Ecosystems and agro-biodiversity across small and large-scale maize production systems

CONABIO
COMISIÓN NACIONAL PARA EL
CONOCIMIENTO Y USO DE LA BIODIVERSIDAD

The Economics
of Ecosystems
& Biodiversity

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[1] Some sections of the final version (*i.e*. section 1, 4, 6.1, 6.4, and 7) were not proofread by our editor.

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[2] Considering that there might be competing uses of crop residues, such as fodder or fuel, and that even small amounts of mulch are effective at conserving water under semi-arid conditions, we calculate conservative values of the application of CA with a minimum quantity of mulch (1.5 ton/ha), compared to CT

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0. EXECUTIVE SUMMARY

Efraín Hernández Xolocotzi/CONABIO

0. Executive Summary

1. Introduction

This study is part of a larger effort by The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgFood), from the United Nations Environmental Programme (UNEP), which has been "designed to provide a comprehensive economic evaluation of the 'ecoagri-food systems' complex, and demonstrate that the economic environment in which farmers operate is distorted by significant externalities, both negative and positive, and a lack of awareness of dependency on natural capital". The underlying goal of this study was to improve the understanding among policymakers and key stakeholders about the economic dependencies and interactions between the maize producing sector and ecosystem services, and their value to society.

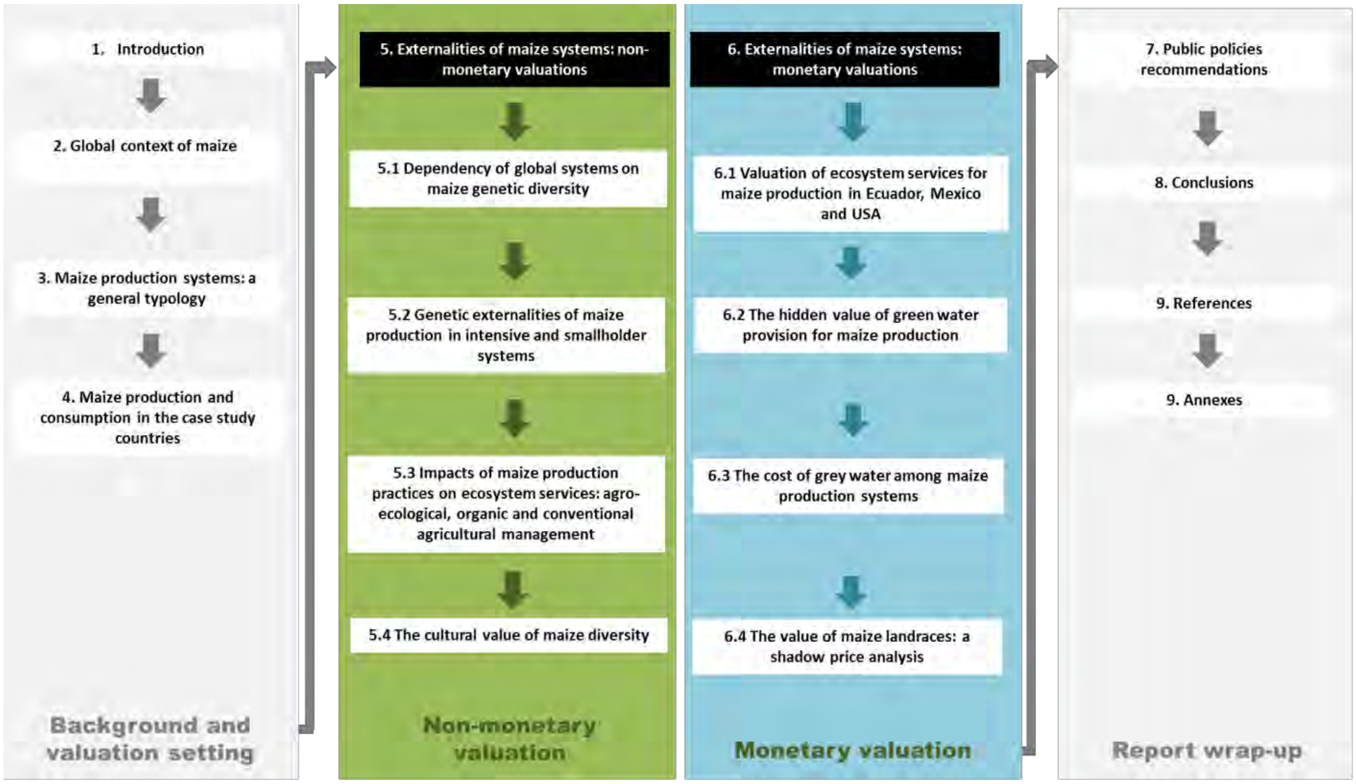
The National Commission on Knowledge and Use of Biodiversity (CONABIO), Mexico, decided to bid for the call made by TEEB on maize production systems valuation mainly because of its interest of making the case that it is indispensable for the present and future of food security in the world to safeguard agrobiodiversity. This implies a coordinated international effort to conserve the *in situ* socio-ecological processes and conditions of agricultural genetic resources in those places where crop wild relatives are found as well as where traditional agriculture is still being practiced. For the past twelve years, CONABIO has been supporting research projects to generate information on crops that have originated in Mexico through the domestication of wild plants that resulted interesting to human use. One of the crops that were domesticated in Mexico is maize. Native maize landraces are still grown today mainly in traditional agricultural settings throughout the whole territory in a diverse realm of agro-ecological conditions by at least two million farmers. Learning and understanding the processes behind this might help us conserve and use maize genetic diversity in ways which are favorable for sustainable development. It is under this perspective that CONABIO has undergone the TEEB study and presents the current report.

