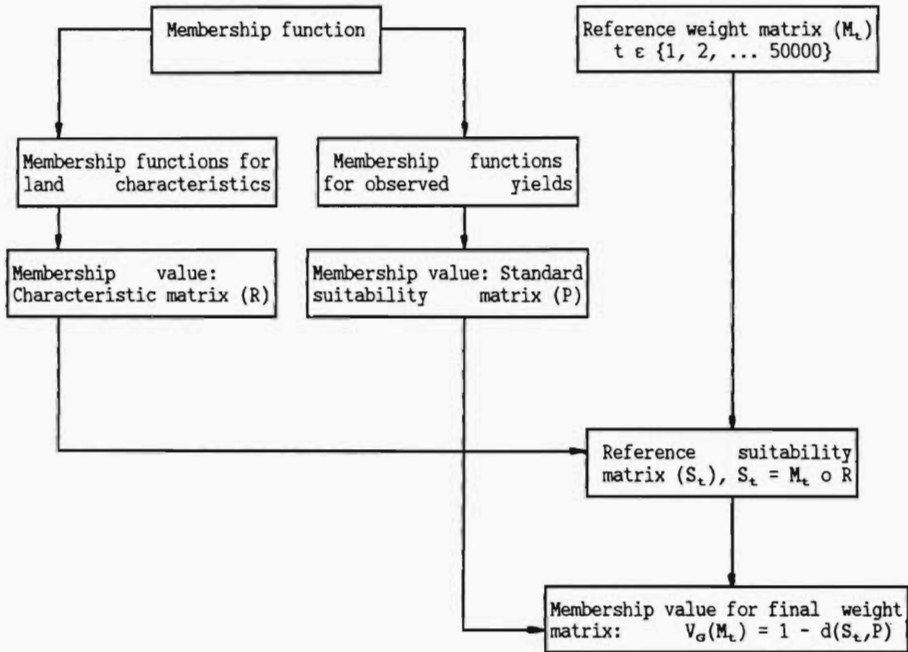


Fig. 3. Graphical representation of the application procedure

stations and the soil characteristics of 20 representative mapping units, influencing the performance of rainfed grain maize in Aitai County, is performed by application of the fuzzy set methodology. The results of the weight values of the different characteristics are given in table 3.

The obtained results indicate a quite good agreement with the study carried out by Zhou et al. (1988) in the same area. Zhou et al. (1988) stated that four land characteristics: rainfall, drainage conditions, texture/structure and effective soil depth have an important impact on crop yield. Matching the characteristics (table 1) with the crop requirements (table 2) shows that apparent CEC and base saturation are optimal; mean temperature, insolation and coarse fragments are nearly optimal; whereas drainage conditions, rainfall, soil depth, texture/structure, and organic carbon content are limiting factors for grain maize production.

In order to judge the accuracy of the fuzzy set methodology, the obtained results of the suitability classification are compared with (1) the results obtained by using the multiplicative parametric approach (Sys et al., 1991) and the maximum limitation method (Zheng et al., 1989) and (2) the observed grain maize yields on the different soil units (table 4). The correlations between the land indices obtained by the different methods and the observed yields are represented in figure 4.

The correlation coefficients are high for the three indices, but the results

**Table 3.**

Calculated weight values for different land characteristics on grain maize production in Aitai County, China

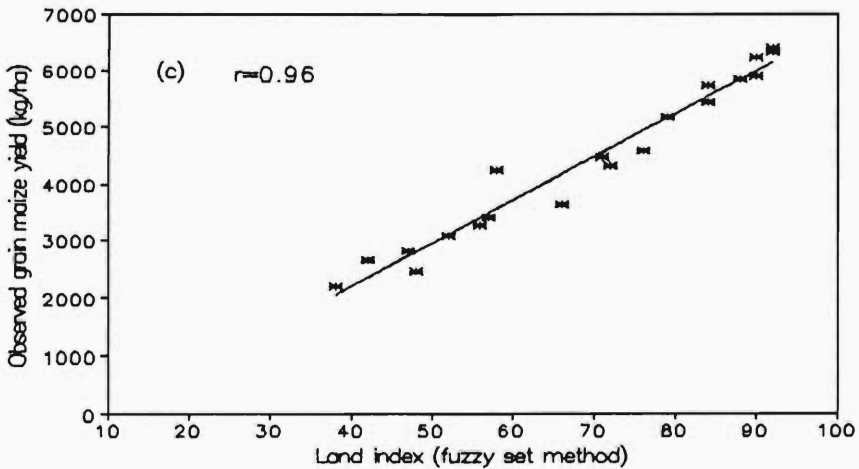
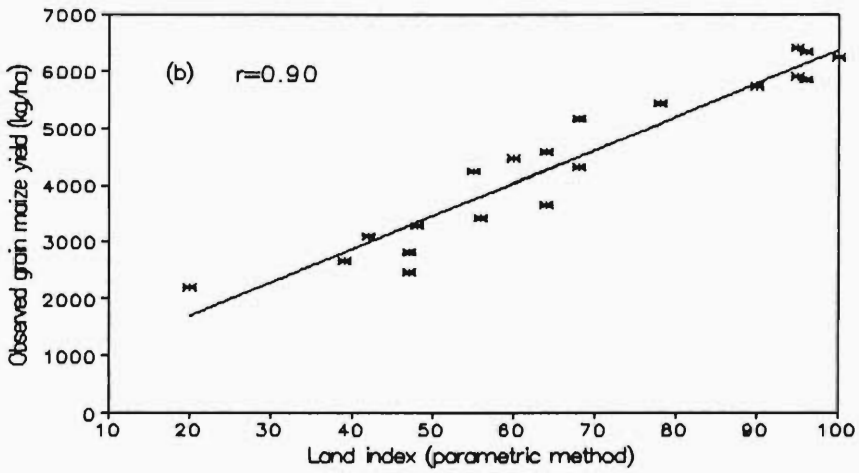
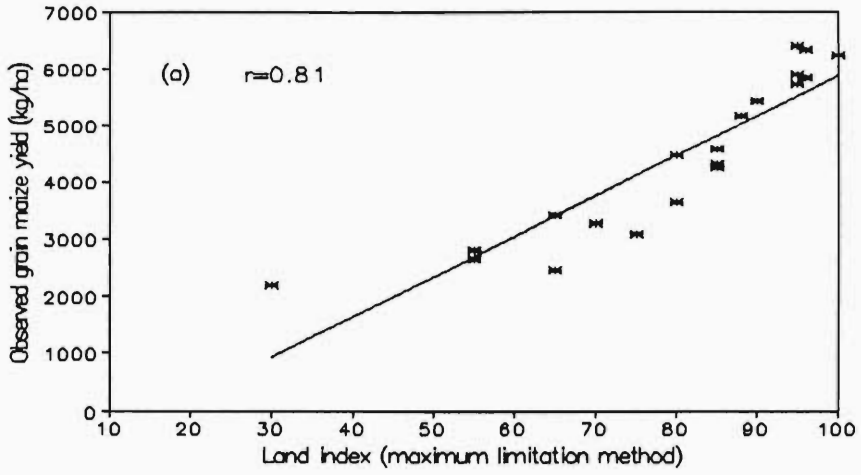
soil units	weight values for different land characteristics *									
	RF	MT	IN	DR	TX	DP	CF	AC	BS	OC
A-1	0.36	0.11	0.10	0.94	0.26	0.45	0.04	0.02	0.03	0.48
A-2	0.32	0.11	0.11	0.49	0.28	0.41	0.08	0.02	0.02	0.24
A-3	0.38	0.12	0.10	0.64	0.24	0.34	0.04	0.01	0.01	0.16
A-4	0.37	0.09	0.08	0.86	0.32	0.68	0.04	0.02	0.02	0.14
A-5	0.38	0.14	0.11	0.86	0.27	0.37	0.06	0.02	0.02	0.14
A-6	0.37	0.11	0.10	0.62	0.31	0.32	0.04	0.02	0.03	0.16
A-7	0.39	0.10	0.08	0.86	0.28	0.34	0.08	0.02	0.04	0.23
A-8	0.37	0.13	0.10	0.68	0.29	0.35	0.06	0.02	0.03	0.27
A-9	0.36	0.12	0.12	0.98	0.37	0.48	0.14	0.01	0.02	0.31
A-10	0.34	0.13	0.16	0.64	0.38	0.62	0.18	0.02	0.03	0.26
A-11	0.84	0.10	0.11	0.83	0.84	0.74	0.04	0.02	0.02	0.68
A-12	0.78	0.14	0.10	0.94	0.34	0.48	0.22	0.01	0.04	0.33
A-13	0.78	0.12	0.13	0.96	0.25	0.66	0.08	0.02	0.03	0.54
A-14	0.86	0.12	0.12	0.98	0.41	0.78	0.02	0.01	0.02	0.27
A-15	0.86	0.10	0.11	0.92	0.28	0.32	0.04	0.02	0.02	0.22
A-16	0.88	0.11	0.11	0.88	0.88	0.36	0.14	0.01	0.04	0.52
A-17	0.79	0.08	0.10	0.78	0.86	0.39	0.06	0.02	0.03	0.38
A-18	0.84	0.13	0.09	0.96	0.28	0.52	0.06	0.03	0.04	0.48
A-19	0.82	0.14	0.12	0.98	0.26	0.78	0.16	0.02	0.03	0.26
A-20	0.79	0.12	0.13	0.56	0.34	0.38	0.06	0.02	0.02	0.23
Mean	0.59	0.12	0.10	0.82	0.39	0.48	0.08	0.02	0.03	0.31

\* with RF, MT, IN represent rainfall, mean temperature, insolation within crop cycle respectively; DR: drainage; TX: texture and structure; DP: effective soil depth; CF: coarse fragment; AC: apparent CEC; BS: base saturation; OC: organic carbon.

obtained with the fuzzy set method ( $r=0.96$ ) show a better agreement with the observed yields than those obtained with the other two methods (maximum method,  $r=0.81$ ; parametric method,  $r=0.90$ ).

The expression of the importance of a land characteristic in the parametric and the maximum limitation methods is strongly experience-dependable and therefore rather subjective.

In the fuzzy set method, the relationship between crop yield and land characteristics is quantified by membership functions and fuzzy relation models, combining the evaluation of land characteristics into a final suitability class or suitability index.



**Fig. 4.** Linear regression of the land indices obtained with (a) the maximum limitation method (b) the parametric approach and (c) the fuzzy set method on observed grain maize yield data

**Table 4.**

Suitability classification results according to different evaluation methods and observed grain maize yields of the soil units in Aitai County, China

Soil units	Observed yield (kg/ha)	Suitability class and land index		
		max. limitation class (index)	Sys' parametric class (index)	Fuzzy set method class(weighted index)
A-2	6415	S1 (95)	S1 (95)	S1 (92)
A-3	6340	S1 (96)	S1 (96)	S1 (92)
A-5	6240	S1 (100)	S1 (100)	S1 (90)
A-4	5900	S1 (95)	S1 (95)	S1 (90)
A-7	5850	S1 (96)	S1 (96)	S1 (88)
A-8	5735	S1 (95)	S1 (90)	S1 (84)
A-6	5440	S1 (90)	S1 (78)	S1 (86)
A-20	5170	S1 (88)	S2 (68)	S1 (79)
A-10	4580	S1 (85)	S2 (64)	S1 (76)
A-15	4470	S1 (80)	S2 (62)	S2 (71)
A-18	4320	S1 (85)	S2 (68)	S2 (72)
A-1	4250	S2 (85)	S2 (55)	S2 (58)
A-16	3645	S1 (80)	S2 (64)	S2 (66)
A-12	3420	S2 (65)	S2 (56)	S2 (57)
A-17	3280	S2 (70)	S3 (48)	S2 (56)
A-13	3100	S1 (75)	S3 (42)	S2 (52)
A-9	2820	S2 (55)	S3 (47)	S3 (47)
A-19	2665	S2 (55)	S3 (39)	S3 (42)
A-11	2470	S2 (65)	S3 (47)	S3 (48)
A-14	2200	S3 (30)	N1 (20)	S3 (38)

#### 4. CONCLUSIONS

Land evaluation focusses increasingly on the application of quantitative procedures. Changes in procedures also call for the use of other kinds of data than hitherto collected. With respect to soil data, the common procedures of averaging and categorizing observed data are less meaningful and less necessary than it used to be. Numerical models need numerical data. The use of the fuzzy set theory to define, describe and generate the required numerical parameters from readily available soil survey data can play an important role.

The relationship between land characteristics and crop yields is mostly treated in an empirical way. The results obtained with the fuzzy set method are however very promising for further development and application in the field of land evaluation.

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## **Toepassing van de theorie van vage verzamelingen in een landgeschiktheidsevaluatie voor maïsproductie**

### *Samenvatting*

De theorie van vage verzamelingen kan gebruikt worden voor het bepalen van landindexen en landgeschiktheidsklassen. Deze theorie werd in deze studie toegepast in een landgeschiktheidsevaluatie voor maïsproductie in de streek van Aitai (China). De nauwkeurigheid van deze nieuwe methodiek werd getest door de volgens deze theorie berekende landindexen te vergelijken met de indexen bekomen met twee andere evaluatiemethoden, zijnde de vermenigvuldigende parametrische- en de maximale limitatiemethode. De respectievelijke landindexen werden vervolgens gecorreleerd met de waargenomen maïsofbrengsten op het terrein; de beste correlatie werd bekomen met de methode van de vage verzamelingen. De bekomen resultaten tonen aan dat het gebruik van de theorie van vage verzamelingen in landevaluatie veelbelovend is.

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## **Application de la theorie des ensembles flous a une evaluation des terres pour la production de maïs**

### *Résumé*

La théorie des ensembles flous peut être utilisée pour déterminer les indices et les classes d'aptitude des terres. Cette théorie est appliquée ici dans

le cadre de l'évaluation de terres pour la production de maïs grain pluvial dans la région d'Aitai (Chine). La précision de cette approche a été testée en comparant les valeurs des indices de terres déterminés à partir de cette théorie à ceux obtenus par deux autres procédures d'évaluation: respectivement les méthodes paramétrique multiplicative et du facteur limitant maximal. Les indices d'aptitude respectifs ont été ensuite corrélés aux rendements observés en champ: la corrélation la plus étroite est obtenue par la méthode des ensembles flous. Ces résultats illustrent le caractère prometteur de l'utilisation de cette approche dans le cadre de l'évaluation des terres.

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## EVALUATION OF TWO MODELS TO CALCULATE THE SOIL ERODIBILITY FACTOR K

F. DECLERCQ  
J. POESEN

### *Abstract*

The soil erodibility factor K used in the Revised Universal Soil Loss Equation can be calculated by two general applicable models. Data on the various soils covering northern Belgium are processed to evaluate the use of these models.

Erodibility factors are calculated for the top layer of soils where rill and interrill erosion occur. The K-values generated by each model are then compared throughout the range of soil types varying erodibility. For both models average K-values per unit area are mapped and spatial differences are discussed.

The K(Dg) model was found to be the most appropriate to predict K. For medium textured soils with a silt content lower than 70% and a known organic matter content, use of the K(nom) equation is preferred.

### *Key-words*

Soil erodibility, soil texture, RUSLE, choropleth maps, Northern Belgium.

## 1. INTRODUCTION

The K-factor described in the Revised Universal Soil Loss Equation, RUSLE (Renard et al., 1991) is a frequently used parameter to express the susceptibility of the soil to interrill and rill erosion. A nomograph based on soil properties is often used to calculate the K-value (Wischmeier et al., 1971). Römken et al. (1986) proposed an alternative procedure to calculate

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K using one texturally derived parameter only.

This study aims to test the two approaches on their reliability and coherence within diverse soil types, using the soil database of northern Belgium (Van Orshoven et al., 1988). The behaviour of both K-factors within the broad range of erosion susceptibility classes for this region will be outlined and compared with global acquired data. Erodibility maps based on both models will be established and differences are evaluated.

## 2. TWO MODELS TO PREDICT THE K-FACTOR

Soil loss due to interrill and rill erosion is related to several factors, as described in the RUSLE (Renard et al., 1991):

$$A = R.K.S.L.C.P.$$

where A is the soil loss per unit area and R, K, S, L, C and P represents the effects of precipitation and runoff (R), soil type (K), slope angle (S), slope length (L), cropping management (C) and conservation practices (P). The erodibility factor K is the longterm average rate of soil loss per unit erosion index (R) as measured on a unit plot, this plot being 22.1 m long, having a 9 percent slope and kept under a clean tilled fallow condition with tillage performed up and down slope (Römken et al., 1986). SI-units for K are ton.hectare.hour/hectare.MegaJoule.milimeter (t.ha.h/ha.MJ.mm).

Renard et al. (1991) state 'The physical, chemical and mineralogical soil properties and their interactions that affect K-values are many and varied. It is therefore unlikely that a few soil properties will accurately describe K-values for each soil. Yet attempts have been made to relate measured K-values to soil properties'. Indeed, erosion susceptibility of each individual soil cannot be determined on an experimental basis. Therefore two general applicable models to calculate K were established over the two decades.

### 2.1. K(nom), based on the nomograph

Measurements on 55 runoff plots on medium textured surface soils of the Corn Belt (Midwest, U.S.A.) lead to the development of the soil erodibility nomograph (Wishmeyer et al., 1971). It is the most widely used and frequently cited model to describe the relation between soil properties and erosion susceptibility (Renard et al., 1991). A useful algebraic approximation for the nomograph is:

$$K(\text{nom}) = ((2.1 \times (S(100-C)))^{1.4} \times 10^{-4} \times (12-OM))/100) \times 0.1317$$

where S = percent silt + very fine sand (2-100µm)  
 C = percent clay (0-2µm)  
 OM = organic matter content  
       = carbon content x 1.72 (Davies, 1974)  
 K(nom) = expressed in ton.ha.h/ha.MJ.mm.

With this equation however, the calculation of K for soils with a very high silt fraction (above 70%) is not allowed and can only be determined in a graphical way (Wishmeier and Smith, 1978). Furthermore, uncertainty arises on the applicability of the nomograph to well-aggregated soils (Römken et al., 1986).

### 2.2. K(Dg), based on the geometric mean particle size

Since K(nom) is based on measurements on medium textured soil types, it is best suited for erodibility prediction of these soil types. To provide an improved basis for calculating K-values irrespective of aggregation status and textural extremes, published data of K-measurements were related to their textural composition (Römken et al., 1986, Poesen, 1988). K-values of 249

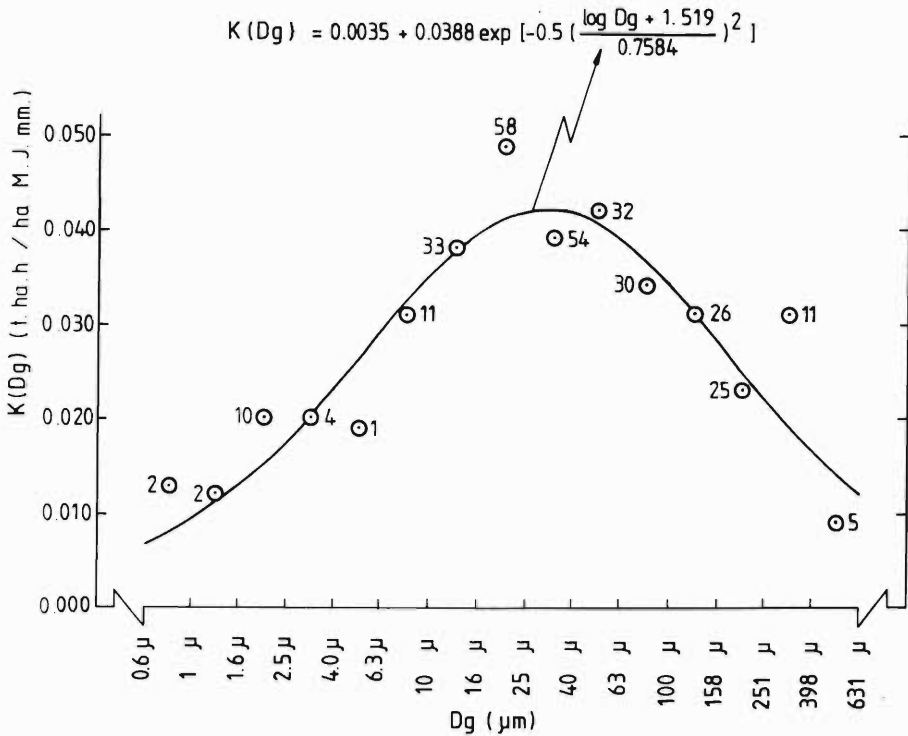


Fig. 1. Relation between K(Dg) and Dg (after Poesen, 1992)

soils, obtained from both natural and simulated rainfall studies worldwide, were grouped into textural classes of the 'geometric mean particle size' ('Dg') expressed as (Shirazi & Boersma, 1984):

$$Dg \text{ (mm)} = e^{(0.01 \times \sum (f_i \times \ln m_i))}$$

where  $f_i$  = particle size fraction  $i$  (weight percent)  
 $m_i$  = arithmetic mean of the particle size limits of fraction  $i$  (mm).

Considering only soils with less than 10% rock fragments (> 2 mm) by weight,  $K$  is obtained from the expression (Römkens et al., 1986):

$$K(Dg) = 0.0035 + 0.0388 \times e^{(-0.5 \times (((\log_{10} Dg) + 1.519) / 0.7584)^2)}$$

where  $K(Dg)$  = given in ton.ha.h/ha.MJ.mm.

Fig. 1 (after Poesen, 1992) illustrates the relation between  $K(Dg)$  and  $Dg$  for 304 soils worldwide. The average  $K$ -value for each  $Dg$ -class (dots) is compared to the regression function of Römkens et al. (1986) based on 249 soils (solid line). The number of soils from which the average for each  $Dg$ -class was obtained is indicated with each datapoint.

### 2.3. Assumed pros and contras of both models

As mentioned above the  $K(\text{nom})$  equation overpredicts  $K$  for soils with a silt content > 70% and is less suited for soils with textural extremes. Additionally, more soil properties (i.e. organic matter content and some specific textural fractions) have to be known to calculate  $K(\text{nom})$ , but as organic matter content is taken into account a more precise prediction of  $K$  is to be expected.

On the other hand, only one parameter needs to be calculated to establish  $K(Dg)$  (i.e.  $Dg$ ) irrespective of the textural classification that is available for the soil data.  $K(Dg)$ , however, yields a high variance in each  $Dg$ -class, especially for medium textured soils (Römkens et al., 1986).

If organic matter content data are available, it is to be expected that  $K(\text{nom})$ -values give the most accurate results since the influence of this property is taken into account in the  $K(\text{nom})$  equation. Römkens et al. (1988), however, found a correlation between  $K(Dg)$  variance and organic matter content. For the finer textured soils ( $Dg=1-80\mu\text{m}$ ) an increase of organic matter content yields lower observed  $K$ -values in each  $Dg$ -class. For coarse textured soils ( $Dg=80-600\mu\text{m}$ ) on the contrary an increase of soil erodibility was observed with increasing organic matter content. The latter can be explained by the water-repellent effect of organic matter on very sandy soils



(cf. Meeuwig, 1971). In the K(nom) model on the other hand, an increase of organic matter content is incorporated as an erodibility decreasing factor for all textural classes. The K(nom) model therefore yields incorrect results for coarse textured soils.

Römkens et al. (1988) also observed a significant negative correlation between clay content and soil erodibility: in each textural class K(Dg)-values decrease with increasing clay content.

To evaluate the assumed pros and contras of both models, the soil database of northern Belgium which consists of diverse soil types covering the whole range of textural classes is well suited. The following questions can be answered:

- a. Do K(nom) and K(Dg) differ in the sense explained above?
- b. What kind of soil type generates significant differences between K(nom) and K(Dg)? Which model is then to be applied?

### 3. K-VALUES OF THE TOP SOIL

Interrill and rill erosion occur in the upper 20 to 30 cm of the soil, i.e. the plough layer (Poesen and Govers, 1990). Hence, when assessing K-values of soils, only properties of the top soil may be considered.

The soil database of northern Belgium as described by Van Orshoven et al. (1988) provides very detailed information on soil properties, covering approximately 20000 km<sup>2</sup>. More than 8000 soil profiles are registered comprising for each horizon a set of 53 properties including those necessary to obtain K-values.

Since soil properties are only available per horizon, K-values for each horizon were calculated with both the K(Dg) and the K(nom) model. To determine the K-factor corresponding to the top 20 to 30 cm of each soil profile, depth-weighted averages of K were calculated taking into account the K-value of each horizon contained in the top soil. To know if a horizon lays partly or entirely within the top soil, two parameters are available in the database: HOR\_DIEP describing the depth of the top of a horizon and HOR\_DIK indicating a horizon's thickness. To calculate the proportion of each horizon in the top soil and thus determine the top soil's average K-value, each horizon's thickness has to be known exactly. The database unfortunately offers estimated values of a horizon's thickness and position (cf. intervals of table 1). Therefore, new variables 'hordeep' and 'horthick' were established as average values of each HOR\_DIEP and HOR\_DIK interval respectively, each with their respective errors.

Three methods were developed to estimate a horizon's proportion in the top soil of each profile.

- (1) The variable hordeep was used. For each profile all horizons with a

**Table 1.**

Parameters describing horizon position (hordeep) and thickness (horthick)

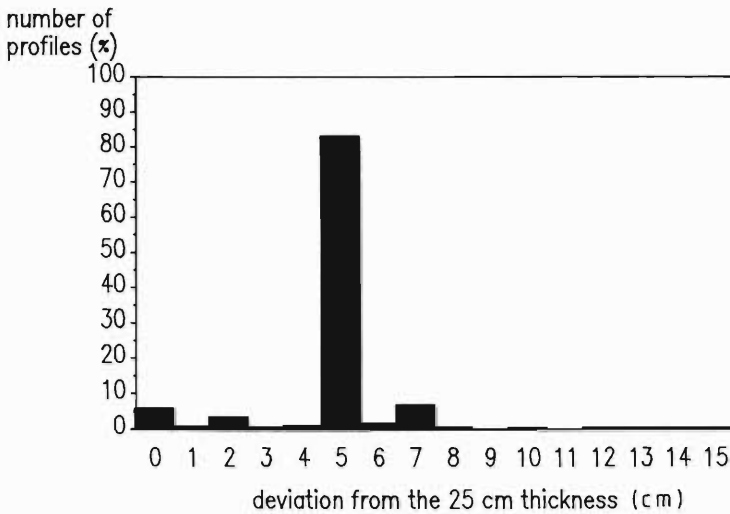
HOR_DIEP (cm)	hordeep (cm)	error (cm)
0 - 5	3	3
6 - 10	8	2
11 - 20	15	5
21 - 40	30	10
41 - 60	50	10
61 - 80	70	10
81 - 100	90	10
101 - 150	125	25
> 150	175	$\geq 25$

HOR_DIK (cm)	horthick (cm)	error (cm)
0 - 2	1	1
3 - 5	4	1
6 - 10	8	2
11 - 20	15	5
21 - 30	25	5
31 - 50	40	10
51 - 100	75	25
> 100	125	$\geq 25$

hordeep of maximum 30 cm were taken into account. Due to the error of 10 cm (table 1) all horizons that occur up to a depth of 40 cm are considered. Consequently a depthweighted average of K was established for the upper 40 cm of each soil profile: a rather large depth compared to our definition of 'top soil'.

(2) In a second method, the horthick-value was used. This variable yields less error than hordeep (table 1). For each profile the horthick-values were summed up to a depth of 25 cm and weighted averages were calculated for the top 25 cm of the soil. The error of each individual horthick-value however is carried on to the summed thickness considered. So 'top soil' depth fluctuates from profile to profile, dependent on the thickness of the constituent horizons. Fig. 2 shows that with this method 98% of all soil profiles have a top soil depth of  $25 \pm 7$  cm while more than 92% have a top soil of  $25 \pm 5$  cm, which

### Error on top soil thickness frequency distribution



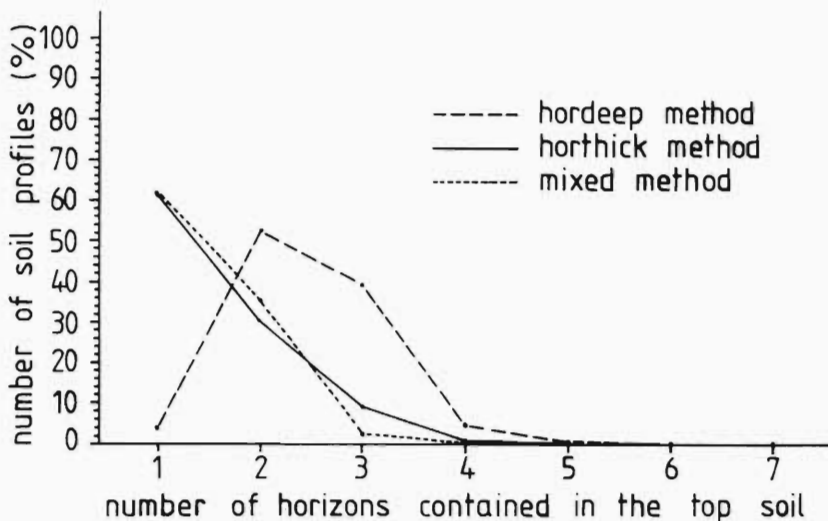
**Fig. 2.**  
Error on considered top soil thickness with regard to the 25 cm thickness limit in the horthick-method

is a very good approximation of the above postulated top soil thickness (20-30 cm).

(3) A 'mixed' method was developed in which for each profile only horizons were retained with a hordeep-value of  $15 \pm 5$  cm or less (table 1). The less error-affected horthick-value was further used to calculate weighted averages up to a maximum depth of 30 cm.

In order to compare the influence of the method used on the top soil thickness considered, the amount of horizons taken into account to calculate K-averages for each profile has been examined (fig. 3). The horthick and mixed method are very much alike: about 90% of all profiles 8542 profiles have a top soil composed of only the upper or the upper two soil horizons. In the mixed method, a lower occurrence of top soils containing three or more horizons indicates that K-values are valid for a top layer smaller than  $25 \pm 7$  cm. The hordeep method on the contrary describes a top soil layer of 40 cm that often contains three or more horizons (fig. 2).

Both the mixed and the horthick method yield depth-weighted K-averages valid for approximately the upper 20 to 30 cm of the soil, but as the horthick method showed the least error (cf. table 1), the latter was chosen for the calculation of the top soil K-average.



**Fig. 3.**  
Influence of the method used on the number of horizons contained in the top soil

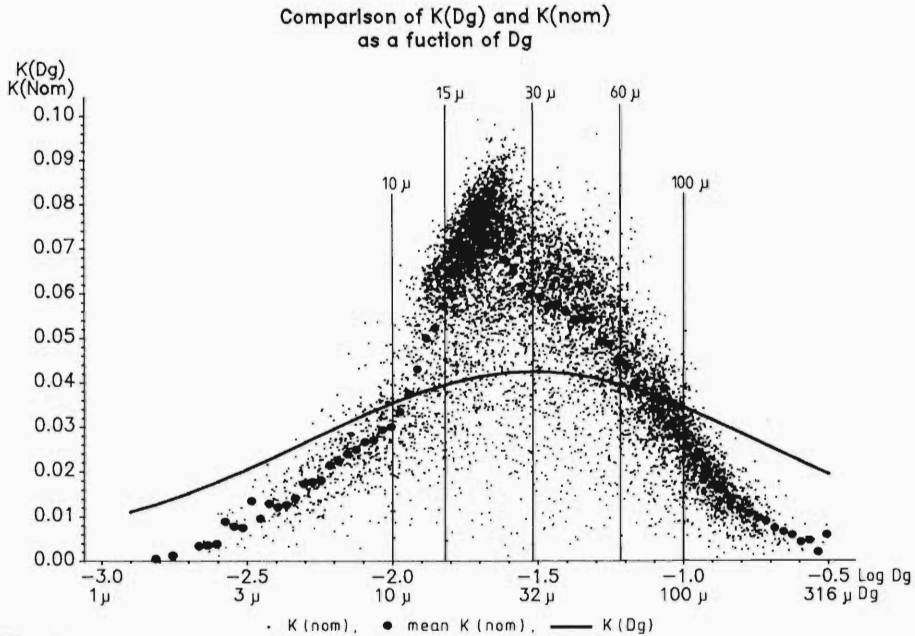
#### 4. K-VALUES OF NORTHERN BELGIAN TOP SOILS

K(nom)- and K(Dg)-values were calculated for all 8542 soil profiles considered in northern Belgium and plotted mean particle size (Dg) (fig. 4). Figures 5a, 5b, 5c and 6 show the soil properties which determine the calculated K-values in both models.

Each point in the graph represents one soil profile. Quadratic or cubic regression through the data points gave insignificant relations. In order to visualise general trends averages were calculated per 'log Dg' interval of 0.03 (represented by dots). One should notice that some averages deviate from the centre of the datascatter, due to extreme values within the interval. In fig. 5-6 certain horizontal lines can be detected. These concentrations parallel to the X-axis are caused by the use of discrete values during textural analysis.

Fig. 4 shows important differences between K(nom)- and K(Dg)-values. We distinguish between four textural classes. In the finest textured soils ( $D_g < 10\mu\text{m}$ ) K(nom) is smaller than K(Dg). Fine medium textured soils ( $D_g = 15\text{-}30\mu\text{m}$ ) have a K(nom)-value varying from 0.060 to 0.075 which is much higher than the K(Dg)-values (0.040 to 0.042). Coarse medium textured soils ( $D_g = 30\text{-}60\mu\text{m}$ ) also have higher K(nom)-values (0.060 to 0.045) that deviate less from K(Dg) (0.042 to 0.040). For coarse textured soils ( $D_g > 100\mu\text{m}$ ) the relationship shifts: K(nom)-values become smaller than K(Dg)-values. Summarizing, it may be stated that while for medium grain size the mean K(nom) yields up to twice the value of K(Dg), K(Dg) exceeds K(nom) by twofold for smaller and larger grain sizes.

To assess which equation is the most effective in predicting K, textural and



**Fig. 4.**

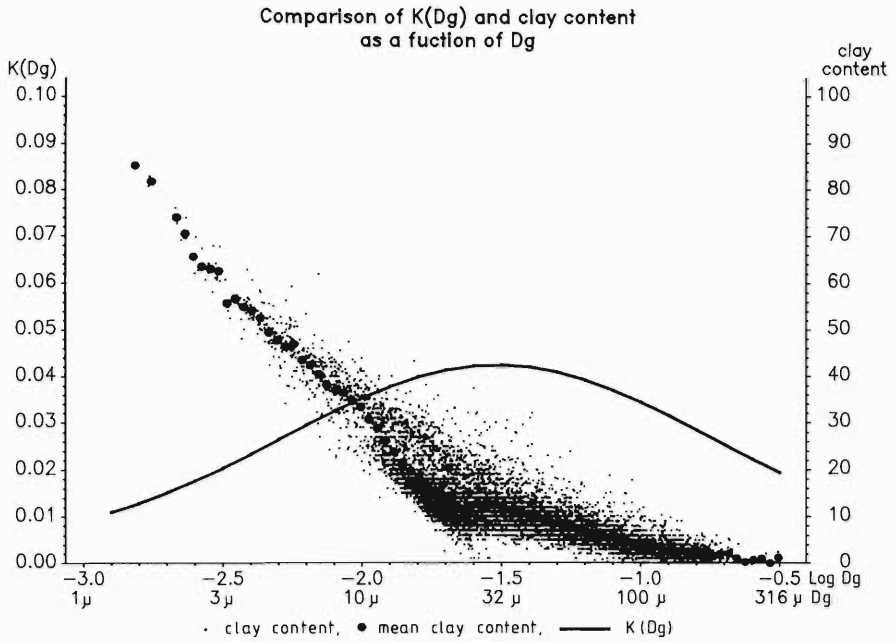
Comparison of the relations between  $K(Dg)$  and  $K(nom)$  with  $Dg$  for 8542 top soils of northern Belgium.

organic matter content properties of Belgian soils will be compared to those of the soils used to establish the empirical  $K(Dg)$  and  $K(nom)$  relations.

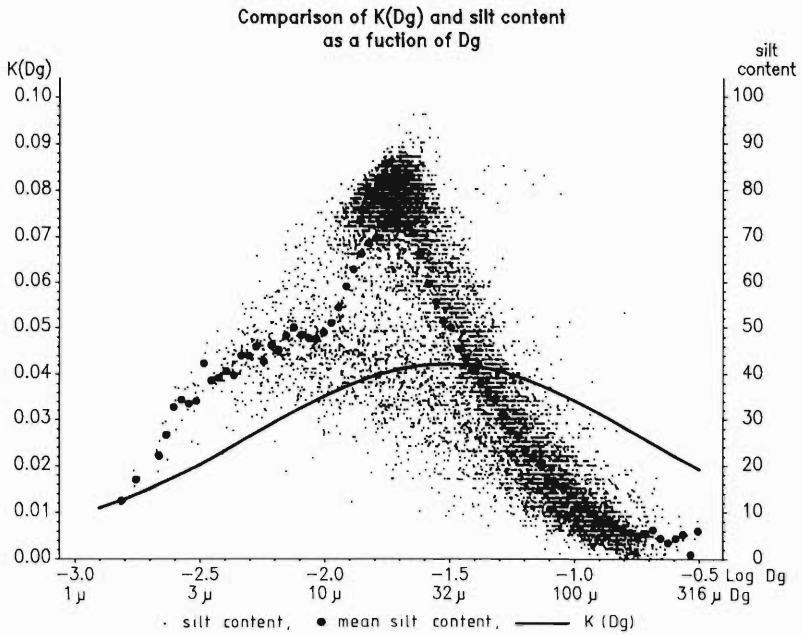
(1) The clay content of soils from northern Belgium throughout the different textural classes (fig. 5a) is very similar to the clay content of soils used to determine the  $K(Dg)$  relation (Römken et al., 1988, fig. 4 p. 383): for soils in class 3 ( $Dg=1-3\mu m$ ) ( $K(Dg)$ -values correspond to a clay content of > 60%, which is identical for Belgian soils; clay content ranged from 45-10% for soils with a  $Dg=10-80\mu m$  (30-5% for Belgian soils, fig. 5a), and from 15-0% (5-0% for Belgian soils, fig. 5a) for coarse textured soils ( $Dg=80-600\mu m$ ). Thus clay content will not substantially influence differences between the calculated  $K(Dg)$ -values and the real  $K$ -values of the Belgian soils.

(2) No data were available in the literature on the silt and sand content of the soils from the global dataset used by Römken et al. (1986) to establish the  $K(Dg)$  relation. Therefore, there is no evidence whether a significant difference in silt or sand content between certain Belgian and global soil types will influence differences between the calculated  $K(Dg)$ -values and the real  $K$ -values of the Belgian soils.