Ecosystem services (ES) have been defined as the biophysical conditions and ecosystem processes through which natural ecosystems and biodiversity conform, sustain and nourish human existence (Daily, 1997; Gordon et al., 2008). While ecosystem services research originally focused on natural ecosystems, greater interest has also built on understanding the ecosystem services provided by and altered by man-made ecosystems such as agricultural land, land transformed by livestock and managed forests (MEA, 2005). In particular, there is increased interest in identifying the ecosystem services underlying agriculture that are recognized as pivotal for the production of food for human societies and to deepen our understanding about how different types of agriculture, characterized by different management practices, erode, maintain or enhance the ecosystem services upon which they depend (Bommarco et al., 2013).

The impacts of agriculture on ecosystem services greatly depend on the particular management practices followed. These practices are somehow determined by the environmental context in which they are inserted, the aim and cultural context of the production systems, and by the level of recognition and value given by human societies (*i.e.* producers) to the ecosystems services on which agriculture depend. From our particular perspective, the concept of ecosystems services defines those services provided by ecosystems that are recognized by a variety of sectors (academia, political decision makers, producers, consumers, etc.). We assume that there is a wealth of services provided by ecosystems and agroecosystems that might not be recognized and which still provide a wealth of benefits but escape our recognition.

CONABIO approached the valuation of maize production systems by paying special attention to agrobiodiversity as a key component of agroecosystems and as a key provider of evolutionary services, which are seldom mentioned or evaluated in the ecosystems services literature. Throughout the report we acknowledge the great variety of maize agroecosystems but focus specifically on two contrasting systems: 1) Semi-subsistence smallholders aiming at the production of quality maize in enough quantities for their needs, and 2) Intensive maize systems focused on profit aiming at the production of a homogenous and abundant product.

The following report is comprised of nine sections depicted in the following roadmap:



In the first section we set down the particular perspective under which we constructed the present report. In the second section, we address the ecological, economic and social status of the maize sector from both historical and current perspectives. The third section represents an effort to map the present distribution of a set of maize production systems and to identify the geo-climatic conditions that characterize these systems. In the fourth section we present the different ways in which maize is produced and consumed in the case study countries and regions, explaining thereby the *rationale* behind their selection. The fifth and sixth section address a set of valuation exercises that aim to bring into attention a set of ecosystems services on which maize systems depend and which maize systems impact. The fifth section is composed by non-economic valuation approaches while the sixth section presents monetary valuations approaches. In section 5.1 we discuss the dependency of smallholder and intensive maize systems on maize genetic diversity, while in section 5.2 we review the negative effects of promoting genetic uniformity and breeding for intensive production systems on crop production and further breeding. Section 5.3 is divided into two subsections. In the first subsection (5.3.1), we focus on the effect of minimal or no soil disturbance through reduced or no-tillage, permanent organic soil cover by retaining crop residues and crop rotation. The ecosystem services assessed are food provision, soil erosion prevention, soil fertility and water regulation. In the second subsection (5.3.2), we compare the provisioning and regulating services provided by both organic and conventional maize systems. Section 5.4 provides an assessment on the paramount importance of maize diversity as a key provider of cultural ecosystem services for smallholder maize systems in Ecuador and México.

The sixth section represents the monetized component of our valuation studies. In section 6.1 we develop a Cobb-Douglas production function to estimate the marginal value of ecosystem services for maize production in Ecuador, Mexico and the USA. In section 6.2 we calculate and monetize the cost of the green water used in maize production in rainfed, mixed and irrigated cantons/municipalities and counties in our case study countries, while in section 6.3 we do the same for grey water cost of low, intermediate and high-yield maize producing units. In section 6.4 we estimate the cultural and evolutionary value of maize landraces using a shadow price-based approach.

In the seventh section we provide a series of recommendations to be undertaken in public policy design in order to help the transit towards a transformation of the maize producing sector. In the section 8 we try to resume our principal findings and provide an integrated view of the entire report. At the end of the report we provide a series of annexes which include tables with the description of the data and variables, data bases and maps used in the various analysis included in this report.

2. Global context of maize

Half of the potentially productive land surface of the planet is under agricultural use. While humanity depends on approximately 150 plant species for food, only three of these (rice, wheat and maize) provide more than half of its calorific energy (IDRC, 2015). In 2013, the cultivated area of these three cereals together totaled more than 570 million ha. While wheat is the cereal that occupies the largest area (38.4% of the total area), maize (32.6%) is the crop with the widest distribution. Maize is cultivated in 166 countries; i.e., in 49 countries more than rice and 44 countries more than wheat. In addition to its high environmental adaptability and productivity, maize has become the most abundant crop globally as a result of this versatility. As well as being directly consumed as food, maize is now used at a large-scale mainly in the production of feed for the poultry and meat industry and for the production of fructose/glucose, flour, oils and ethanol.

Maize produced for non-direct human consumption represents the vast majority of the crop worldwide, produced by approximately 17 countries the output of which accounts for almost 90% of maize production worldwide. These countries differ from those that consume maize as a staple crop in terms of production, commerce, inputs, socio-economic conditions and uses. Practically all maize used as direct human food comes from white maize varieties, which represent only 4% of the total quantity of internationally traded maize; the rest is yellow maize, mainly destined for other uses. White maize varieties represented 12-13 percent of the annual world output of all maize in 1996, and over 90% of it was produced in developing countries (Dowswell et al. 1996 quoted in FAO, CIMMYT 1997). White maize production regions coincide with the regions where people have adopted maize as a staple crop. These countries are located almost entirely in Sub-Saharan Africa, Latin America and Southern Asia.

Maize destined for direct human consumption is mostly produced by smallholders. Most smallholders of different regions of the world manage landraces of high genetic diversity under a wide range of socio-ecological conditions, in spite of intense pressure to limit its use. The factors believed to contribute to the conservation of maize landraces are the socioeconomic conditions of farmers, greater performance stability of native varieties under biotic and abiotic stress conditions and cultural preferences for specific qualities required for diverse uses, among others.

The smallholder production system differs from other types of system: In general, smallholders depend on a high diversity of interspecific and intraspecific diversity, as well as practices such as intercropping, crop rotation and the use of fallow, to manage ecosystem services such as soil fertility, pest and disease control and food production. These traditional systems are swiftly disappearing and giving way to agricultural plots that resemble, albeit on a smaller scale, those of intensive systems. Intensive maize systems are characterized by the simplification of landscape structure, use of monocultures and improved seeds that are poor in genetic variability, and intensive use of inputs, among others. The impacts that these practices have had on ecosystem services have been extensively reviewed and include, among others, deleterious effects on biodiversity, pest control, pollination, water provision and quality, climate regulation and nutrient cycling.

A relatively recent management practice of intensive maize producers is the cultivation of genetically modified (GM) maize, which has gained ground over its conventional (non-GM) counterpart over the last two decades. GM maize is cultivated in 27 countries and currently accounts for 35% of global maize production. Five of the major maize producing countries account for 97% of GM maize production worldwide It is directed mainly towards the livestock and ethanol industries. In addition to the deleterious environmental effects driven by their associated agronomic packages, the introduction of GM maize has caused concern in several areas. These include GM and non-GM coexistence, monitoring capacities (along the production and supply chain) and the possible consequences of intellectual property issues on maize diversity, especially in the centres of origin and diversity of this crop (Acevedo et al., 2009; Acevedo et al., 2011; Burgeff et al., 2014; You et al., 2014). Intellectual property rights tied to agricultural GM organisms are potentially and indirectly detrimental to the traditional seed exchange systems managed by smallholders, which have been key to the evolution and conservation of agrobiodiversity.

The agricultural policy of the United States of America has played a critical role in global maize production, trade and supply. Subsidies that cause or encourage overproduction have been a central component of agricultural policy in the USA for almost four decades and have affected almost every component of national and global food systems; they have mostly benefited the livestock and sweetener industries, and have encouraged input-intensive large-scale maize production systems.

3. Maize production systems: A general typology

Typologies have been used to study, program, plan and evaluate agricultural systems, rural and regional development, natural resource management, public policies and technical innovations. Maize farming systems vary not only in terms of productivity and the purpose of their output, but also in their level of mechanization, management practices, crop uses and characteristics of the producers and their production units, as well as in the socioeconomic, cultural and biophysical environment in which they develop. Depending on the management practices adopted, production systems can provide ecosystem services or generate negative impacts on the environment (also known as ecosystem disservices). The typology of the main production systems proposed in this study is the result of a review and analysis of the existing literature. Despite the substantial overlap among the management practices that exist, at least three main systems, each with two subtypes, can be distinguished from the literature review: 1) smallholder (shifting or stable), 2) intensive (irrigated or rainfed), and 3) organic (small-scale or large-scale) systems.

Smallholders were characterized as subsistence or semi-subsistence production units in which part or all of the production is consumed directly by the household. Smallholder maize production systems represent not only the most extended maize system around the world, but also the most diverse in terms of agricultural inputs, levels of mechanization, production aims, and inter and intraspecific agrobiodiversity. We mapped smallholder distribution using yield as a proxy for input intensity and the available spatially explicit data of global maize production (You et al., 2014). We found that smallholder systems are concentrated throughout Sub-Saharan Africa, Mexico, Central America, Brazil, and India, and scattered throughout southern and northern Asia. Compared to intensive rainfed producers, most smallholders have had to adapt to producing on soils with nutrient limitations, areas with higher or lower temperatures, higher altitudes and steeper slopes.

Intensive maize systems are fully commercially-oriented and their main focus lies in maximizing profit. In these systems, profit is made from producing the highest marginal yield possible per unit cost incurred. This is achieved by controlling almost every factor that affects the growth of a plant, including the genetic makeup of the seeds, nutrient input, incidence of weeds, pests and diseases, water provision and plant density. These systems have flourished in regions with fertile soils, sufficient rainfall, relatively low evapotranspiration and an even topography. They are located predominantly in Western Europe and in the northern portion of the American, European and Asian continents. Intensive irrigated systems are sparsely distributed in places with lower rainfall and higher temperatures and evapotranspiration rates. They are present in central, southeastern and western coastal USA, Portugal, Spain, Greece, and certain parts of Saudi Arabia, western Iran, northeastern and northwestern China and on the east coast of Australia.

Finally, organic maize systems are characterized as agricultural schemes that prohibit the use of genetically modified seeds, chemical fertilizers, pesticides and insecticides. Organic systems can be seen as a fusion between intensive and traditional systems since they are basically commercially-orientated systems that depend on management practices developed by traditional agriculture, including intercropping, crop rotation and the use of organic fertilizers, among others. While the number of countries producing organic maize is high (53), the area dedicated to this product is relatively small (43.1 million ha).

In sum, the maize systems mapped here, which were defined solely on the basis of yield, differ significantly in terms of the main environmental conditions assessed. This suggests the importance of environmental conditions as limiting factors for agricultural production and for the maintenance of agricultural knowledge systems that remain vital for a large part of maize production worldwide.

4. Maize production and consumption in the case study countries

There are significant differences between the contribution of maize production to food security in Ecuador, Mexico and the USA. In Mexico, maize is used primarily as a staple food for the entire population and for millennia has been mostly consumed in the form of tortillas. Maize for self-consumption (23% of the total production) is a fundamental component of the food security of about two million Mexican smallholder families, who live in a context of fragile socioeconomic and biophysical environments and who depend on the natural capital. Smallholders (in this case, defined as those producing 0-3 ton/ha) make a fundamental contribution to fulfilling the maize supply requirements of Mexico, in spite of the relatively low yields they produce.