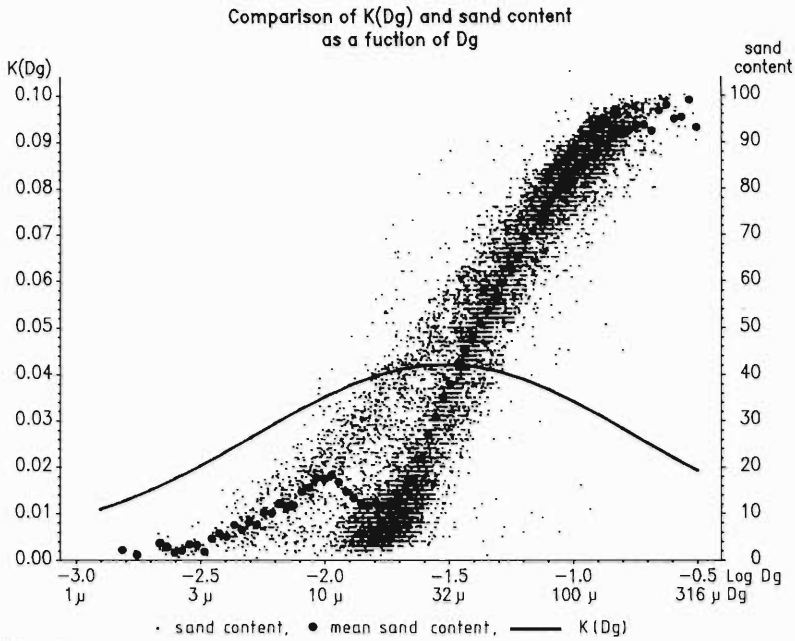
(3) The influence of organic matter content on  $K(Dg)$  and  $K(nom)$  is described above (cf. 1.3). Based on differences in organic matter content, an analysis of the deviation between both erodibility factors was made for each distinguished textural class:



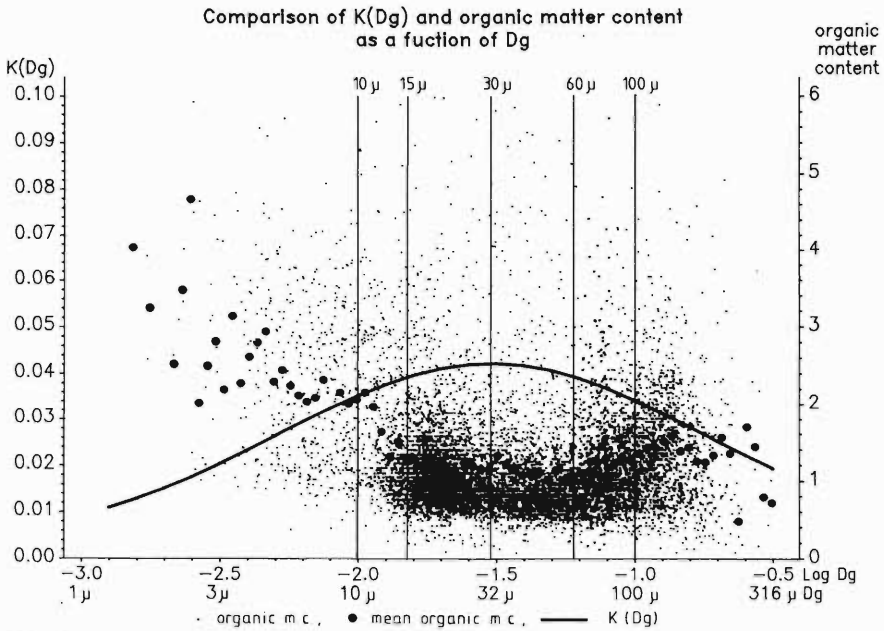
**Fig. 5a.**  
Comparison of the relations between  $K(D_g)$  and clay content with  $D_g$  for 8542 top soils of northern Belgium



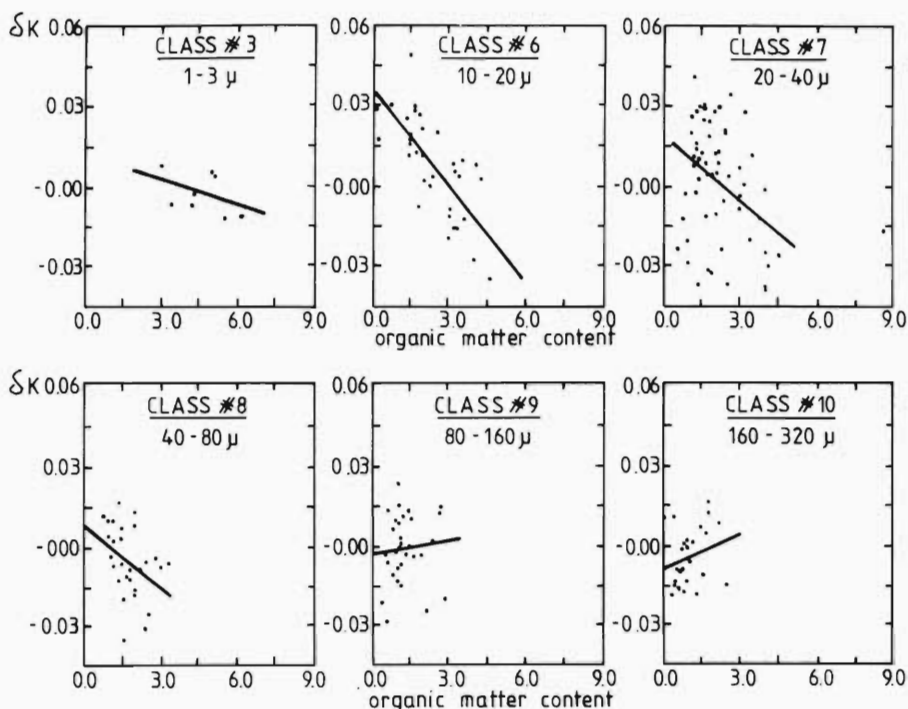
**Fig. 5b.**  
Comparison of the relations between  $K(D_g)$  and silt content with  $D_g$  for 8542 top soils of northern Belgium



**Fig. 5c.**  
Comparison of the relations between K(Dg) and sand content with Dg for 8542 top soils of Northern Belgium



**Fig. 6.**  
Comparison of the relations between K(Dg) and organic matter content with Dg for 8542 top soils of northern Belgium



**Fig. 7.**

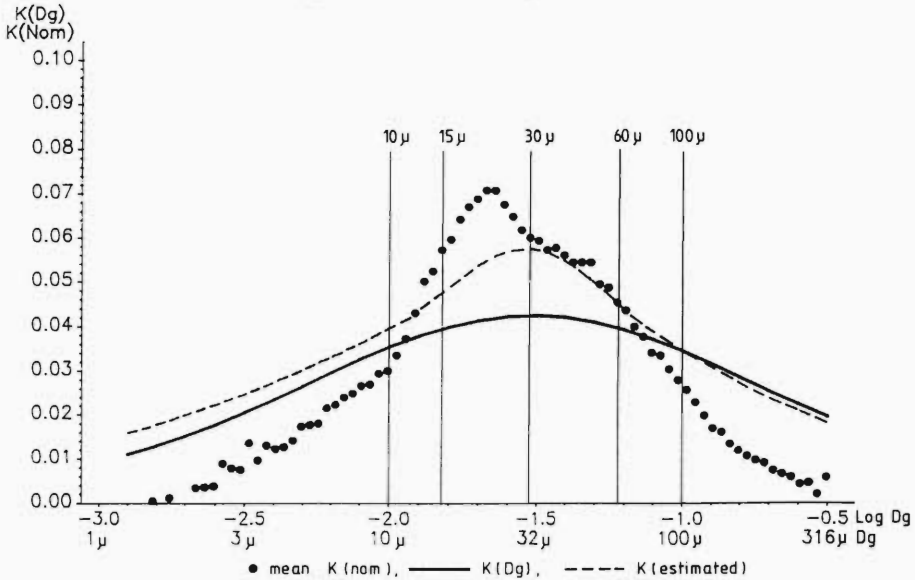
Relationship between  $\Delta K(Dg) = (K_{\text{observed}} - K_{\text{predicted}})$  and organic matter content for different Dg-classes, based on 223 soils worldwide (after Römken et al., 1988)

1. For fine textured soils ( $Dg < 10 \mu\text{m}$ ) the empirically obtained  $K(Dg)$ -values are derived from soils worldwide with an organic matter content varying from 3-6% (fig. 7, class 3). In the Belgian test soils this ranges from 2-5% (fig. 6). Fig. 7 shows that for textural class 3 and 6 predicted  $K(Dg)$ -values ( $\Delta K = 0$ ) are valid for soils with an organic matter content of 4% and 3% respectively. Considering the lower organic matter content of the Belgian test soils, a realistic  $K$ -value for the Belgian soils can be estimated based on the regression lines in fig. 7 (class 3 and 6). This realistic  $K$ -value called ' $K(\text{estimated})$ ' is  $\pm 0.005$  higher than the predicted  $K(Dg)$ -value (fig. 8). For these fine textured soils  $K(\text{estimated})$ -values are even 0.015 higher than  $K(\text{nom})$ -values (fig. 8).

2. In the finer medium textured class ( $Dg = 15-30 \mu\text{m}$ ) mean organic matter content of Belgian soils varies from about 0.8-1.2% (fig. 6), in contrast to the  $\pm 3\%$  to which the average  $K(Dg)$ -value corresponds (fig. 7, class 6 and 7). Based on the regression lines in fig. 7 (class 6 and 7) realistic  $K$ -values for Belgian top soils will therefore be 0.010 to 0.015 higher than the  $K(Dg)$  model predicts, namely  $\pm 0.050-0.057$  (fig. 8). Mean  $K(\text{nom})$ -values on the contrary are much higher (0.060-0.080, fig. 4 and 8). This must be attributed to the overestimation of  $K$  by the  $K(\text{nom})$  computation when silt content exceeds 70% (fig. 5b).



Comparison of  $K(Dg)$ ,  $K(nom)$  and  $K(estimated)$   
as a function of  $Dg$



**Fig. 8.** Comparison of the relations between  $K(Dg)$ ,  $K(nom)$  and  $K(estimated)$  with  $Dg$  for 8542 top soils of Northern Belgium

3. Coarser medium textured Belgian top soils ( $Dg=30-60\mu m$ ) have a lower organic matter content (0.8-1.2%, fig. 6) compared to that of the  $K(Dg)$ -soils worldwide (mean=2.5-1.5%, fig. 7, class 7 and 8). Consequently,  $K(estimated)$ -values will be about 0.015 to 0.005 above the calculated  $K(Dg)$ -values (fig. 7, class 7 and 8), namely  $\pm 0.057-0.045$  (fig. 8). Average  $K(nom)$ -values are a good approximation of top soil erodibility for this textural class (fig. 8).

4. Coarse textured Belgian top soils ( $Dg>100\mu m$ ) have a mean organic matter content of about 1.2-1.8% (fig. 6), which is slightly less than that of the soils worldwide used to establish the  $K(Dg)$  relationship (fig. 7, class 9 and 10). The positive correlation between organic matter content and erodibility for this textural class therefore yields a  $K(estimated)$  slightly lower than  $K(Dg)$ . The positive correlation is not incorporated in the  $K(nom)$  model that yields an underestimation of erodibility by  $\pm 0.015$  (fig. 8).

According to our analyses  $K(Dg)$  yields more accurate  $K$ -values for the fine textured clayey soils ( $Dg<10\mu m$ ) and coarse sandy soils ( $Dg>100\mu m$ ) than  $K(nom)$ . This confirms that  $K(nom)$  is neither well suited for clayey soils (which are well-aggregated) nor for sandy soils for which the negative correlation between soil erodibility and organic matter content is inverted. On the other hand, for medium textured soils ( $Dg=15-60\mu m$ ) the  $K(nom)$  equation is a more precise prediction of erodibility although silt content may not exceed 70%.

In general, the K(Dg) model gives the best estimates of erodibility throughout all textural classes, although it becomes more inaccurate than the K(nom) equation when organic matter content differs from a value of 2-3% for medium textured soils ( $Dg=15-60\mu m$ ) with a silt content below 70%.

## 5. ERODIBILITY MAPS OF NORTHERN BELGIUM

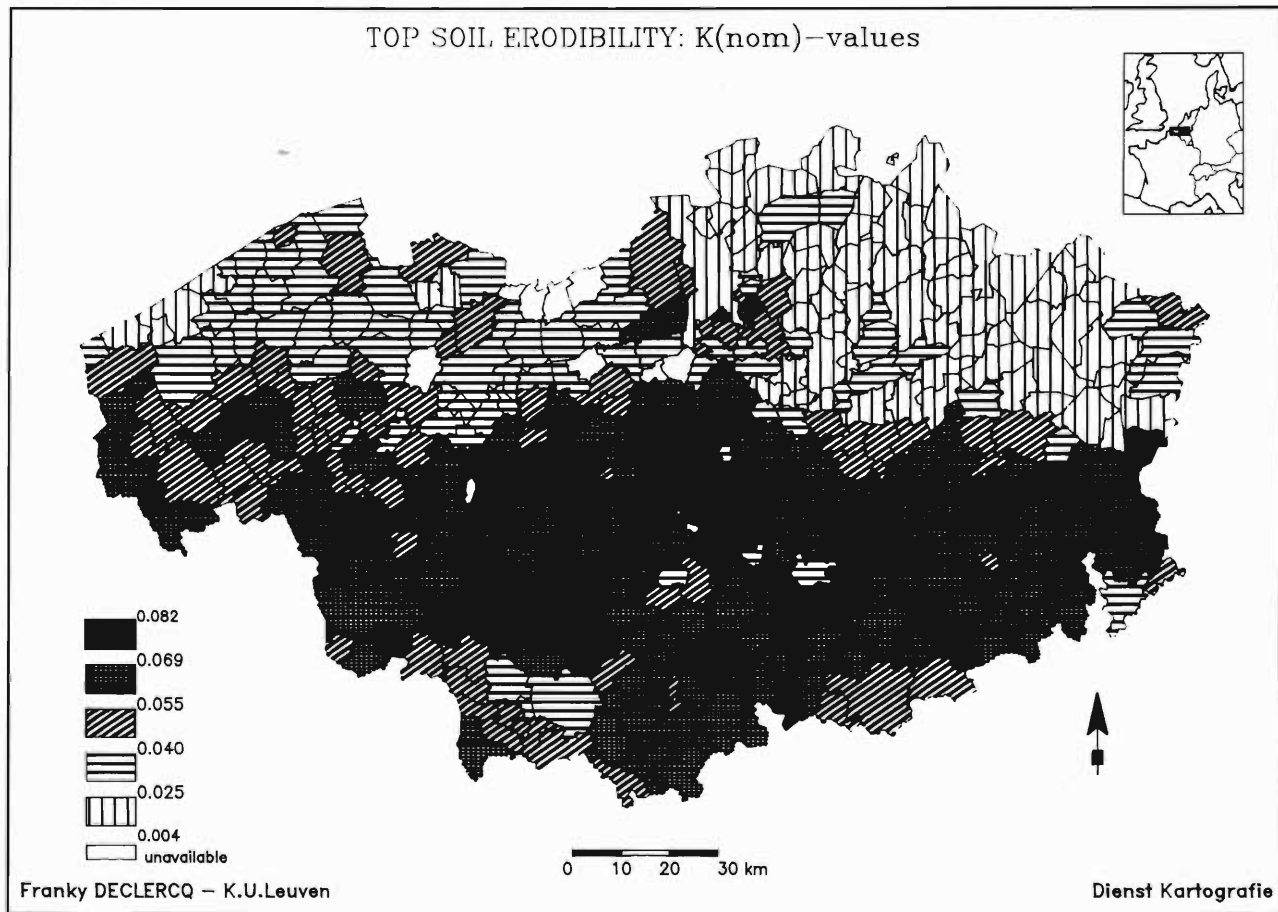
To represent the spatial distribution of top soil erodibility, choropleth maps were made which represent averages per municipality. K-values were grouped into five erodibility classes. Class limits were determined using the optimization method of Jenks, including aspects of round class breaks and map image complexity (Declercq and Poesen, 1991). As a result, statistically optimal class intervals were established of which the variance between the intervals is maximized, and thus variance within each interval is minimal (Coulson, 1987). Within a range of five values around these optimal class breaks, actual class breaks are chosen to be more rounded values and to yield a less fragmented map image (Declercq, 1989).

One should notice that data on organic matter content were collected between 1950 and 1980. During this period soils' organic matter content has changed, but still the regional differences have remained (compare Declercq and Poesen, 1991, fig. 12, p. 44 and Pauwels et al., 1988, fig. 6a, p. 18).

Erodibility maps of both models K(Dg) and K(nom) give a similar picture of top soil erodibility in northern Belgium: highest erodibility in the central part, less high in the south and least in the northern part (fig. 9 and 10).

The upper K(Dg)-class, however, extends over a much larger area than the upper K(nom)-class. This is related to the highest K(Dg)-values which only vary between 0.040 and 0.042 (fig. 8) and account for 50% of all observations (fig. 10 and 11). The highest K(nom)-class, on the contrary, consists of a small number of observations with very high K(nom)-values varying from 0.069 to 0.082 (fig. 9). The majority of these values are overestimated (fig. 11 and 12) and form a separate group within the K(nom) equation, because of the high silt content of the top soils (fig. 5b and 8). The municipalities with K(nom)-values that are an underestimation of the estimated K-values (fig. 12) are mapped in the lowest class of both fig. 9 and 10. These K(nom)-values do not form a separate group of observations on the K(nom) map in comparison with the K(Dg) map, due to the similar evolution with the K(Dg)-values in function of Dg (fig. 8).

The differences between the course of the function of the K(nom) equation and that of the estimated K-values in the range of  $Dg=30-60\mu m$  (fig. 8) introduces a separate upper class in the map image generated by the K(nom) equation. With the K(Dg) model, on the contrary, calculated K(Dg)-values and estimated K-values only differ in their upper values. Maps based on the K(Dg) model are therefore better suited for soil erodibility mapping.