Self-consumption of maize is also important in Ecuador (9%), but in this country the largest share of maize is used by the poultry industry. In all three countries, maize plays an important role in feeding animals. Approximately 77, 40 and 36% of the total production in Ecuador, Mexico, and the USA, respectively, is used for feed. While there is a surplus of white maize in Mexico, there is a deficit in the production of yellow maize, which is mostly imported and used as feed and in the starch industry. Remarkably, the production of maize for ethanol in Iowa alone is double the total amount of maize production in Mexico used for food, feed and self-consumption. About 14% of the maize produced in Iowa is used for processed products, including processed foods. An important percentage of the total maize production is wasted (approximately 9% in Mexico and Ecuador).

Maize plays an important role in the diet of these three maize-producing countries, but in different ways. In Mexico, maize for human consumption is mostly based on the preparation of dough through a traditional process called *nixtamalización* that acts to increase the nutritional value of the proteins present in the maize grain. The per capita daily calorific intake from maize grain in Mexico, mainly in the shape of tortillas and other traditional maize-based foods and drinks, is over one thousand kilocalories, compared to 97 in the U.S and 36 in Ecuador. The contribution of maize to the daily necessary protein intake in Mexico is 26.86 g, while in the USA, this is 1.76 g and in Ecuador 0.95 g.

Maize also plays a fundamental role in the US diet, but in the shape of feed, sweeteners and other processed foods. During the last century, the consumption of meat and high fructose corn syrup (HFCS) has dramatically increased in the US. Currently, the average diet in that country includes more animal protein per capita than recommended by official nutritional authorities. The higher demand of HFCS and meat in the U.S. and globally has been a major driver of the expansion of the highly specialized, intensive and industrialized production of genetically uniform maize.

Maize subsidies in the USA have deeply transformed the food system, not only nationally but also globally. A substantial proportion of these subsidized low-cost commodities are transformed into meat and dairy products, high-calorie sugar-sweetened beverages and processed and packaged foods. Increased consumption of calories from subsidized maize and other food commodities is associated with a greater probability of cardio-metabolic risks and lower nutritional quality. The North American Free Trade Agreement has also led to important changes in the consumption and production of maize and has, in general, transformed food systems in the United States and Mexico. Since NAFTA, exports of HFCS from the USA to Mexico increased by 863%. Soda producers are the main consumers of HFCS and Mexicans are some of the main consumers of soda worldwide. Mexico is currently facing a public health crisis due to overweightness and obesity and associated non-communicable diseases. Consumption of sugar-sweetened beverages (SSB) represents 70% of the Mexican daily intake of added sugars. Previous studies estimated that Mexico had the greatest number of disability-adjusted life years per million adults that are attributable to the consumption of SSB in 2010.

5. Externalities of maize systems: non-monetary valuations

5.1 The Dependency of global systems on maize genetic diversity

In this section, we conducted a literature review on maize domestication and plant breeding, focusing on the role of genetic diversity in increasing yields and allowing adaptation to different conditions and production systems. All maize production systems depend on the availability of genetic diversity. However, the extent of that dependency differs in terms of the nature of the diversity required for the crop in each setting, as well as the way in which the farmer accesses this diversity. On one hand, intensive maize production systems rely on genetically stable hybrid commercial seeds and predominantly seek to enhance yield through heterosis. These systems permit the use of mechanization, high plant density, use of fertilizers and other agrochemical inputs, and as such they are suitable for well-controlled environments. Their production is very uniform and presents the desired characteristics of the global uses of the crop. On the other hand, small traditional production, conducted in multiple climatic contexts and, in many cases, in marginal settings, is the extreme example of how maize copes with ever changing climatic and productive conditions and, in order to do so, also depends on existing and future sources of genetic variability, i.e., the diverse genetic combinations that result from and are required in order to confront biotic and abiotic stresses.

Regardless of the production system, the huge range of maize phenotypes and the total genetic potential for yield increase that has been achieved by modern breeding came from developing new arrangements of native genetic diversity. While breeding has focused on producing “pure” lines, breeding programs have continuously introduced exotic materials in order to harness their ability to provide beneficial genetic responses, particularly to new or unusual sources of stress but also for yield. This genetic diversity is maintained and generated by smallholders, who produce maize in different environments with systems that involve continuous recurrent selection, experimentation and gene flow with wild relatives.

5.2 Genetic externalities of maize production in intensive and smallholders systems

We evaluated the genetic externalities of maize production following a literature review and calculations based on population genetics estimates. The literature review focused on three topics: a) the history of maize breeding and domestication, b) the effect of genetic homogeneity on the spread of pest and diseases and, c) genomic studies conducted on maize lines, landraces and wild relatives. Population genetics calculations were then used to estimate the contribution of native maize landraces to the continuity of the evolutionary process. For this, we used known mutation rates, data concerning the area in Mexico grown with maize landraces (SIAP, 2010) and ethnobotanical data on smallholder seed selection practices.

Our review shows that the increase in yield gained through modern breeding not only relied on genetic improvements, but also on modifying the environment through the high use of inputs. This in turn has had negative externalities for the environment. Another widely recognized externality is that hybrid maize cultivars grown in intensive production systems are susceptible to the rapid spread of pests and diseases, since they are composed of genetically similar or identical individuals cultivated in large monoculture areas.