**Fig. 9.**  
Top soil erodibility: K(nom)-values

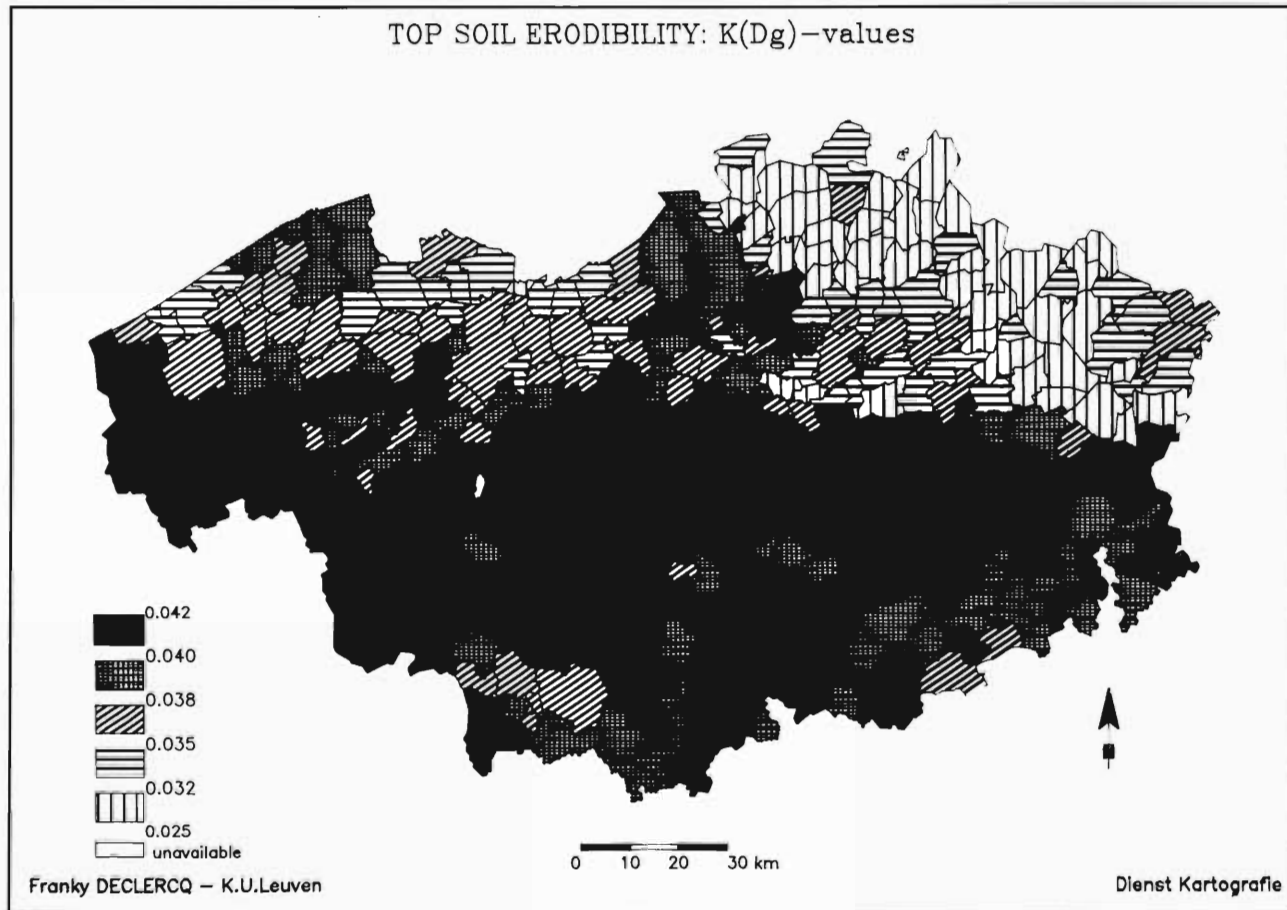
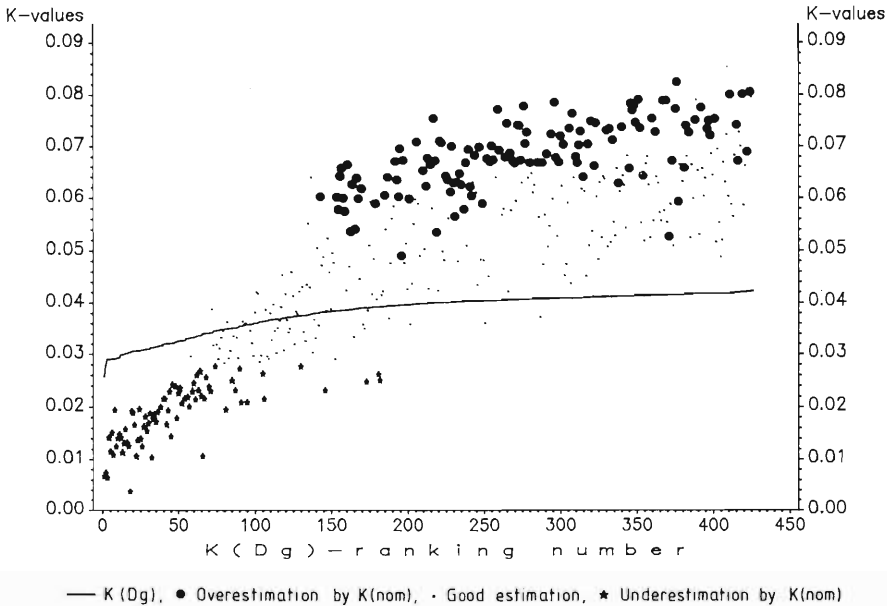


Fig. 10.  
Top soil erodibility: K(Dg)-values

Comparison of  $K(Dg)$  and  $K(nom)$   
values per municipality



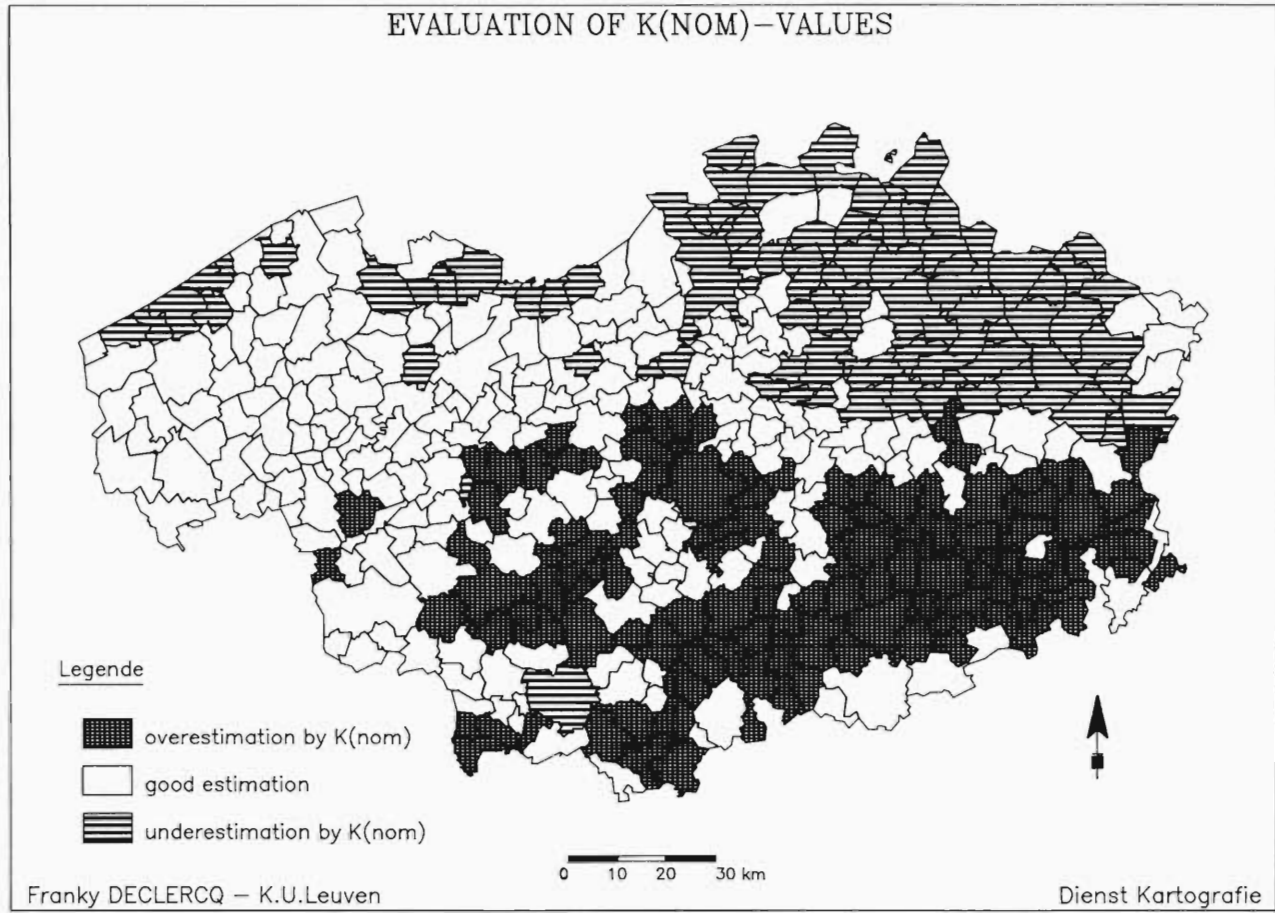
**Fig. 11.**

Comparison of  $K(Dg)$ - and  $K(nom)$ -values per municipality. Municipalities are ranked by  $K(Dg)$ -value

## 6. CONCLUSIONS

Based on a large soil database covering northern Belgium, the use of two different models to calculate soil erodibility was evaluated. The test included both, very fine textured, coarse textured and highly silty top soils ( $Dg$  ranging from 2-350 $\mu m$ , silt content > 70%) for which the  $K(nom)$  equation is not well suited, and top soils for which organic matter content deviates strongly from that of the soils upon which the  $K(Dg)$  model is based. Therefore realistic erodibility values of Belgian top soils, called  $K(estimated)$ -values, were determined based on calculated  $K(Dg)$ -values, taking into account the correlations described by Römken et al. (1988) between organic matter content on the one hand and differences between calculated  $K(Dg)$ -values and observed  $K$ -values on the other.

In contrast to the  $K(nom)$ -values, the  $K(Dg)$ -values were found to correspond well to  $K(estimated)$ -values for very fine and coarse textured soils ( $Dg < 10\mu m$ ,  $Dg > 100\mu m$ ). For medium textured soils ( $Dg = 15-60\mu m$ )  $K(Dg)$ -values are a 25% underestimation of  $K(estimated)$ -values, due to the low organic matter content of the Belgian soils. The  $K(nom)$  equation takes into account organic matter content and gives a good approximation of soil erodibility for medium textured soils, except when silt content exceeds 70%.



**Fig. 12.**  
Evaluation of K(nom)-values

The K(nom) equation namely generates peak values for the very silty top soils with  $D_g=15-30\mu\text{m}$ . In contrast, the K(Dg) model yields a function that is similar to the function of K(estimated) over the whole range of soil textures. As a result maps based on the K(Dg) model give a more accurate image of erodibility because the K(nom) equation puts extremely silty soils in a separate class of high erodibility.

The K(nom) equation can only be recommended if organic matter content is known and silt content is below 70%. For clayey or sandy soils ( $D_g<10\mu\text{m}$ ,  $D_g>100\mu\text{m}$ ) the K(Dg) model should be preferred, even if organic matter content is known. Furthermore, K(Dg) gives good results for medium textured soils with an organic matter content between 2 and 3%, irrespective of the soils' silt content.

## ACKNOWLEDGEMENTS

The authors wish to thank the Laboratory of Land Management (Prof. Dr. J. Feyen and Dr. J. Van Orshoven) for providing the database on Belgian soil profiles, Prof. Dr. F. Depuydt for his helpful comments on the cartographic design and Dr. K. Bunte for comments on an earlier draft.

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## Evaluation de deux modèles de calcul du facteur d'érodibilité du sol K

### *Résumé*

Le facteur d'érodibilité du sol K de l'équation universelle de perte de sol révisée (Revised Universal Soil Loss Equation, RUSLE) peut être calculé en utilisant deux modèles universellement applicables. Les données des divers sols du nord de la Belgique sont utilisées pour évaluer l'usage des deux modèles.

Les facteurs d'érodibilité sont calculés pour la couche supérieure du sol où se produit l'érosion en nappe et en rigole. Pour la grande variation des classes d'érodibilité, les valeurs de K correspondant aux deux modèles sont comparées. Les moyennes de K pour des surfaces d'unité sont dressées sur carte et les différences spatiales, invoquées par le modèle utilisé, sont discutées.

Le modèle K(Dg) est le plus approprié pour la prédiction du facteur K. Pour les sols de texture moyenne contenant moins de 70% de limon et dont la teneur en matière organique est connue, l'usage du modèle K(nom) est à préférer.

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## FORMS OF EVOLUTION OF GYPSUM IN ARID SOILS AND SOIL PARENT MATERIALS

T.G. BOYADGIEV  
A.H. SAYEGH

### *Abstract*

In gypsiferous soils there are many forms of gypsum because of the several sources and the varied conditions of its precipitation. This paper discusses the forms and evolution of gypsum collected from different areas of the Middle East and North Africa on the basis of electron microscope observations. A relationship was found between attapulgitic formation and the forms of gypsum present.

### *Key-words*

Arid soils, Attapulgitic formation, Gypsum evaluation, Gypsum formation, Gypsum forms, Soil parent materials.

## 1. INTRODUCTION

Gypsiferous soils are widespread in arid and semi-arid zones, their total area is estimated to be about 707,000 km<sup>2</sup> (Boyadgiev, 1985). They are found especially in North Africa, South-West Asia, the Mediterranean part of Europe (van Alphen, 1971), Argentina and Chile, and Australia. (FAO, 1990).

Gypsiferous soils have been studied in relation, *inter alia*, to numerous hydro-agricultural projects. The implementation of these projects has met with enormous difficulty linked with the damage to the canal lining and the hydraulic structure in the gypsiferous soils. Morphological observation has shown that the forms of gypsum play an important role in this respect, which lead to this study of gypsum forms using the electron microscope.

Gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O) is formed from aqueous solution, or from the

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hydration of the anhydride. It crystallizes into monoclinic prisms and occurs in a finely granular form (alabaster), as fibrous aggregates (satin gypsum, selenite), or rose-like clusters (desert roses). "Lance-headed" and dovetailed macles are also very frequent (Kostov, 1957). In the soil, gypsum crystallizes in numerous forms: mealy crystals, large nodules, concretions, slabs, compact, spongy, porous mass, or crust (FAO-Unesco, 1973°).

Gibb and Kocks (1967) observed twelve forms of gypsum in the Balikh basin in Syria. Le Houerou (1960) described the encrustations of intumescence layers in Tunisia, as well as the "pulverulent gypsum agglomerated into a rather hard sandstone, vibrating, and having cavernous structure". Pouget (1968) considers that gypsum in the soil above a groundwater level evolves in the following sequence: very fine crystals-spots-encrustation-crust. Observed in the electron microscope (Beutelspacher and Van der Marel, 1968), gypsum crystals may appear as elongated spots ("Parallelepipedic crystals"), dark with clear, irregular edges (gypsum crystals of the Dead Sea), or dark spots in the shape of sand-glasses with irregular boundaries (altered gypseous rock in Italy).

Taking into account their mode of formation, the gypsum forms observed in the field by Boyadgiev (1973a, 1973b) may be grouped as follows:

1. Pseudomycelium spots "rigons" (elongated accumulations of 1-2 mm in diameter), or with powdery pellicle on the surface. These are recent neoformations found in fine or medium textured horizons, resulting from soil solution rising by capillarity.
2. Separate crystals or crystals in small agglomerations. These are found in coarse textured horizons immediately above the water-table or in voids of fine textured horizons; these too are recent neoformations.
3. Powdery-fibrous gypsum with various compaction. (Nettleton, 1991). This is found in medium or fine textured horizons towards the superior level of the capillary fringe of ground water. It can result also from in situ weathering of primary gypsum or leaching from a coarse textured horizon and accumulation at depth. These are recent or relic neoformations.
4. Gypseous crust. When powdery gypsum rises to the surface of the soil or to the borders of crevices, it forms hard polygons at the surface, flat rocky subsoil, or vertical flag-layer.
5. Spongeous gypsum (agglomerated crystals). These crystals are seen in well drained horizons with coarse texture. These are residual neoformations. If the adjacent horizons are very rich in calcium carbonate, the gypsum is powdery and fluffy. Crystals or encrustation ("beard") around the gravel are also included in this form of gypsum.
6. Gypseous sand. Two cases were observed: a) an aeolic accumulation at the surface of the soil which forms dunes of stabilized sand of different dimensions ("lunettes"), b) a secondary gypsum accumulation through the profile of the soil: grains of sand are finer in the upper part and coarser underneath. These are ancient neoformations.

7. Desert roses. The small-winged shape is characteristic for a semi-arid climate, and the large-winged shape for arid and hyper-arid climates.
8. Hard gypseous rock, well crystallized, of geologic origin.

## 2. MICROSCOPIC STUDY

Samples of the following forms of gypsum were chosen for electron microscopy: hard gypseous rock, gypseous crust powdery-fibrous gypsum, roses of the desert, secondary gypsum on the periphery of gypsum rock, spongy gypsum, horizons with compact powdery-fibrous gypsum. In addition, samples of white, discontinuous thin encrustation on the surface of gypsum soils were included.

Electron micrographs were obtained with an RCA EM4 electron microscope with a beam voltage of 50KV. Exposure times were 1 sec. Copper grids of 300 mesh size were coated with a "formvar film<sup>1</sup>". A small quantity of the sample was placed in a beaker containing distilled water. This suspension was washed through a 60-mesh sieve. The concentration of the suspension was adjusted visually to provide adequate quantities of solids on the copper grids. The suspension was sprayed onto the grid with a nebulizer.

The microforms of gypsum that were observed by the aid of electron microscope are described in the following sections.

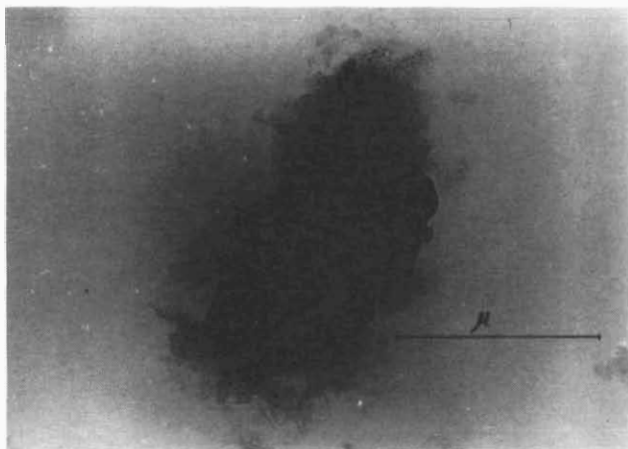
### 2.1. Gypseous rock

A hard, well-crystallized gypseous rock of Tortonian age was collected from Wadi-al-Fayd in Syria. The sample examined shows a dark matrix with irregular borders with an aureola of rounded, equally dark dots. Their dimensions are 0.4 $\mu$ m in diameter near the matrix but reduce gradually to 0.01 $\mu$ m and become clearer as they are further away from the border. Further out they change into a nebulous mass and finally disappear at a distance of 0.2 to 0.6 $\mu$ m from the border. The pieces of matrix are about 1.6 by 0.3-0.7 $\mu$ m in size; the aureola is about 0.2 $\mu$ m thick.

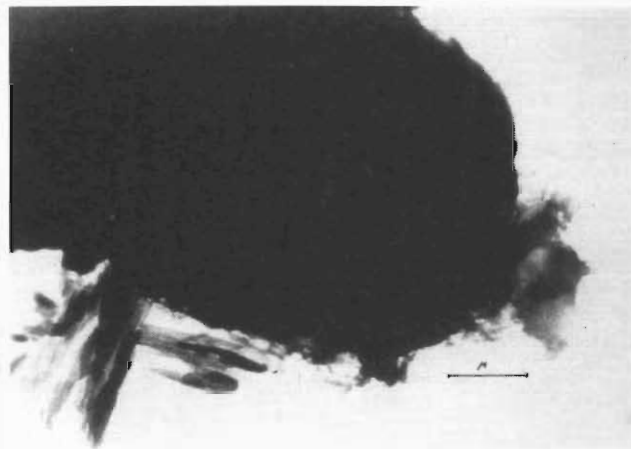
These observations suggest that gypsum alteration begins with the separation of the dark, rounded dots from the matrix. The initial phase consists of a "swelling up" at the border of the matrix, especially in the corners of the crystals. At the terminal stage there is a formation of a clear nebulous mass which gradually thins and disappears with distance. This thinning with distance may be an artifact caused by preparation of the suspension.

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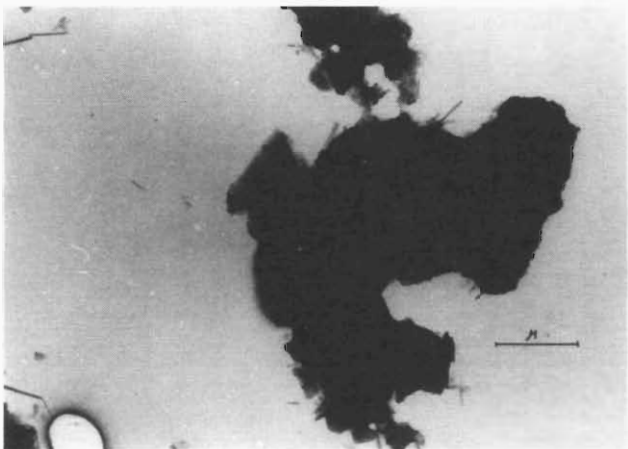
1. We express our appreciation to Mrs. Joanne Salman of the American University of Beyrouth for technical assistance.



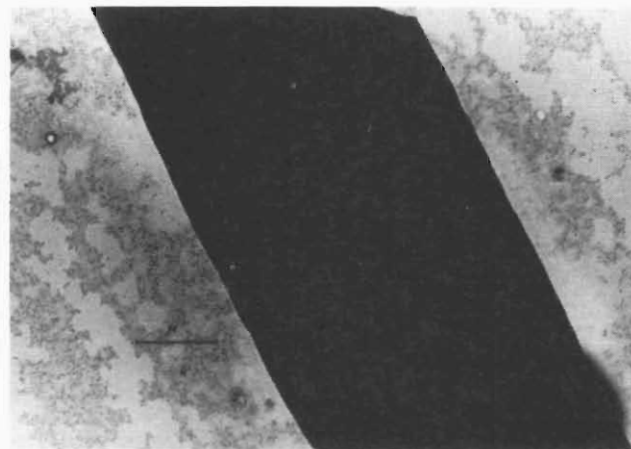
**Fig. 1.**  
Electron micrograph of a hard, well crystallized gypsum rock  
( $1 \mu = 5.22 \text{ cm}$ )



**Fig. 2.**  
Electron micrographs of a gypseous crust of pliocene age  
( $1 \mu = 2.04 \text{ cm}$ )



**Fig. 3.**  
Electron micrograph of a gypseous crust of ancient quaternary  
age ( $1 \mu = 2.04 \text{ cm}$ )



**Fig. 4.**  
Electron micrographs of a gypseous crust of middle quaternary  
age ( $1 \mu = 2.04 \text{ cm}$ )

## 2.2. Gypseous crust

Three kinds of gypseous crust were selected and examined. Material from a gypseous crust generally appears in the form of a dark matrix with clear borders, 5-7 $\mu$ m long and 3-5 $\mu$ m wide. Some attapulgite needles and clouds of 2:1 type clay minerals as well as dark dots of organic matter were also observed.

A sample of Pliocene age with a slightly darker pellicle at the surface of the crust, obtained from Maskane, Syria shows well crystallized gypsum with clear borders and angles, having a small quantity of attapulgite and 2:1 clay minerals; aggregates with part numerous clear spots (0.001 $\mu$ m) of organic matter on their exterior (Fig. 2).

An early Quaternary sample with an irregular alternation of thin, dark and white strips, obtained from Hodna, central Algeria shows less well crystallized gypsum with rounded angles, having more attapulgite and 2:1 clay minerals. The attapulgite needles are 0.2 to 0.6 $\mu$ m long and 0.025 $\mu$ m wide (Fig. 3).

A mid-Quaternary sample with alternation of strips slightly differentiated by colour, obtained from Hodna, central Algeria (polygenic deposit) shows well crystallized gypsum with clearly defined borders, surrounded by a dotted cloud of organic matter (Fig. 4).

Clearly, the degree of crystallization, or the quantity of attapulgite, cannot be associated with age. The dark colour of the pellicles in the crust is due to organic matter.

## 2.3. Powdery-fibrous gypsum

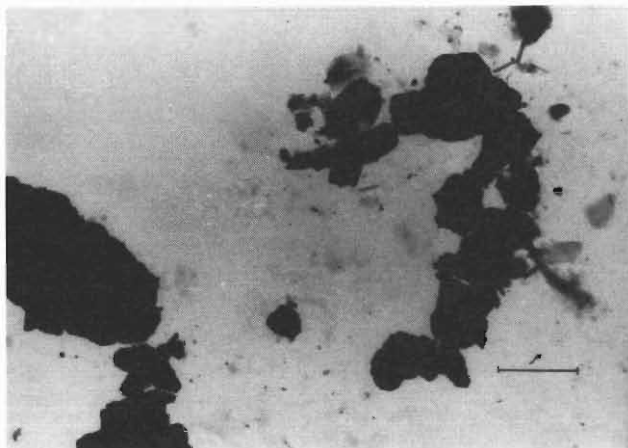
This sample was obtained from Hodna, central Algeria and is of mid-Quaternary age. It is a white compact mass of microcrystalline gypsum, with dark pellicles on the surface of aggregates and galleries filled with clay.

The crystals of powdery-fibrous gypsum are smaller than those of the gypseous crust. One may suppose that as the crystals grow, they become harder and encrustation changes into crust.

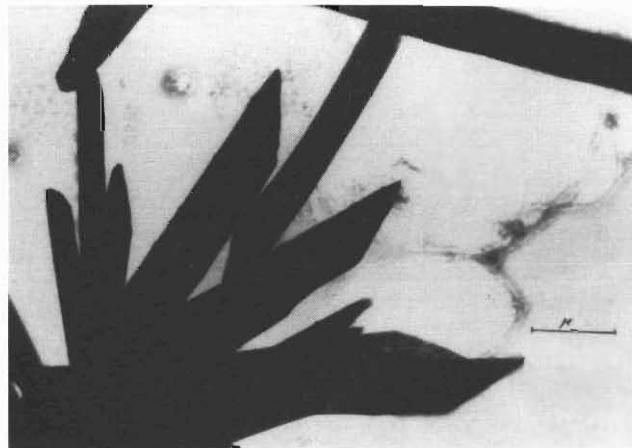
## 2.4. Desert roses

Two samples were selected: a greyish yellow-coloured sample of hard and compact consistency, and with wings 2-3 cm long, from the Algerian Sahara and a sample of the same colour and consistency with wings 0.2 and 0.5 cm long, agglomerated into plates 20 cm in diameter, from Sidi Aissa, Central Algeria.

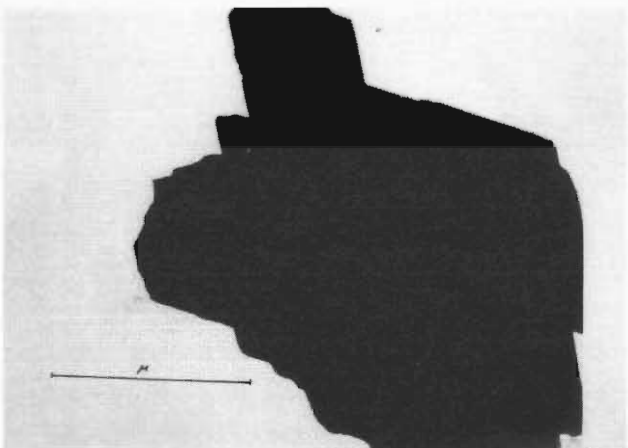
Material from the desert roses with long wings contains long dark crystals with clear boundaries, straight well marked angles, and their macles are "lanceheaded" (Fig. 6). The wings are 1.2 to 4.5 $\mu$ m long and 0.3 to 0.7 $\mu$ m wide. Besides this form there are also rounded stains with wavy borders (amorphous material), associated with 2:1 clay minerals and some attapulgite needles.



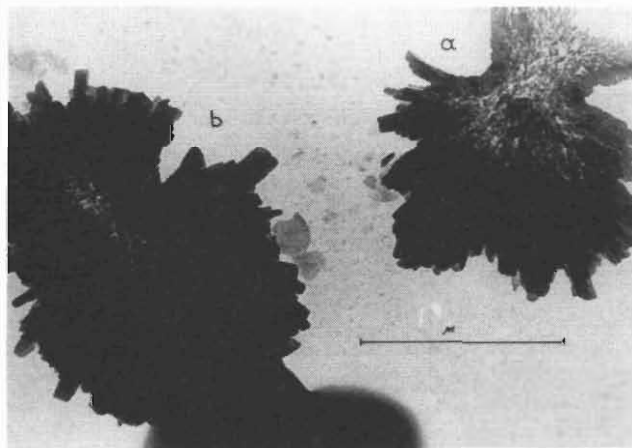
**Fig. 5.**  
Electron micrograph of a powdery-fibrous gypsum middle quaternary age ( $1 \mu = 2.04 \text{ cm}$ )



**Fig. 6.**  
Electron micrograph of roses of desert from the Sahara ( $1 \mu = 2.04 \text{ cm}$ )



**Fig. 7.**  
Electron micrograph of roses of desert from Central Algeria ( $1 \mu = 5.22 \text{ cm}$ )



**Fig. 8.**  
Electron micrograph of secondary gypsum on the periphery of gypsum rock of Tortonian age ( $1 \mu = 5.22 \text{ cm}$ )



The short-winged roses of the desert have more compact crystals (Fig. 7) with less visible macles; the grouped crystals are from 1.6-2.1 to 4.6-5.8 $\mu$ m in size.

When the Sahara samples are compared with those from Central Algeria, it appears that aridity contributes to growth and individualisation of crystals.

### **2.5. Secondary gypsum on the periphery of gypsum rock**

A compact microcrystalline gypsum on the surface of greenish gypseous rock of Tortonian age was collected from the basin of Balikh in Syria.

The gypseous neof ormations look like sand-glasses filled with fine particles (0.02 $\mu$ m). On the border of the central part, the particles concentrate and resemble a necklace (0.1 $\mu$ m thick), whereas towards the extreme periphery this concentration gives way to individualized crystals and to macles. Half of the sand-glass and the crystals of the periphery are 1.0-1.4 $\mu$  in size.

The sample described above shows that the recrystallization of gypsum begins with the concentration of fine particles which form a kind of a necklace in the central part of the sand-glasses and crystals on the extreme periphery. We can suppose that the growing of the crystals is following axis 010.

### **2.6. Spongeous gypsum**

Two samples were examined. One sample, containing agglomerated compact crystals with dark ferromagnesium spots and a cemented clay of mid-Quaternary age was collected from some gravel terraces of the Euphrates near Raqqa, Syria (Fig. 9). Another sample containing agglomerated crystals with wings 0.5 cm in diameter (with clay between the crystals) of mid-Quaternary age was collected from a terrace of Wadi-al-Fayd at Balikh, Syria (Fig. 10).

The electron micrographs plainly show the predominance of attapulgite needles. The crystals are agglomerated, compact, and very irregular where they adjoin the needles. Clay minerals of 2:1 type and probably goethite are also present.

The dimensions of the crystals are as follows:

Compact agglomerated crystals: 3.4-4.5 $\mu$ m

Nebulous spots: 0.65  $\mu$ m in diameter

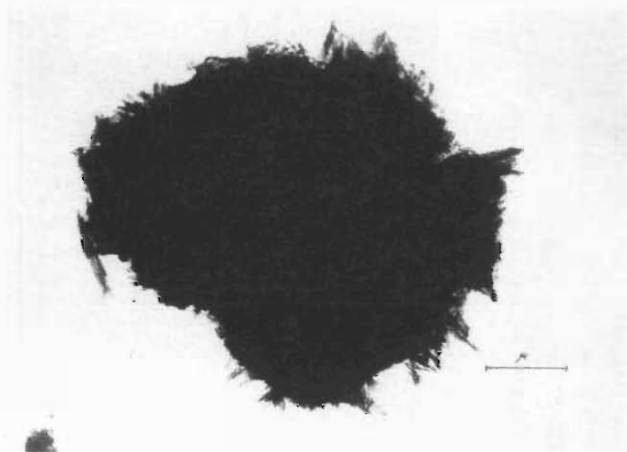
Gypsum crystals in macles: 1.2-2.1 $\mu$ m long

Attapulgite crystals: 1-2 $\mu$ m long

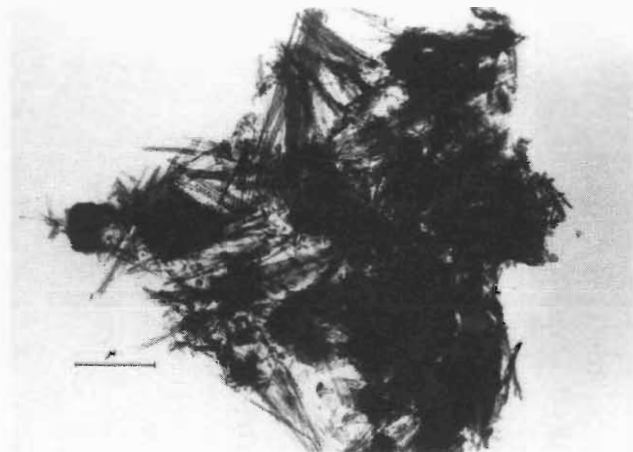
The presence of a great quantity of attapulgite is the most characteristic peculiarity of this gypsum form. One may suppose that the spongeous habitus of gypsum favours the neof ormation of attapulgite.

### **2.7. Horizons with compact powdery-fibrous gypsum**

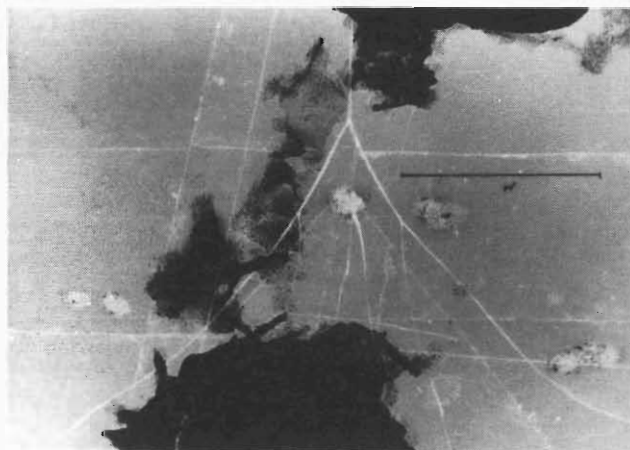
Three samples were selected from the gypseous soil in Wadi-al-Fayd in Syria; the chemical composition of these samples was as follows:



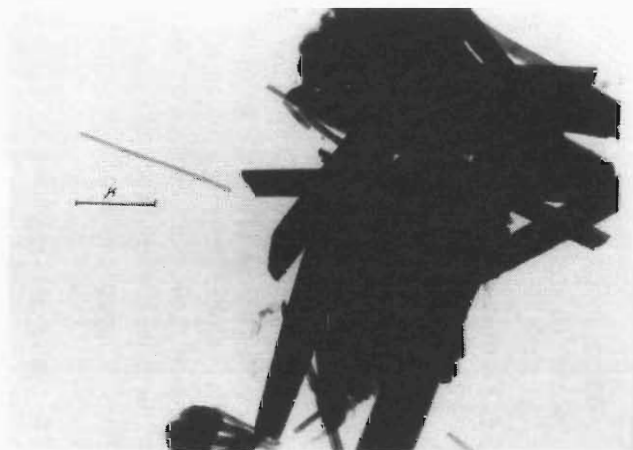
**Fig. 9.**  
Electron micrograph of spongy gypsum ( $1 \mu = 2.04$  cm)



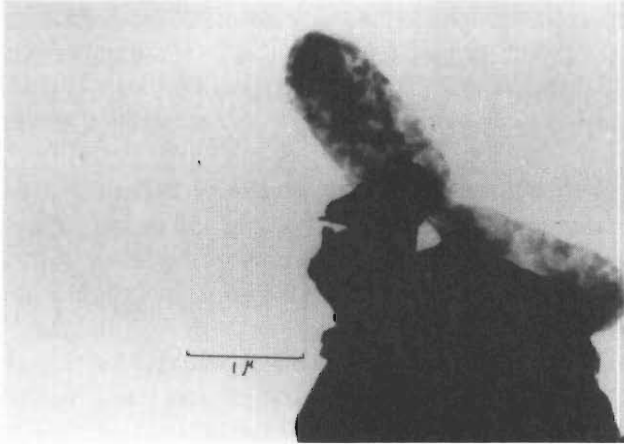
**Fig. 10.**  
Electron micrograph of spongy gypsum ( $1 \mu = 2.04$  cm)



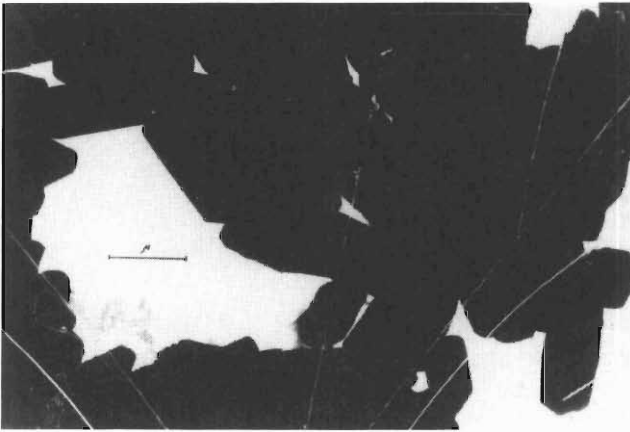
**Fig. 11.**  
Electron micrograph of compact powdery-fibrous gypsum ( $1 \mu = 5.22$  cm)



**Fig. 12.**  
Electron micrograph of powdery-fibrous gypsum ( $1 \mu = 2.04$  cm)



**Fig. 13.**  
Electron micrograph of thin discontinuous encrustation on the surface of gypseous soils ( $1 \mu = 3.06 \text{ cm}$ )



**Fig. 14.**  
Electron micrograph of powdery-fibrous gypsum from Wadi-al-Fayd, Syria

Sample No.	Gypsum %	CaCO <sub>3</sub> %	Organic Matter %	Electrical Conductivity in dS/m (solution 1:1)	pH (H <sub>2</sub> O)
12	70.4	-	0.1	10.5	8.1
11	70.0	2.2	0.3	8.1	8.1
10	31.0	8.8	1.4	3.7	7.8

The electron micrographs show the gypsum in the form of more or less dark spots ( $5\mu\text{m}$ ) with irregular borders (Fig. 11), together with gypseous spangles ( $30\text{-}0.2\mu\text{m}$ ), and/or dark dots. Gypsum crystals (Fig. 12) found in these samples have clear borders with a maximum width of  $0.7\mu\text{m}$ .

### **2.8. Thin discontinuous encrustation on the surface of gypseous soils**

This discontinuous encrustation is a pellicle of 3 to 5 cm in diameter and 1 to 2 mm thick with a concentration of roots in the lower part. In gypseous horizons, gypsum is also found in close contact with the lower part of biological encrustation (lichens).

The electron microscope has revealed organic forms (Fig. 13), crystals with clear, irregular or rounded borders as well as lance-headed crystals in macles and some needles of attapulgite.