However, there are other less-visible but crucial externalities. Modern breeding and high-input agriculture has unintentionally narrowed the opportunity for further development due to breeding from a limited original source material, genetic bottlenecks and loss of local adaptation. In contrast, on-farm cultivation of maize landraces permits the generation of new diversity and promotes local adaptation. As an example of this, in Mexico, native maize is grown by smallholders over around 4.6 Million ha, which translates into 1.33×10^9 mother plants contributing to the next generation with their background genetic diversity and with rare alleles. By planting maize landraces, Mexican smallholders are therefore conserving allelic diversity in the most effective way possible. In this context, conservation not only means preserving, but also subjecting genomes to *in situ* natural selection and allowing new mutations to occur and be selected.

We must change our mentality in order to take advantage of that evolutionary process by aiding the local breeding of native maize and considering the smallholders as an integral part of the solution.

5.3 Impacts of maize production practices on ecosystem services: agro-ecological, organic and conventional agricultural management

Agricultural production systems face the challenge to sustain the production of sufficient, safe, nutritious and culturally appropriate food to feed a population of over 8 billion by 2030 while minimizing negative environmental impacts. We assume that the current farming landscape is not socially optimal and there is an urgent need to transit towards more sustainable agricultural practices. In this section we discuss the impacts on ecosystem services (ES) of three “typical” maize production systems in Mexico, Ecuador and the United States. The objective of this section is to make visible and compare the biophysical impacts of different maize production systems. More specifically, a detailed description of two major agroecological systems relevant to maize production is developed: conservation agriculture and organic systems.

5.3.1 Conservation agriculture

In the case of conservation agriculture (CA), we focus on the effect of minimal or no soil disturbance through reduced-tillage or no-tillage, permanent organic soil cover by retaining crop residues, and crop rotations. The ES discussed are provisioning ES or maize yields, soil erosion prevention, soil fertility, and water regulation. We evaluate the negative externalities of water sediments and water usage in the case of irrigated systems. In the specific case of semi-arid México, the literature showed that CA could create synergies by enhancing regulating ES while increasing yields. CA reduces soil erosion by 25-70%, compared with conventional practices. It improved soil fertility by increasing the amount of nitrogen available to the plant (60%), and it enhanced water regulation by increasing the amount of percolated water by 50%-200%, depending on precipitation intensity. This resulted in higher maize yields (26%-190%), depending on weather conditions and the type of interventions. Moreover, by reducing runoff and water soil erosion, CA decreased the amount of transported pesticides, nutrients and sediments to water bodies, in detriment of water quality. Compared to conventional practices, the adoption of CA enhances ecosystem services and reduces negative externalities.

The promotion of CA in Mexico and in other parts of the world has been linked to the use of improved varieties as part of the technological package and farmers have been reluctant to their adoption. Such is the case of indigenous households. Chiapas is characterized by self-consumption traditional maize production systems. In this region of Mexico, indigenous producers value the food quality provided by maize landraces, among other qualities. When their production is valued at a market price, smallholders seem to incur in cash loses. When the production of native maize is valued at its shadow price (Arslan and Taylor, 2009), it makes sense to them to continue using their landraces.

5.3.2 Organic maize systems

In terms of management practices, the fundamental difference between organic systems (OS) and conventional maize production is the use of synthetic fertilizers, insecticides and herbicides, which are banned in OS. The evidence on positive outcomes of OS relative to conventional systems is conclusive for three ES: soil structure and fertility enhancement -including increasing soil organic carbon, biodiversity, and water flow regulation. Organic systems do result in lower maize yields (approximately 11% and up to 28% lower during the transitioning period). However, given their premium price, the value of provisioning ES (maize for food and raw materials) in OS is higher than conventional maize, in spite of their lower yields. Regarding regulating ES, according to existing literature, OS perform better than conventional maize production: percolated water in OS was 15-20% higher; they retained 200-300% more SOC, and N in the soil was 34% more.

In 2004 maize producers in the U.S. applied approximately 8.9 million tons of fertilizers and 68 thousand tons of herbicides. Nitrogen was the most widely used fertilizer and herbicides were the most used pesticides. Regarding herbicides, atrazine was the most used active ingredient followed by glyphosate isopropylamine. Insecticides and fungicides were applied in a relatively smaller proportion of maize planted hectares. The overall use of synthetic insecticides to maize has decreased in large-scale farms since the introduction of insect-resistant maize (Bt). However, there has been a dramatic increase in the specific use of neonicotinoid insecticides in maize fields since 2003. The total amount of all types of herbicides applied per hectare since herbicide–resistant crops (Hr) were adopted has also decreased. However, there is evidence that such decrease has not generally been sustained and that it could be simply reflecting a transition towards high-efficacy herbicides. Information on the total amount of pesticides used in maize production is insufficient to make conclusions on their impacts to human health and the environment. The use of smaller amounts of more potent herbicides is not necessarily desirable. Studies that evaluate case-by-case are therefore necessary.

The economic value of banning atrazine: Atrazine is the pesticide most frequently found in groundwater and rain. A vast amount of research has studied its toxicity and effects on plants and animals, leading to mixed results. A recent exhaustive risk assessment by EPA (currently under public consultation) concludes that "aquatic plant communities are impacted in many areas where atrazine use is heaviest, and there is a potential chronic risk to fish, amphibians, and aquatic invertebrates in these same locations. In the terrestrial environment, there are risk concerns for mammals, birds, reptiles, plants and plant communities across the country for many of the atrazine uses. EPA levels of concern for chronic risk are exceeded by as much as 22, 198, and 62 times for birds, mammals, and fish, respectively. Terrestrial plant biodiversity and communities are likely to be impacted from off-field exposures via runoff and spray drift". Until conclusive evidence is confirmed, the economic valuation of the effect of atrazine and other pesticides on human health and ecosystems is challenging. A ban of atrazine in the U.S. would reduce yields at an estimated cost of $US490 million-$US2.9 billion. This amount is to be contrasted to the potential value of the impacts of atrazine.