## **3. DISCUSSION**

The gypsum microforms, evaluation of gypsum forms and the attapulgite formation are discussed in relation to the morphological forms taking into consideration the processes of gypsum formation and the role of gypsum for hydro-agricultural development.

### **3.1. Gypsum microforms**

By means of the electron microscope, the microforms of gypsum were classified as follows:

- a) "dark dots" having a dimension of  $0.01$  to  $0.04\mu\text{m}$  in diameter (Fig. 1);
- b) "sand-glasses" having a dimension of  $2\mu\text{m}$  in length and  $1.5\mu\text{m}$  in width (Fig. 8);
- c) "nodules" with irregular, rounded outlines,  $0.15\text{-}0.25\mu\text{m}$  to  $5\text{-}6\mu\text{m}$  in size (Fig. 5);
- d) "parallelepipedic crystals" with clear outlines and well-marked  $40^\circ$  angles, generally without macles. The crystals are  $1.5\mu\text{m}$  long and  $0.7\mu\text{m}$  wide (Fig. 4);
- e) "canons" having longer crystals, often with macles. The thinner crystals are  $0.07\mu\text{m}$  wide and  $0.35$  to  $2.0\mu\text{m}$  long, whereas the thicker ones are  $0.7\mu\text{m}$  wide and  $2.5\mu\text{m}$  long (Fig. 6);
- f) "sponges" constituted from masses of nodules  $0.25\text{-}1.8\mu\text{m}$  in diameter and attapulgite needles  $0.02$  to  $2.0\mu\text{m}$  long (Fig. 10).

All of these gypsum microforms can be found in any combination in gypsiferous soils. The most frequent cases refer to crystals composed of canons and nodules.

### 3.2. Evolution of gypsum forms

Dark dots derive from the peripheral weathering of nodules and from the total weathering of thin crystals or long narrow crystals of recent origin. The dots are on the edge of the matrix; as they get further from the matrix, they become smaller and smaller, changing into a nebulous mass and finally will dissolve (Fig. 1).

In cases of recrystallization, the dots assume an elongated shape (0.01-0.6 $\mu$ m) in the narrow part of the sand-glass and then become a kind of necklace or elongated crystal (Fig. 8). The growth of the crystals starts from the outer part of the sand-glass and continues towards its central part. Picture "a" in fig. 8 shows the initial stage of the recrystallization and "b" shows the near terminal stage of this phenomenon. The entire transformation of dots into crystals and the complete filling of the neck of the "sand-glass" mark the formation of a "nodule". "Crystals" and "canons" constitute the terminal stage of the crystallization of gypsum. The "sponges" are gypsosilicate formations (gypsum and attapulгите).

In conclusion, the weathering of gypsum begins in the outer part of the nodules whereas recrystallization takes place within the "sand-glass".

The agglomerated crystals of fluffy, spongy consistency and their microforms associated with attapulгите seem most likely to be carried away by mechanical action of the water.

### 3.3. Attapulгите formation in relation to gypsum

Some authors (Barzanji, 1973, Belouan, 1971 and Nettleton, 1991) consider that the origin of gypsum is connected with the concentration of solutions in gypsiferous soils. Previous study (Boyadgiev, 1973b) on gypsiferous soils did not permit to evaluate separately the role of gypsum or limestone in the formation of attapulгите. The present study, however, suggests a direct relationship between the form of gypsum and attapulгите as follows:

1. Attapulгите is found in large quantities in gypsiferous soils where gypsum has a spongy form. The spongy gypsum is normally found in mid-Quaternary gravelly terraces. Horizons with spongy gypsum forms are generally located below the horizons containing significant amounts of powdery fibrous gypsum. The spongy gypsum is produced under conditions of periodic wetting and drying, which would favour the neoformation of attapulгите from the solutions found in the gypseous medium.
2. Attapulгите found in the discontinuous encrustation on the surface of gypsiferous soils showed a biological activity (lichen) which contributes to the neoformation of attapulгите.
3. Attapulгите found in the gypseous crust of the soil can be considered as residual.
4. Wind blown materials of loess size from desert areas may bring attapulгите into top soils where it would not have formed under the local conditions.

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## VARIABILITÉ SPATIALE DES PROPRIÉTÉS PHYSICO-CHIMIQUES D'UN CHAMP AFFECTÉ PAR LA SALINITÉ DANS LE NORD-OUEST DU MEXIQUE

O. A. CÁMARA D.  
D. CLUIS

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### *Abstract*

A spatial variability study was carried out on a 50 ha experimental field, highly affected, by salinity, in North-Western Mexico. Both physical and chemical characteristics: clay, sand and silt content, hydraulic conductivity at saturation (Ks), saturation percentage, PH, electrical conductivity (CE) and ion concentration ( $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ), were measured, and their variability was analysed by classical statistical methods and geostatistics. The sampling design, for most variables, was established from 50 observation points according to a 100 m square grid (500 x 1000 m). The samples were drawn from the first 0,25 m of soil, except for Ks which was determined in situ at variable depths. The property with the lowest variability was pH (CV=7%), while  $\text{Na}^+$  ion showed the highest variability (CV=81%). The probability distributions for soil texture, pH and CE were recognized as normal at a significance level of 5%. The spatially structured variables are soil textural composition, pH, CE and Ks, while the variables describing the chemical composition of the soil didn't show any spatial structures for the selected sampling step. When independent samples are necessary, the minimum distance between two samples should be 500 m for textural composition, 300 m for Ks and 350 m for pH and CE. Kriging was used as a cartographic interpolation method to predict values of these variables.

### *Key-words*

Spatial variability, Geostatistics, Soil texture, Salinity, Hydraulic conductivity.

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## 1. INTRODUCTION

L'irrigation pratiquée dans la vallée du Fleuve Yaqui dépend de la disponibilité des eaux de surface (stockée dans des barrages) et souterraines (pompées dans la vallée). Ces eaux constituent l'un des facteurs déterminants pour l'intensification des cultures, l'extension des surfaces cultivées et la mise en valeur des surfaces affectées par la salinité et l'alcalinité. Dans un rapport récent (Cámara, 1991), il a été établi qu'environ 10 pour cent des 229000 ha de terres cultivables et irriguées, sont atteints par des problèmes de salinité. Les facteurs les plus importants qui sont à l'origine de cette salinisation des sols sont l'aridité du climat, la géomorphologie, la topographie et l'hydrologie du terrain, les caractéristiques physico-chimiques du sol et les modes de gestion des sols et des eaux. Ces problèmes sont d'autant plus fréquents et intenses que l'on s'approche de la côte puisque la mer a une influence directe ou indirecte sur la salinité des sols et de l'eau souterraine. L'irrigation peut aussi provoquer une salinisation secondaire lorsque la nappe phréatique monte au-dessus d'un seuil minimum, ou que l'on a utilisé, à tort, une eau salée. Cependant, dans des cas où les sols sont fortement affectés et inutilisables pour l'agriculture traditionnelle, le lessivage de l'excès des sels solubles du profil du sol peut être envisagé par une application de fortes doses d'eau douce ou usée et par la mise en place d'un réseau de drainage souterrain.

Pour être utilisées efficacement, ces techniques d'aménagement nécessitent cependant une bonne connaissance de la variabilité spatiale des descripteurs physico-chimiques des sols concernés (Carter et Pearen, 1985; Chang et al., 1988). L'analyse de ces descripteurs est sujette à deux types d'erreur: les erreurs d'échantillonnage et les erreurs de mesure. Le problème d'échantillonnage associé à l'apparition de la salinité a été constaté depuis longtemps par Kelley (1922), mais Sayegh et al. (1958) ont été les premiers à aborder le problème en lui appliquant un traitement statistique. Le nombre d'échantillons nécessaire pour estimer la concentration totale en sels d'une surface particulière, a été traditionnellement calculé en utilisant le théorème de la limite centrale. Cependant, un problème se pose en utilisant cette approche sur des petites surfaces. En effet, un très grand nombre d'échantillons est requis lorsque les descripteurs présentent une grande variabilité. Or, l'indépendance des observations est une prémisse à l'utilisation des statistiques paramétriques (Snedecor et Cochran, 1967). Cette hypothèse est souvent compromise car les observations, par leur nombre et leur proximité, présentent de l'autocorrélation. En fait, ces descripteurs sont des variables régionalisées dont les valeurs dépendent de l'endroit étudié. L'étude et la caractérisation de leurs structures spatiales requièrent l'utilisation d'outils statistiques plus complexes tels que le semi-variogramme ou le corrélogramme (Gascuel-Odoux, 1987). Depuis une vingtaine d'années, l'étude de



la variabilité spatiale des descripteurs physico-chimiques et hydrodynamiques du sol s'est développée de manière considérable (Webster, 1985).

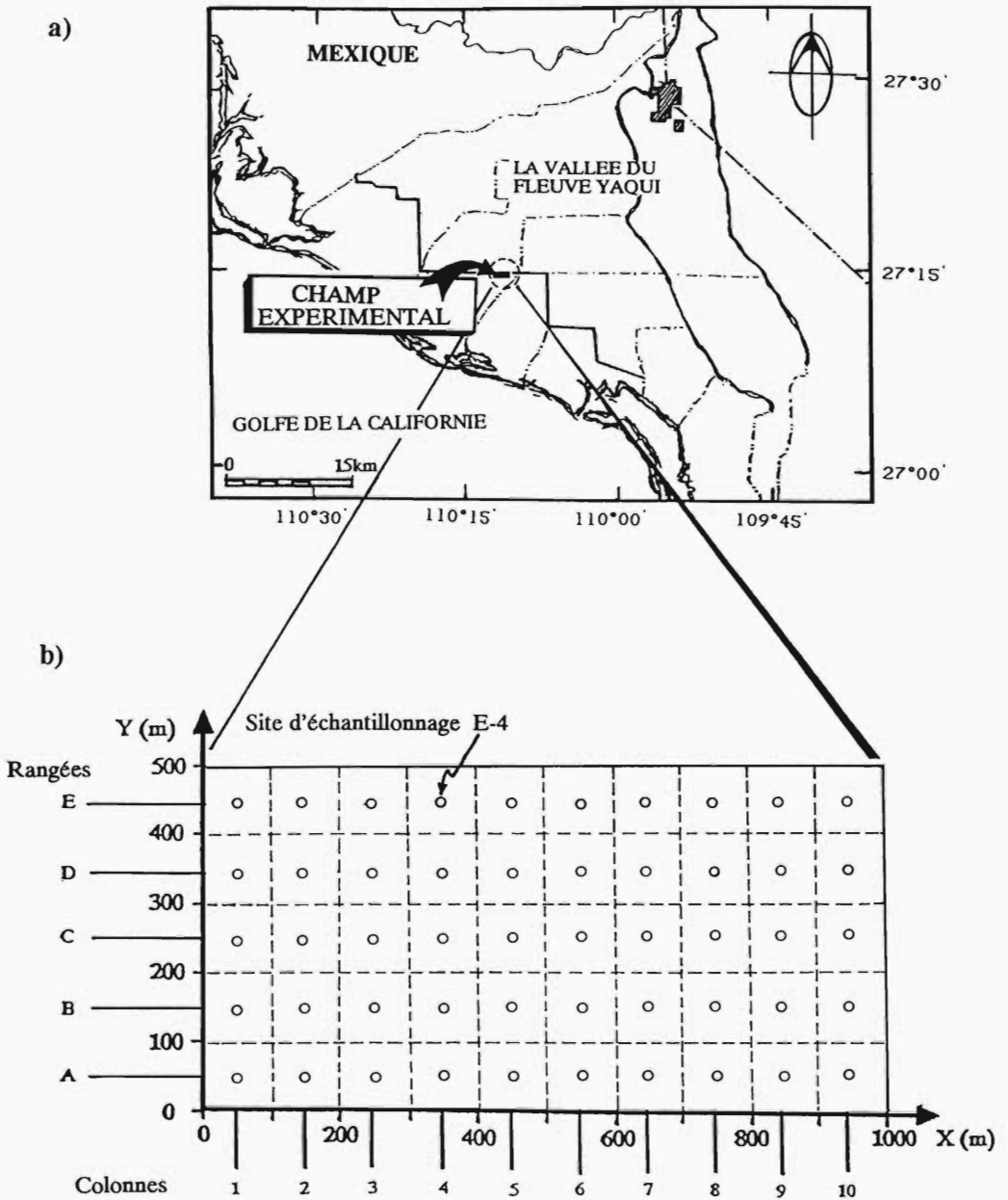
Il est important de caractériser la variation spatiale de quelques descripteurs physico-chimiques des sols salins, avant d'entreprendre toute action que vise à l'amélioration de ces sols. La présente étude considère la variabilité spatiale initiale de quelques descripteurs physico-chimiques d'un nouveau champ expérimental (non cultivé) situé dans la région semi-aride du Nord-Ouest du Mexique, qui sera ouvert pour la recherche sur les pratiques agricoles des sols marginaux et sur la réutilisation des eaux usées agricoles et urbaines. L'objectif de cette étude est donc d'analyser la variabilité spatiale des contenus en sable, limon et argile, la conductivité hydraulique à saturation, le pH, la conductivité électrique et les ions majeurs dissous dans le sol (i) par les méthodes statistiques classiques et, (ii) par les méthodes géostatistiques.

## 2. MATÉRIEL ET MÉTHODES

### 2.1. Site d'étude

Le champ étudié, d'une superficie de 50 ha, fait partie d'une nouvelle ferme expérimentale l'Institut Technologique du Sonora. Il est situé dans la Vallée du Fleuve Yaqui (Fig.1). Le climat dominant dans la région est modérément chaud et sec, avec un hiver doux et une humidité déficiente durant l'été et l'hiver. La température moyenne annuelle est de 22,8°C (1969-1983), avec une moyenne mensuelle maximale de 38,6°C en août et minimale de 5,3°C en janvier. La précipitation moyenne annuelle est de 263 mm (1969-1983) dont 68,3% tombe durant l'été (juillet - septembre). L'évaporation moyenne annuelle (mesurée avec des bacs classe A) est de 1915 mm (1970-1980) avec un maximum de 2090 mm et un minimum de 1800 mm. Le nouveau champ expérimental a été occasionnellement utilisé, avant d'être acquis, en pâturage non intensif. Il était constitué de terres vierges dont les espèces végétales étaient très tolérantes à la salinité ou halophiles (e.g. *Salsola sp.*, *Atriplex sp.*, *Tamarix sp.*, *Amaranthus sp.*, *Salicornia sp.*).

Une étude préliminaire visant à déterminer quelques descripteurs physico-chimiques du site a été effectuée en juillet 1986. La nappe phréatique se trouvait alors à une profondeur variant de 1 à 1,4 m en raison d'un problème de drainage. Le sol salin du champ expérimental est un Solonchak actif à magnésium et à sodium, selon le système de classification Russe (Szabolcs, 1989). L'excès de sels solubles dans l'eau (chlorures et sulfates de Na, K, Mg et Ca) est dû aux apports provenant de l'eau ascendante de la nappe qui varie entre 0,5 et 3 m durant l'année. Ces sols n'ont subi aucun lessivage artificiel ou entraînement de sels en profondeur et ne présentent pas de morphologie différenciée avec une succession caractéristique d'horizons. C'est aussi un



**Figure 1.**

a) Localisation du champ expérimental étudié dans la vallée du fleuve Yaqui dans le Nord-ouest du Mexique, b) Dispositif adopté pour l'échantillonnage du champ

**Tableau 1.**

Descripteurs physico-chimiques d'un profil représentatif (site E-4) du champ expérimental

Descripteur	Profondeur (m)					
	1 0-0.36	2 0.36-0.96	3 0.96-1.27	4 1.27-1.43	5 1.43-2.22	6 2.22-3.00
Composition texturale (%)						
Argile	11.3	23.4	21.6	60.1	34.5	20.7
Sable	34.4	32.4	18.3	4.4	12.2	64.8
Limon	54.3	44.2	60.1	35.5	53.5	14.5
Classification texturale <sup>z</sup>	Loam limoneux	Loam	Loam limoneux	Argile lourde	Loam limono-argileux	Loam sablo-argileux
Cations (cmol L <sup>-1</sup> )						
Ca <sup>2+</sup>	46	20	20	13	10	8
Mg <sup>2+</sup>	22	15	10	8	11	12
Na <sup>+</sup>	50	39	25	15	22	77
K <sup>+</sup>	0.4	0.3	0.20	0.1	0.1	0.2
Anions (cmol L <sup>-1</sup> )						
HCO <sub>3</sub> <sup>-</sup>	0.04	0.03	0.03	0.04	0.03	0.04
SO <sub>4</sub> <sup>2-</sup>	1	0.9	0.8	1	1.5	0.5
Cl <sup>-</sup>	300	177	155	92	12	13
pH(1:1 H <sub>2</sub> O)	6.9	7.1	7.1	7.1	7.4	7.4
CE <sup>y</sup> (dS m <sup>-1</sup> )	135	110	90	50	70	88
SAR <sup>x</sup> (mmol L <sup>-1</sup> ) <sup>0,5</sup>	19	21	14	10	17	54
Degré de salinité <sup>w</sup>	Extrêmement affecté	Extrêmement affecté	Très fortement affecté	Fortement affecté	Très fortement affecté	Très fortement affecté

z D'après Soil Survey Staff (1975)

y Conductivité électrique de l'extrait de la pâte de terre saturée (CE).

x Taux d'adsorption de sodium  $SAR = Na^+ / \sqrt{(Ca^{2+} + Mg^{2+})/2}$

w D'après Peña (1979)

Solontchak pauvre en matière organique du fait du peu d'abondance de la végétation.

Un profil caractéristique (E-4) de ces sols, ainsi que sa classification texturale et son degré de salinité sont montrés au Tableau 1. La variabilité texturale en profondeur est importante, bien que le limon soit en général plus abondant. Les sols contiennent une quantité très grande de Cl<sup>-</sup> et Na<sup>+</sup>. Les sels se présentent sous une forme hygroscopique et les sols ont une coloration foncée. La CE semble diminuer en profondeur, indiquant que le mouvement

ascendant capillaire des sels est favorisé par la faible profondeur de la nappe et par la forte évaporation de beaucoup supérieure à la précipitation. La classification du degré de salinité de ce même profil de sol varie d'extrêmement à fortement affecté (Peña, 1979).

## 2.2. Dispositif d'échantillonnage

Le dispositif d'échantillonnage est illustré à la Fig. 1. La localisation des 50 points d'observation a été établie selon un quadrillage régulier de 100 m de maille. Les profils de sol ont été observés sur une profondeur de 3 m à l'aide d'une tarière de type hollandaise (diamètre 0,12 m). La couche superficielle du sol a toujours été prélevée selon une épaisseur constante de 0,25 m. Les puits ont aussi été utilisés pour la détermination "in situ" de la conductivité hydraulique à saturation ( $K_s$ ), par la méthode du trou à la tarière et en appliquant les formules empiriques développées par Ernst (1950). La profondeur de la nappe phréatique minimale et maximale des puits ont varié entre 0,8 et 1,70 m respectivement, lorsque la détermination de la  $K_s$  a été effectuée 24 h après avoir fait les forages, cela afin de permettre à la nappe phréatique de retrouver son niveau stable.