The economic value of glyphosate resistance: There is also an ongoing debate regarding the impacts of glyphosate on human health and ecosystems. However, there is consensus in that weeds have been evolving resistance to glyphosate in many locations, creating a major agronomic problem and costs. There is clear evidence of an increase in herbicide use, which might be explained by the emergence of glyphosate weed resistance. Glyphosate resistance represents a reduction in total returns that affect maize producers. The total returns of farmers reporting GR were US$166.23/ha lower. The potential aggregate economic loss from glyphosate resistance is not trivial. About one-third of the farmers in Iowa reported to have glyphosate-resistant weeds. The adoption of agro-ecological weed management techniques such as cover crops and crop rotations, particularly in agricultural areas that have not been exposed to constant applications of glyphosate is encouraged by previous studies, instead of trying new chemicals to combat resistant weeds.

The value of negative externalities of fertilizers in the Gulf of Mexico: Eutrophication and hypoxia in the northern Gulf of Mexico have been mostly attributed to nitrogen loadings from the Mississippi River. Organic rotations using compost leached les N/year compared conventional production. According to the *Action Plan for Reducing, Mitigating and Controlling Hypoxia in the Northern Gulf of Mexico* a 30% reduction in the N load would achieve the total goal of reducing the size of the Northern Gulf´s hypoxia to 5,000 km2. The adoption of OS management practices could contribute to such goal. The benefits of restoring wetlands in the southern part of the Mississippi River, an intervention that could help reduce the amount of nitrates entering the river and eventually the Gulf of Mexico, have been previously estimated at a value of US$900 -US$1,900/ha of land considered.

5.4 The cultural value of maize diversity

The presence of native maize landraces is conspicuous in smallholder farms in both Mexico and Ecuador. Ecuador, one of the countries with the highest agro-biodiversity per unit area in the world, is home to a large variety of ecosystems and cultures. At least twenty-nine maize landraces and several complexes were identified in the country. There are 35 indigenous peoples and nationalities in Ecuador, 14 of which live in the mountains and depend on maize cultivation. Most producers (54%) plant from two to seven maize varieties along with other associated crops, mainly beans (50%), and 98% of the production is for their auto-consumption. Maize is of great importance in the Ecuadorian diet, and the many uses given to this staple in both rural and urban settings have ensured the conservation of its genetic diversity. The diversity of uses for maize among rural communities is manifested in the many dishes prepared with this staple in everyday life as well as in religious festivals and entertainment events in both urban and rural settings. By using the framework proposed by Gandini and Villa (2003) to identify the cultural significance and value of any given species, the unique position of maize in Mexico compared to Ecuador and the USA becomes evident. In Mexico, maize can be considered a culturally salient species that, to a great extent, shapes the cultural identity of a people. This is reflected in its role as a fundamental element of the myths of origin of Mesoamerican cultures, its ubiquitous place in the landscape, its essential irreplaceable place in daily nourishment and cuisine, its multiplicity of uses, as well as in cultural narratives and ceremonial roles.

6. Externalities of maize systems: monetary valuations

6.1 Valuation of ecosystem services for maize production in Ecuador, Mexico and USA

Agriculture is always a joint production system yielding multiple crops that depend on a set of agricultural inputs, and a set of biophysical conditions and ecosystem processes, conceptualized here as ecosystem services (ES). Production functions define the relation between a production input and the produced output. In simple terms, a production function is a mathematical function that relates the various inputs involved in the production of a good with the amount of goods produced. The production function method has been used as way to uncover the value of specific attributes of the environment, or of particular ecological functions and processes (Barbier, 1994; Barbier, 2007; Kumar, 2013).

The aim of the present study was to identify the relation between a set of ecosystem services and maize production in our three case study countries in order to value their contribution to maize production. For this we developed a Cobb-Douglas production function to estimate the value of the marginal product (VMP) of ecosystem services for maize production among high-yield irrigated, high-yield rainfed, mixed and low-yield rainfed municipalities/counties in Mexico and USA, and among Ecuadorian cantons located in the Amazonia, Andean and Coastal region.

The selection of variables representing ecosystems services was done with the help of expert knowledge and the availability of data for the three case study countries. Annual precipitation and irrigated maize area were selected as proxies for provision services for agriculture. Rainfall seasonality and maximum temperature were selected as regulation services, while soil organic carbon and sowed maize area were selected as support services for agriculture. In addition to these, data on agricultural management practices were also included. It should be noted that the main aim of this study was to estimate the contribution of ecosystem services to maize production; as such we only used agricultural inputs as covariates to control for their contribution. For this reason we do not deal with them in detail neither in the results nor the discussion sections.

We run a series of linear regressions with heteroscedasticity correction for the relevant maize production systems in each country. Administrative units of Mexico and USA were classified as 1) high-yield irrigated (> 2 ton/ha and > 75% of maize area under irrigation), 2) high-yield rainfed (> 2 ton/ha and > 95% of maize area rainfed), 3) mixed (>5% and <75% of maize area under irrigation irrespective of yield), and 4) low-yield rainfed (< 2 ton/ha and > 95% of maize area rainfed). In the case of Ecuador we grouped cantons according to their region: Amazonia, Andes and coastal region. Before running the regressions we transformed all variables into their natural logarithms. Additionally, since precipitation and temperature are a quadratic function of maize yield (Schlenker and Roberts, 2006; Lobell et al., 2011; Lobell et al., 2013; Ren et al. 2014), we included a quadratic term in the original Cobb-Douglas function.

In the Cobb-Douglas production function the regression coefficients are interpreted and used as output elasticities (*i.e.* measurement of the responsiveness of output to a change in levels of inputs) through which the value of the marginal product is calculated. The regression coefficients represent a measure of the percentage change in the output given the increase in 1% in the input (*i.e*. ecosystem services and management factors).