## 2.3. Méthodes de Laboratoire

Les échantillons de sols ont été séchés à l'air, passés au tamis de 2 mm et analysés. La détermination de la composition granulométrique (limon, sable et argile) des échantillons a été effectuée par la méthode de l'hydromètre (Day, 1965). Le pH a été mesuré dans l'eau avec une suspension 1:1 ( $H_2O$ -pH). De plus, l'extrait d'eau a été utilisé pour mesurer la conductivité électrique (CE), le taux d'adsorption de sodium (SAR) ainsi que les contenus en  $HCO_3^-$ ,  $SO_4^{2-}$ ,  $Cl^-$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ , et  $K^+$  (Richards, 1954). Le pH et la CE ont été mesurés pour tous les échantillons. Les autres analyses chimiques n'ont été faites que sur la moitié d'entre eux (25) en raison de leur grand nombre. Ces échantillons correspondent donc à un quadrillage régulier de 200 m de maille.

## 2.4. Méthodes statistiques

**La statistique classique.** Les données ont été analysées selon les techniques statistiques classiques de l'analyse exploratoire (Snedecor et Cochran, 1967) telles que le calcul de la moyenne, de l'écart-type, du coefficient de variation et des lois de distribution. Ces calculs ont été utilisés pour appuyer l'interprétation des variables compte tenu de la corrélation et localisation relative des échantillons.

Quant à la théorie géostatistique et son application dans les sciences du sol, elle a été présentée en détail par Webster (1985) et Warrick et al. (1986); nous n'en donnons ici qu'une brève description.

**Le semi-variogramme.** La structure spatiale des descripteurs du sol peut

être étudiée et modélisée à partir du semi-variogramme. Celui-ci est une fonction qui quantifie la corrélation spatiale entre les données. Le taux de corrélation entre deux variables aléatoires,  $Z(x)$  et  $Z(x+h)$  séparées dans l'espace par un vecteur de distance  $h$ , dépend de la nature du phénomène étudié. De façon générale, la valeur prise par le semi-variogramme augmente avec la distance  $h$  qui sépare les deux variables. Elle peut aussi varier selon la direction du vecteur. En termes probabilistes, on définit le semi-variogramme comme étant la moitié de l'espérance du carré des écarts entre des valeurs distantes du vecteur  $h$ .

$$\gamma(h) = \frac{1}{2} E\{[Z(x) - Z(x+h)]^2\} \quad (1)$$

Pour assurer l'évaluation du semi-variogramme, on fait l'hypothèse de stationnarité intrinsèque d'ordre 2 pour  $Z(x)$  limitée à l'incrément de  $[Z(x) - Z(x+h)]$ . Dans ce cas, le semi-variogramme existe et dépend uniquement du vecteur  $h$  et non plus de la localisation des points expérimentaux  $x_i$ . On peut ensuite calculer un estimateur de  $\gamma(h)$ , c'est à dire le semi-variogramme expérimental  $\hat{\gamma}(h)$  défini comme la moyenne arithmétique.

$$\hat{\gamma}(h) = \left[ \frac{1}{2n(h)} \right] \sum_{i=1}^{n(h)} [z(x_i) - z(x_i + h)]^2 \quad (2)$$

où  $n(h)$  est le nombre de paires de valeurs  $[z(x_i) - z(x_i + h)]$ . Dans une première étape, l'analyse structurale cherche à définir quelques caractéristiques du semi-variogramme, notamment son comportement à l'origine et à l'infini. Souvent,  $\hat{\gamma}(h)$  apparaît comme une ligne brisée qui atteint un palier ( $C_1$ ) après une distance appelée portée ( $a$ ). Cette portée est la distance au-delà de laquelle les valeurs de deux mesures ne sont plus corrélées; elle quantifie le concept intuitif de la zone d'influence de la fonction aléatoire  $Z(x)$ . L'ampleur du palier correspond à la variance des valeurs utilisées pour calculer le semi-variogramme. On doit noter toutefois que, pour certains variables régionalisées, ce palier peut ne pas exister. A l'origine, il se peut qu'on observe une discontinuité appelée effet de pépité ( $C_0$ ), dans la pratique, la plupart des descripteurs pédologiques présentent cette effet. Ceci peut être dû, soit aux erreurs dans les valeurs de mesure, soit à diverses causes qui se manifestent à des échelles différentes selon l'intervalle d'échantillonnage (Goovaerts et al., 1989).

Une fois que le semi-variogramme expérimental a été calculé, on procède à effectuer la seconde étape qui consiste à l'ajuster à l'aide de fonctions mathématiques "définies positives", de façon à ne pas engendrer de variances d'estimation négatives lors du krigeage. Ici, quatre modèles ont été étudiés,

soit les modèles exponentiel, gaussien, sphérique et linéaire (McBratney et Webster, 1986).

Les modèles doivent respecter les deux conditions suivantes: 1)  $\gamma(h)$  doit être une fonction définie positive, et 2)  $\gamma(h)/h^2$  doit tendre vers 0 lorsque  $h$  tend vers l'infini. En absence de palier, le modèle linéaire est fréquemment utilisé. Le semi-variogramme plat est caractéristique des phénomènes aléatoires purs où il n'existe aucune corrélation entre deux observations aussi rapprochées soient-elles. En général l'estimation est faite à partir d'un petit nombre de points voisins. On recherche alors un ajustement du modèle au semi-variogramme sur une distance  $h$  limitée. On parle alors d'estimation locale, à partir d'un voisinage glissant. Lorsque l'inférence du semi-variogramme est réalisée, on envisage le problème de l'estimation par krigeage.

**Le Krigeage.** Le krigeage fait partie de la géostatistique qui, elle même, est une application de la théorie des processus stochastiques aux phénomènes naturels. Le krigeage est une technique d'estimation d'un phénomène connu en un certain nombre de points et a en particulier l'avantage, parmi d'autres techniques d'interpolation, d'utiliser la structure spatiale du descripteur pour l'estimation (Delhomme, 1978). Il s'adapte donc bien aux phénomènes régionalisés. La méthode présente trois caractéristiques: 1) elle est linéaire, c'est-à-dire que l'estimation de  $Z$  en  $x_0$  est une combinaison linéaire des valeurs expérimentales  $z_i$  aux points  $x_i$ ; 2) elle est non biaisée, c'est un choix selon lequel l'erreur moyenne doit être nulle, et 3) elle prend en compte une condition optimisée, minimisant la variance de l'écart entre  $Z$  et son estimation. Ces caractéristiques conduisent à des équations qui sont développées à l'aide du modèle ajusté au semi-variogramme. Elles permettent de calculer l'estimation de  $Z$  en tout point  $x_0$  et son écart-type d'estimation.

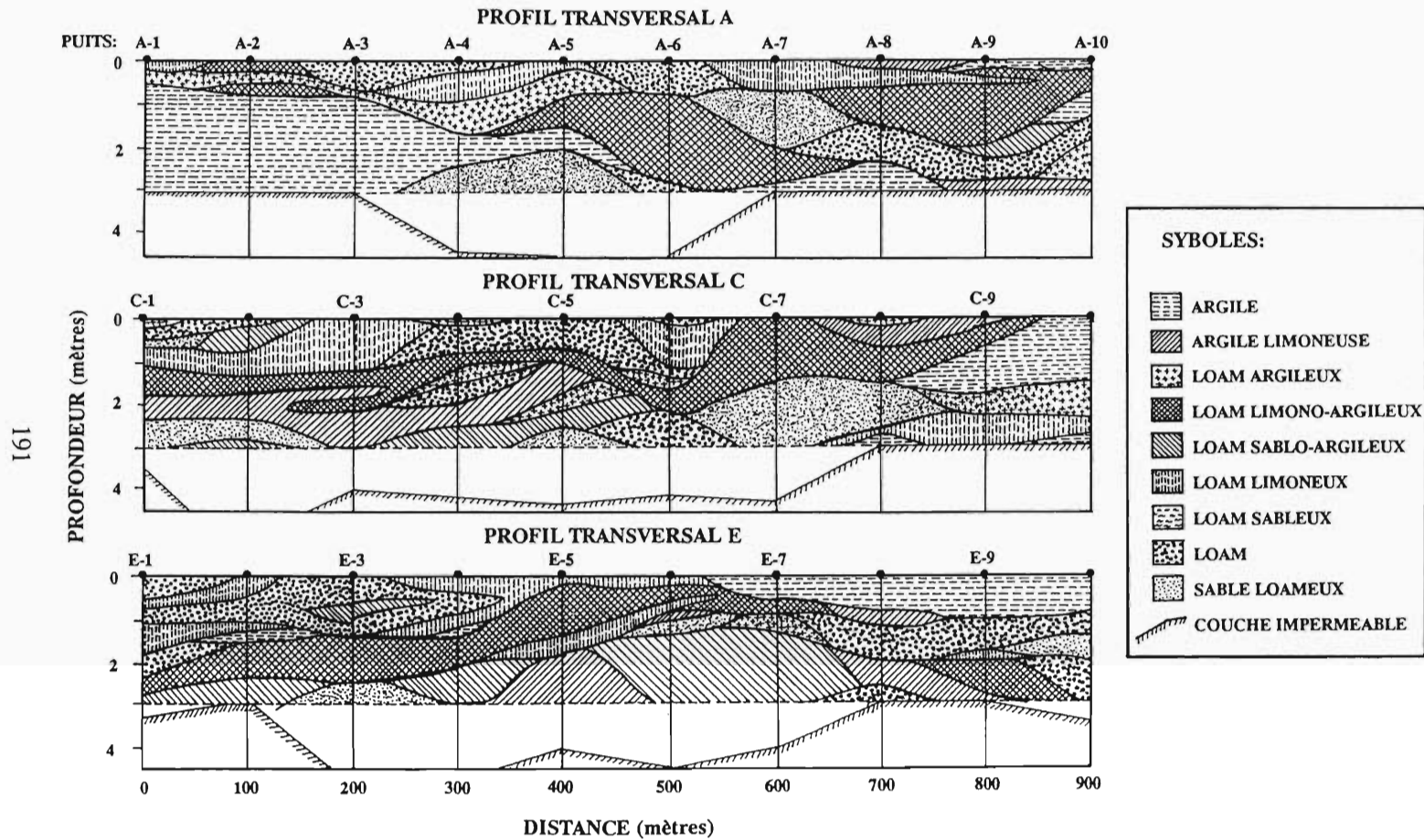
## 2.5. Logiciels utilisés

Les statistiques classiques ont été calculées à l'aide du logiciel **Statgraphics** (Statistical Graphics Corporation, 1988). L'analyse de la structure spatiale des propriétés physico-chimiques telles que les semi-variogrammes expérimentaux et l'ajustement des modèles théoriques correspondants, ainsi que le krigeage, ont été réalisés à l'aide du logiciel **Geo-EAS** (Englund et Sparks, 1988).

## 3. RÉSULTATS ET DISCUSSION

### 3.1. Statistique classique

Le Tableau 2 présente, pour les différents descripteurs physico-chimiques étudiés, la moyenne, les valeurs maximale et minimale observées, l'écart type ( $s$ ), le coefficient de variation (CV) ainsi que les coefficients d'asymétrie ( $g_1$ )



**Figure 2.**  
Variation de la texture du sol de le long de trois transects d'échantillonnage

**Tableau 2.**

Statistiques paramétrique de quelques descripteurs physico-chimiques de la couche de surface (0-0,25 m) des sols du champ étudié

Descripteurs	n <sup>z</sup>	Moyenne	Minimum	Maximum	CV <sup>y</sup> (%)	g1 <sup>x</sup>	g2 <sup>w</sup>
<i>Propriétés physiques</i>							
Argile (%)	50	33	11	65	49	0.6	3.0
Sable (%)	50	22	1	42	55	-0.1	2.8
Limon (%)	50	44	22	68	25	0.4	2.2
Log Ks (cm j <sup>-1</sup> )	50	2.6	-0.4	2.9	28	-0.5	3.1
Teneur en eau à saturation (%)	50	42	18	66	29	0.7	2.4
<i>Propriétés chimiques</i>							
pH (unités pH)	50	7.2	6.5	8.2	7	0.4	2.9
Ca <sup>2+</sup> (cmol L <sup>-1</sup> )	25	17	2	48	77	0.7	2.7
Mg <sup>2+</sup> (cmol L <sup>-1</sup> )	25	18	0.6	40	77	0.3	1.6
Na <sup>+</sup> (cmol L <sup>-1</sup> )	25	106	2.8	293	81	0.9	2.7
K <sup>+</sup> (cmol L <sup>-1</sup> )	25	0.2	<0.1	0.8	73	1.4	4.7
HCO <sub>3</sub> <sup>-</sup> (cmol L <sup>-1</sup> )	25	0.2	0.2	0.6	96	1.8	5.4
SO <sub>4</sub> <sup>2-</sup> (cmol L <sup>-1</sup> )	25	6	1	20	95	1.1	2.8
Cl <sup>-</sup> (cmol L <sup>-1</sup> )	25	205	14	471	76	0.2	1.5
<i>Salinité</i>							
CE (dS m <sup>-1</sup> )	50	97	10	180	59	-0.3	2.5
<i>Sodicité</i>							
SAR (mmol L <sup>-1</sup> ) <sup>0.5</sup>	25	56	5	132	59	0.6	2.6

z Nombre de points d'échantillonnage.

y Coefficient de variation.

x Coefficient d'asymétrie.

w Coefficient d'aplatissement.

et d'aplatissement (g<sub>2</sub>) des 50 ou 25 échantillons du champ expérimental. Les CV obtenus sont de 49% pour l'argile, 55% pour le sable et 25% pour le limon. Ces résultats indiquent une variabilité qui, bien qu'importante, demeure dans la gamme normale de variabilité observée pour les descripteurs d'état (Vauclin, 1982). L'examen de trois transects (A, C et E) confirme la grande variabilité spatiale de la texture (Fig. 2). Ces constatations sont d'ailleurs caractéristiques de la plupart des sols affectés par les sels (Samra et Singh, 1990). Malgré les variations de la texture, on peut la considérer en termes globaux dans une granulométrie moyenne (limoneuse). Le CV pour la conductivité hydraulique à saturation (log Ks) est de 28%. D'autres travaux ont rapporté des valeurs de CV supérieures (65 à 190%) à celles obtenues dans cette étude (Gumaa, 1978; Russo et Bresler, 1981). La faible variabilité

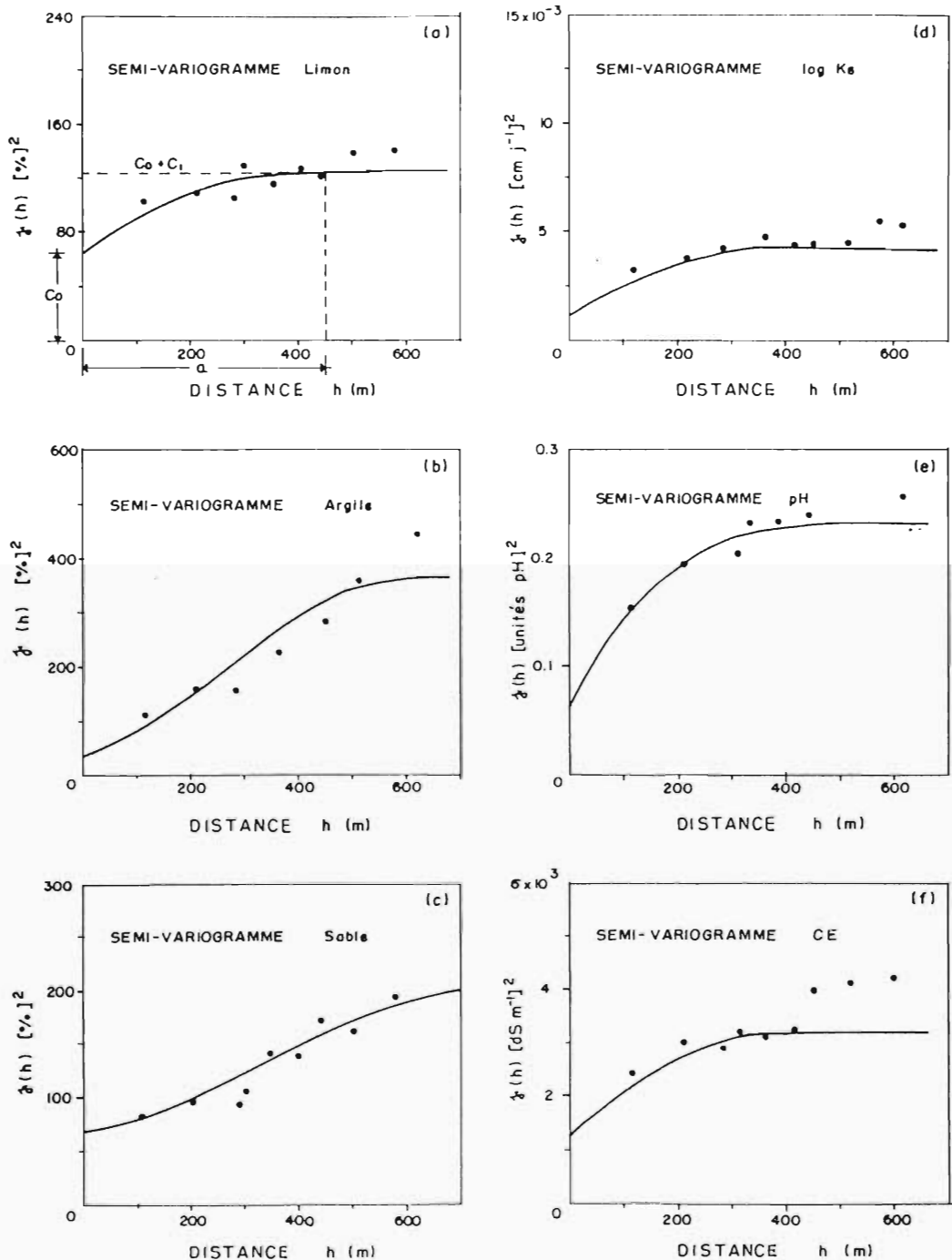


du pH (CV = 7%) est comparable aux résultats obtenus dans d'autres études (Gajem et al., 1981; Goovaerts et al., 1989). Le fait que le pH soit une mesure logarithmique explique partiellement sa valeur de CV inférieure à celle des autres descripteurs étudiés. Quant à la concentration chimique en sels solubles, elle est nettement plus variable que les descripteurs physiques. Ainsi, les CV varient de 73% pour le  $K^+$  et 96% pour le  $HCO_3^-$ . Les résultats de la concentration de l'ion  $Na^+$  mettent en évidence une dispersion considérable ( $3-293 \text{ cmol L}^{-1}$ ), ce qui se traduit par un CV de 81%, typique des sols affectés par la salinité (Moolman, 1989). Sur ces mêmes descripteurs, Vauclin (1982) mentionne que des CV supérieurs à 300% ne sont pas rares. La conductivité électrique (CE) présente un CV de 59%, ce qui est relativement faible si on la compare à la forte variabilité (CV=112-163%) rapportée dans des travaux similaires (Hajrasuliha et al., 1980; Wagenet et Jurinak, 1978).

Le coefficient de variation a été utilisé précédemment pour quantifier la variabilité spatiale des descripteurs physico-chimiques du sol. Cependant, il ne rend pas complètement compte de la nature de la loi de distribution des mesures dont la connaissance est indispensable lorsqu'on désire appliquer les techniques géostatistiques, puisque les semi-variogrammes sont théoriquement calculés pour des variables normalement distribuées. Les coefficients d'asymétrie ( $g_1$ ) et d'aplatissement ( $g_2$ ) des descripteurs mesurés sont présentés au Tableau 2. Ces résultats sont utilisés pour comparaison avec la distribution normale, pour laquelle  $g_1=0$  et  $g_2=3$ . On n'a pas cependant voulu, dans cette étude, rechercher des fonctions théoriques de distribution plus adaptées aux variables étudiées. On a plutôt appliqué des tests de signification sur les différences à 0 pour  $g_1$  et 3 pour  $g_2$ , pour démontrer si l'hypothèse nulle de la loi normale peut être acceptée au seuil de  $\alpha$  et ce, pour l'ensemble des variables (Snedecor et Cochran, 1967). Les données sur les contenus en argile et en limon présentent une asymétrie positive légère et la courbe de distribution est légèrement aplatie par rapport à la distribution normale. Les contenus en sable, limon et argile sont cependant normalement distribués ( $g_1 \approx 0$ ), ce qui avait déjà été constaté dans la littérature (Gumaa, 1978; Van Meirvenne et Hofman, 1989). Les coefficients d'asymétrie et d'aplatissement pour la Ks montrent cependant que la distribution est légèrement biaisée à droite et aux fortes concentrations; cette situation est caractéristique d'une distribution non normale. Dans ce cas, des transformations logarithmiques des valeurs initiales ont été effectuées afin de normaliser ce descripteur, comme l'ont réalisé Nielsen et al. (1973) et Russo (1984) dans leurs travaux respectifs. Le pH et la CE, suivent une distribution normale, tandis que les concentrations en sels solubles suivent des distributions non normales.

### 3.2. Semi-variogrammes

Les descripteurs retenus comme spatialement structurés sont: les contenus en argile, sable et limon, la Ks, le pH et la CE. Le Tableau 3 reprend les



**Figure 3.**

Semi-variogrammes expérimentaux de quelques descripteurs physico-chimiques de la couche de surface (0-0,25 m) du sol: a) argile, b) sable, c) limon, d) conductivité hydraulique à saturation (Ks), e) pH et f) conductivité électrique (CE)

**Tableau 3.**

Modèles théoriques ajustés aux semi-variogrammes expérimentaux de quelques descripteurs physico-chimiques des sols du champ étudié

Descripteur	Modèle <sup>z</sup>	Pépite C <sub>0</sub>	Palier C <sub>1</sub>	100C <sub>0</sub> /(C <sub>0</sub> +C <sub>1</sub> ) (%)	Portée a (m)
Argile (%)	gaussien	40	360	10	700
Sable (%)	gaussien	70	130	35	700
Limon (%)	exponentiel	65	60	52	450
Log Ks (cm j <sup>-1</sup> )	exponentiel	0.0012	0.0030	29	300
pH (unités pH)	exponentiel	0.06	0.17	26	400
CE (dS m <sup>-1</sup> )	exponentiel	1300	1860	42	350

<sup>z</sup> - modèle gaussien avec palier (C<sub>1</sub>) et portée (a):

$$\gamma(h) = C_0 + C_1 \left[ 1 - \exp\left(-\frac{h^2}{r^2}\right) \right]$$

$$\gamma(0) = 0$$

- modèle exponentiel avec palier (C<sub>1</sub>) et portée (≈ 3a)

$$\gamma(h) = C_0 + C_1 \left[ 1 - \exp\left(-\frac{h}{a}\right) \right]$$

$$\gamma(0) = 0$$

principales propriétés des semi-variogrammes représentés à la Fig. 3. Les semi-variogrammes expérimentaux s'ajustent bien jusqu'à des distance entre échantillons variant de 300 à 700 m, selon le descripteur en question. Les courbes obtenues montrent comment l'information acquise en un point se détériore lorsqu'on s'en éloigne. La vérification des hypothèses d'isotropie et de stationnarité locale a été effectuée par l'examen des semi-variogrammes expérimentaux. Dans l'étude de ces cas, on obtient un modèle unique représentatif de la structure spatiale dans les directions nord-sud et est-ouest, cela pour permettre de satisfaire aux hypothèses statistiques. Toutes les caractéristiques des semi-variogrammes (pépite, palier et portée) modélisés ont été ajustées pour donner les plus petits écarts entre le modèle et les points expérimentaux du semi-variogramme. Le pas de distance entre échantillons, utilisé pour l'ajustement des modèles, est la moitié du pas réel (50 m).

La majorité des semi-variogrammes possède un palier (C<sub>0</sub>+C<sub>1</sub>) qui est atteint plus ou moins rapidement et qui correspond généralement à la variance globale de l'échantillon. Ce palier met en évidence l'existence de variances finies, caractéristiques de processus stationnaires du second ordre. Tous les modèles présentent un effet de pépite (C<sub>0</sub>); cet effet correspond, soit à la variabilité qui a lieu à des distances plus petites que l'intervalle d'échantillonnage, soit à l'erreur expérimentale. Dans certains cas, dont le limon et la CE, l'effet de pépite représente plus de 40% de la variabilité totale

( $100 C_0/(C_0+C_1)$ ). Le Tableau 3 montre que la portée (a) varie d'un descripteur à un autre; ainsi la portée la plus basse est de 300 m pour la Ks et la plus grande est de 700 m pour l'argile et le sable. Les observations de la composition chimique ( $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ ,  $K^+$ ,  $HCO_3^-$ ,  $SO_4^{2-}$  et  $Cl^-$ ) n'ont pas présenté de structure spatiale pour le pas d'échantillonnage adopté (200 m). Le pas d'échantillonnage est donc trop grand, allant au-delà de l'échelle du phénomène local et/ou le nombre de points d'observation trop faible.

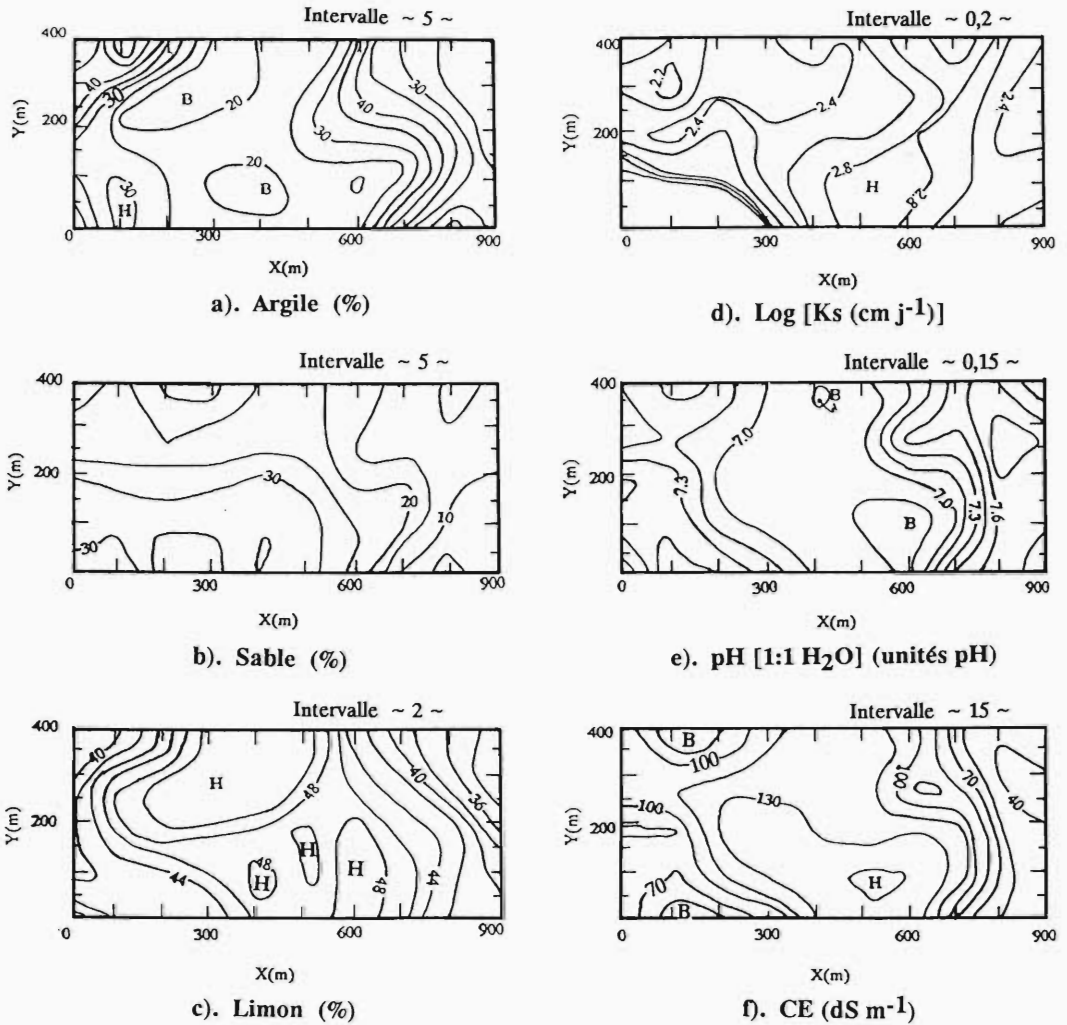
Les Figs. 3a, 3b et 3c présentent les semi-variogrammes de la composition texturale du sol. Les modèles ajustés sont du type gaussien pour l'argile et le sable, et du type exponentiel pour le limon. L'effet de pépité du contenu en argile (10%) est plus faible que celui du contenu en sable (26%), tandis que la portée est la même pour tous les deux ( $a=700$  m). Cela indique qu'à des distances supérieures à 700 m, les observations des deux descripteurs deviennent indépendantes; cependant, l'effet de pépité du contenu du sable montre une sensibilité supérieure aux variations dues à des distances plus petites que celles de l'intervalle d'échantillonnage.

En ce qui concerne le semi-variogramme de  $\log(K_s)$  (Fig. 3d), on remarque notamment que  $\gamma$  croît exponentiellement pour atteindre un palier relativement stable ( $C_0+C_1=0.0042$ ) dont la portée est de 300 m. Cela met en évidence que, à des pas de 300 m ou plus, les observations ne présentent plus d'autocorrélation. Cela devrait être spécialement pris en compte dans l'avenir, lors de l'estimation de la  $K_s$  représentative (moyenne) du champ expérimental, valeur requise pour dans le calcul de l'écartement des drains. Le semi-variogramme de la teneur en eau à saturation n'est pas présenté ici; cependant, il montre une croissance continue caractéristique d'un processus non stationnaire du second ordre.

Le pH présente une structure spatiale dont le semi-variogramme ajusté est de type exponentiel (Fig. 3e). La portée (400 m) et l'effet de pépité (26%) de ce semi-variogramme sont les plus faibles rencontrés parmi les propriétés chimiques. Finalement, pour les mesures de la CE, le semi-variogramme est aussi de type exponentiel et la portée en est de 350 mètres. La structure spatiale de ce descripteur est l'une des plus importantes de tous les descripteurs mesurés, puisqu'elle est indicatrice du degré d'affectation de la salinité dans le champ expérimental.

### 3.3. Krigeage

La corrélation spatiale des descripteurs permet l'application de méthodes d'interpolation par krigeage, conduisant à une cartographie thématique des surfaces. Les cartes ont été préparées en utilisant les modèles des semi-variogrammes et les 50 données localisées sur une maille de 100 par 100 m (Fig. 4). La technique de validation croisée a été utilisée après le krigeage pour vérifier les paramètres des modèles et évaluer ainsi toute la procédure suivie. En général on effectue le krigeage en voisinage glissant, c'est-à-dire à



**Figure 4.**

Isolignes estimées par krigeage de quelques descripteurs physico-chimiques de la couche de surface (0-0,25 m) du sol: a) argile, b) sable, c) limon, d) conductivité hydraulique à saturation (Ks), e) pH et f) conductivité électrique (CE). Les symboles H et B représentent respectivement des valeurs croissantes et décroissantes par rapport à l'isoligne

partir d'un nombre limité de points voisins. L'application de cette technique à l'ensemble des 50 échantillons expérimentaux a démontré que les modèles choisis sont appropriés.

Comme toute méthode d'interpolation, le krigeage implique une erreur. Cependant cette technique à l'avantage de fournir une estimation de la variance de cette erreur. Cette variance, ou sa racine carrée, est une bonne mesure de la précision de l'interpolation obtenue. Puisque les cartes krigées sont basées sur l'élaboration d'un maillage d'estimation, l'un des avantages

**Tableau 4.**

Gamme de variation des valeurs de l'écart-type ( $s_k$ ) et indice de la qualité du krigeage ( $Q_k$ ) pour les 50 points d'échantillonnage du champ expérimental étudié

Variables mesurées	Gamme de variation $s_k$	$Q_k$
Argile (%)	4.58 - 5.46	4.8
Sable (%)	5.09 - 6.12	5.4
Limon (%)	4.82 - 5.50	5.0
Log Ks (cm j <sup>-1</sup> )	0.097 - 0.106	.09
pH (1:1 H <sub>2</sub> O)	0.22 - 0.24	.225
CE (dS m <sup>-1</sup> )	24.73 - 27.67	5.05

de l'application de la géostatistique en cartographie automatisée tient au fait que cette technique permet de comparer plusieurs modèles de semi-vario-grammes. Matheron (1971) a en effet démontré l'équivalence formelle entre les méthodes d'interpolation par splines et le krigeage, ce qui autorise à utiliser le krigeage comme les autres méthodes d'interpolation, c'est-à-dire à construire une fonction d'interpolation au lieu d'effectuer une interpolation ponctuelle sur la maille.

L'écart-type du krigeage,  $s_k$ , a été obtenu pour tous les points d'échantillonnage sur les 50 ha du champ expérimental. La cartographie de ces résultats indique les régions où l'estimation est précise et donne une indication des améliorations possibles du plan actuel d'échantillonnage. Le Tableau 4 présente les valeurs maximales et minimales de  $s_k$ . Cependant, afin d'obtenir un indice unique de la précision du krigeage ( $Q_k$ ) pour tout le champ expérimental, on a effectué une simple moyenne de l'erreur (Stein et al., 1991). L'expression qui définit cet indice est:

$$Q_k = \sqrt{\frac{1}{N} \sum_{i=1}^{j=N} S_k^2} \times 100 \quad (7)$$

De ces résultats se dégage le fait que le pH et le log(Ks) présentent le meilleur indice de précision du krigeage (3 et 6 % respectivement). L'interprétation cartographique de ces descripteurs est donc adéquate. Les variables avec les moins bons indices de précision, sont la CE et le limon (34 et 40%). Cependant, ces valeurs peuvent être considérées à toutes fins pratiques comme acceptables.

Les Figs. 4a, 4b, et 4c montrent les cartes de krigeage obtenues pour la

composition texturale de la première couche de sol (0-0,25 m), ces résultats indiquent clairement une variabilité spatiale continue. La composition granulométrique comprise entre 0-30% en argile représente environ 40% de la surface totale, localisée principalement dans la région centrale du champ. La cartographie de ces descripteurs devrait permettre de mieux gérer le plan d'irrigation et de drainage lorsque la récupération de ces sols sera entreprise.

Le comportement variable des sols salins dont la nappe phréatique est peu profonde, à la différence des sols non affectés, peut poser de sérieux problèmes techniques lorsqu'on veut déplacer le surplus d'humidité et de sels solubles présents dans le profil du sol. Les propriétés physiques, telles que la composition texturale et la conductivité hydraulique à saturation, ainsi que leur distribution spatiale, jouent un rôle important lorsqu'un réseau de drainage efficace doit être mis en place (Rao et Leeds-Harrison, 1991). Les résultats du krigeage de la  $K_s$  (Fig. 4d) permettent de déduire que la presque totalité du champ expérimental montre une capacité de drainage convenable; car plus de 80 pour cent de la surface du terrain présente une valeur de  $K_s$  supérieure à  $3 \text{ m j}^{-1}$  (valeur retransformée). Seules deux petites surfaces localisées à l'extrême nord-ouest et à l'extrême sud-ouest du champ présentent une  $K_s$  très faible, pouvant entraîner des problèmes de saturation prolongée des sols lors de l'application de fortes doses d'eau en vue du lessivage des sels solubles.

La Fig. 4f montre qu'environ 30% de la surface de 50 ha présente une CE supérieure à  $130 \text{ dS m}^{-1}$ . Cette surface est localisée dans la région centrale du champ expérimentale est orienté d'est en ouest. De plus, 80 pour cent de la surface présente des valeurs supérieures à  $100 \text{ dS m}^{-1}$ ; ces résultats confirment clairement la forte concentration en sels solubles et, par conséquent, la forte salinité de ces sols.

#### 4. CONCLUSIONS

L'expérience présentée dans cette étude a permis de mettre en évidence la grande variabilité spatiale de quelques descripteurs physico-chimiques des sols au niveau d'un champ expérimental de 50 ha fortement affecté par la salinité (Solonchak actif), localisé dans le Nord-ouest du Mexique. Des descripteurs mesurés, la composition texturale, la  $K_s$ , le pH et la CE ont été reconnus comme spatialement structurés tandis que la composition chimique ( $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$  et  $\text{K}^+$ ) n'a pas montré de structure spatiale pour le pas d'échantillonnage adopté (200 m). Vauclin et al. (1983) recommandent l'utilisation du co-krigeage entre variables pour améliorer la prédiction du descripteur ayant un nombre limité d'observations; ainsi l'application éventuelle de cette technique pourrait préciser certains éléments non expliqués et réduire les limitations reliées au plan d'expérience dans le cas de

la composition chimique.

L'utilisation des semi-variogrammes démontre que les observations de quelques variables mesurées étaient autocorrélées. Ces résultats permettent de suggérer des recommandations sur la stratégie d'un plan d'échantillonnage futur. Ainsi donc, lorsque des échantillons indépendants s'avèrent nécessaires, ceux-ci pourront être prélevés au moins entre 450 et 700 m pour la composition texturale, tous les 300 m pour la Ks et, finalement tous les 350 m pour le pH et la CE.

La technique de krigeage a été utilisée comme méthode d'interpolation cartographique univariée pour la prédiction des valeurs de la composition texturale (argile, sable et limon), de la Ks, du pH et, de la CE. Les cartes de krigeage obtenues pour la Ks et la CE montrent l'utilité des méthodes géostatistiques. Par exemple, la carte de la CE permet de mieux connaître la distribution et la variabilité spatiale des sels dans le champ expérimental. A partir de ces données, on peut mieux gérer le taux d'application et la distribution de l'irrigation, ainsi que les amendements nécessaires lors de la mise en valeur de ces sols salins. Quant à la carte de la Ks, elle nous permet une meilleure connaissance des zones présentant des problèmes de mobilité de l'eau souterraine, un aspect important lorsque l'on désire implanter le réseau de drainage.

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**SUMMARY**

**SOMMAIRE**

**INHOUD**

**L. Ngongo & R. Langohr**

Classifying strongly weathered soils from the Zairian Basin into the revised international soil classification systems 99

**A. Vermoesen, P. Demeyer, G. Hofman & O. Van Cleemput**

Field measurement of ammonia volatilization upon application of different  $\text{NH}_4^+$ -fertilizers and urea 119

**Tang Huajun & E. Van Ranst**

Quantification of the influence of land characteristics on crop performance using Fuzzy set theory 129

**F. Declercq & J. Poesen**

Evaluation of two models to calculate the soil erodibility factor K 149

**T.G. Boyadgiev & A.H. Sayegh**

Forms and evolution of gypsum in arid soils and soil parent materials 171

**O.A. Cámara D. & D. Cluis**

Variabilité spatiale des propriétés physico-chimiques d'un champ affecté dans le Nord-Ouest du Mexique 183