Results from the regression model for the three Ecuadorian regions show that land had one of the largest effects over maize production. Increasing in 1% the sown area would increase maize production in 1.09% in the Amazonia, 0.50% in the Andean region, and 0.75% in the coastal region. This would increase in maize production cast a VMP of land of USD $21,928 in the Amazonia, USD $56,185 in the Andean region and USD $344,951 in the coastal region of Ecuador. Soil organic carbon had a positive relation with maize production only in the coastal region of Ecuador were most of the maize is produced. In this region, increasing in 1% the organic carbon content of soil would increase maize production in 0.30% representing a gain of USD $138,988. Annual precipitation resulted in a negative elasticity for maize production in the Amazonian region of Ecuador. An increase of only 23.1 mm in the annual precipitation would represent a loss of the maize output equivalent to USD $2,672 in that region. In the Andean region, rainfall seasonality showed to have a significant negative effect on maize production. Therefore, if rainfall would become less homogeneously distributed the loss in maize production would amount to USD $25,413. In the Andean region, were heat and solar radiation represent a limited resource, maximum temperature positively affected maize production. Here, the marginal value of maximum temperature was of USD $61,793, given by an average increase in 0.2 ^{o}C.

For Mexico, we found that when the sown area is increased in 1%, maize production would increase in 1.024% in high-yield irrigated municipalities, 0.948% in high-yield rainfed, 0.890% in mixed, and 1.017% in low-yield rainfed systems. The marginal value of land for all municipalities amounted to USD $49,935,640. Soil organic carbon was significantly related to maize production in mixed, high-yield irrigated and rainfed municipalities. The VMP for soil organic carbon amounted to USD $2,293,750 in high-yield rainfed units and USD $4,198,587 in mixed municipalities. Precipitation was as expected also important for maize production in Mexico. Our results show that increasing the annual precipitation in 12.3 mm in average has the potential to increase 0.193% the production of maize in low-yield rainfed areas, implying a gain of USD $1,990,839. In high-yield Irrigated and mixed areas, the lack of adequate precipitation involves the need of external irrigation. The water that is used to irrigate maize fields is obtained from rainfall stored in dams and deep wells, which is the reason why we consider it an ecosystem service. The elasticity of irrigated area in high-yield irrigated areas was highly significant: an increase in 1% of the irrigated area would increase maize production in 0.95% amounting to USD $12,734,053. In mixed systems, the VMP of this ecosystem input was valued in USD $5,955,556. Rainfall seasonality was, on the other hand, the climate factor with the greatest impact on maize production in all Mexican maize producing municipalities. An increase in 1% in the rainfall seasonality coefficient had the potential to increase maize production in 0.40% in high-yield irrigated areas, 0.64% in high-yield rainfed, 1.27% in mixed and 0.32% in low-yield rainfed areas, representing a total VMP of USD $40,412,021. On the other hand, maximum temperature had, as expected, a negative impact on maize production in mixed and low-yield rainfed areas. Results show that an increase of only 0.3 ^{o}C in the maximum temperature would imply a loss of 9,348,459 USD in maize production in mixed areas and of USD $2,108,467 in low-yield rainfed areas.

In USA when the harvested area is increased in 1%, the value of the marginal product was estimated in USD $92.5 million in high-yield irrigated areas, USD $473.7 million in high-yield rainfed areas and USD $154 million in mixed areas. Soil organic carbon was relevant for maize production in high-yield rainfed and mixed counties were the VMP of soil organic carbon was valued in USD $113 and USD $21 million respectively. The irrigated area in high-yield irrigated and mixed counties was valued in USD $68.6 and USD $38.2 million respectively, while the VMP of annual precipitation was of USD $31.7 million in mixed areas. With regards to the effect of temperature, our results indicate that an increase of only 0.3 ^{o}C in the maximum temperature would imply a loss of maize equivalent to USD $241 million in high-yield rainfed counties, and of USD $46.5 million in mixed maize producing areas. Our results are consistent with the National Climate Assessment (NCA) (2014) projections on the negative impact of high temperatures on the development of maize plants. In doing so, the recommendations/ adaptation issued by ERS USDA in the face of climate change are crucial. Rainfall seasonality, on the other hand, showed a negative relation to maize production, which implies that an increase of 1% in the seasonality of rainfall would represent a loss of USD $10 million in high-yield irrigated areas in the USA.

In sum, our results provide an estimate of the marginal value product of a set of selected ecosystem services for maize production in different maize producing areas in Ecuador, Mexico and USA. Through this approximation we tried to unveil the contribution that a set of ecosystem services have on maize production. Future attempts to will greatly benefit from longitudinal data, data at a lower level of aggregation (*e.g*. farm level), the use of primary instead of modelled data (*e.g.* data on soil and climate), and maize-specific management data (as available for Ecuador).

6.2 The hidden value of green water provision for maize production

Supply of water is a critical ecosystem service for agriculture. It is estimated that around 70% of the water extracted from aquifers, rivers and lakes is used in agricultural production (FAO, 2011b). Water availability in agricultural ecosystems depends not only on irrigated water but more importantly on infiltrated water and moisture retained by the soil. The aim of the present valuation-based approach was to quantify the hidden value of green water provision in maize production. Green water is defined as rainwater consumed by a crop (Mekonnen and Hoekstra, 2011: p. 1578). The reason for this valuation exercise was to monetize the dependency of maize systems on green water, using the cost of irrigation water in our three case study countries to estimate its value.

To analyze the data according to maize systems, we collected the spatially explicit data of green water (in millimeters) modeled for 1996-2005 by Mekonnen and Hoekstra (2011) available in a 5 by 5 ARC minute raster grid and spatially explicit data about maize production, modelled for 2005 by You *et al.* (2014), also available at the same resolution. We then classified each pixel as rainfed (<25% of the harvested area is irrigated), mixed (between 25 and 75% of the maize area is irrigated), and irrigated (> 75% of the maize area is irrigated) using the percentage of maize irrigated area in each pixel. We deleted all pixels that had absolute zeros for green water and maize production. To obtain total green water in cubic meters, we multiplied the millimeters of green water by the area of each pixel in square meters and divided the resulting number by a 1000. To estimate the value of green water per maize system, we used the mean of the deflated cost of irrigation water in USA in 2005 (USD 1.144/m^3), which was priced at USD 1.53/m^3 (Agricultural Resources and Environmental Indicators, 2006). For Ecuador, we used the deflated market price of pumped irrigation water (2015: USD 0.25/m^3, 2005: USD 0.165/m^3) (Y. Cartagena Ayala, pers. comm.), and for Mexico we used the shadow price of water (2015: USD 0.274/m^3, 2005: USD 0.184; C. Cabrera Cedillo, pers. comm.). The justification for using irrigation water prices is clear since any reduction in the amount of natural precipitation will require external supplementation with irrigation water if yields are to be maintained.

For Ecuador, the estimated cost of blue water was close to 26 million USD in rainfed areas, 3.9 million in mixed areas, and 4.2 in irrigated areas, while the green water value amounted to 140, 10.7 and 24.9 million USD, respectively. In 2005, Ecuadorian farmers received an estimate of USD 345 for every ton of maize[3] they sold at the farm gate (FAOSTAT, 2016b). Thus, without taking any production costs into account, the estimated earnings for maize production was USD 180,698,476 in rainfed areas, USD 39,346,180 in mixed areas and USD 24,975,861 in irrigated areas. If the green water used for maize production were to be included as a production cost, this would represent 77.5%, 27.4% and 54.9% of the output value of each system. However, it must be noted that the output value from maize production in Ecuador may be much lower, given that the price listed in the FAO includes only maize for human consumption whereas the maize production data from You et al. 2014 includes the total amount of maize produced. This means that the relative value of green water may be much higher considering lower maize prices.

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[3] The price listed for Ecuador is for maize used for human consumption.

In Mexico, rainfed units used an estimated quantity of green water priced at 4 billion USD, while mixed and irrigated units used an equivalent of 708 and 517 million USD, respectively. With respect to the blue water, we estimated that rainfed units paid 52 million USD for irrigation water, while mixed areas paid just over 2 million USD and irrigated areas a total of 3.5 million USD. Given that the cost of irrigation water is higher in Mexico than in Ecuador and that the income gained from maize production is lower than in Ecuador (USD 144.9 per ton: FAOSTAT, 2016b), the value of this service would represent 290% of the value of maize production of rainfed units, 165.3% of mixed units and 193% of the production of irrigated ones.

Using the deflated price for irrigated water in the USA, we estimate that the total value of green water use in rainfed, mixed and irrigated areas would amount to 49.1, 8.0 and 8.7 billion USD, respectively. For rainfed areas, this amount is approximately 63.8 times higher than that paid for irrigation water, but only 2.8 and 1.9 times higher than the estimated cost of irrigation water in mixed and irrigated areas. To determine how the estimated value of green water compares to the earnings obtained from maize production, we calculated the value of maize production (USD 79 per ton: FAOSTAT, 2016b) at 7.2 and 1 billion USD in rainfed and mixed areas, respectively, and at 938 million USD in irrigated areas. If one compares the earnings from maize production to the value of green water, this would represent 678% (in rainfed areas), 772% (mixed) and 932% (irrigated) compared to the earnings from maize production.

The results presented here highlight that the potential value of green water for all maize production systems is very significant, yet it remains broadly unaccounted for both in maize markets and policies. Here, the hidden value of green water provision to maize production systems is shown by representing it as the dependency on or contribution of green water in maize production. The areas producing maize in the USA are those that "save" most if green water were considered an asset with economic value or, put another way, they would be those that "lost" the most if green water suddenly became unavailable and had to be replaced by irrigation.

Finally, a word of caution regarding our estimates presented here: we merged data from two different sources; those pertaining to maize areas and maize production came from You *et al.* (2014) while those pertaining to the green and blue water came from Mekonnen and Hoekstra (2011). While both of these sources used spatially explicit data about maize production generated by the FAO as their base, You *et al.* (2014) added subnational data from a network of data resources from various local subnational offices. This means that the data may not necessarily be compatible, which may produce estimates that are not entirely accurate.

6.3 The cost of grey water among maize production systems

Among the most widely acknowledged impacts of agricultural production on ecosystem services is the contamination of water by agrochemicals and nutrient loads (Conley et al., 2009b). It has been estimated that 50% of the nitrogen used in agricultural systems is used by the plants, 2 to 5% remains in the soil, 25% is released as N_2O emissions and 20% is leached into aquatic ecosystems (Galloway et al., 2004). The main consequence of leaching nitrogen-based fertilizers into water sources is the eutrophication of those water bodies with the resulting hypoxic or anoxic conditions for aquatic organisms. The impacts of hypoxic conditions on individual species and ecosystems have been extensively reviewed and involve diverse impacts on the behavior and physiology of organisms, causing a reduction in their fitness or even mortality in the organisms (Diaz and Rosenberg, 2008; Ekau et al., 2009; Diaz et al., 2010).

We decided to use the grey water estimates calculated by Mekonnen and Hoekstra (2011) to generate a partial estimate of the externalities of chemical nitrogen fertilizer used in maize production. Grey water refers to the "volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards" (p. 1578). This means that the externalities calculated here capture only the cost of meeting one water quality standard. To analyze the data according to maize systems, we collected the spatially explicit data of grey water (in millimeters) modeled for 1996-2005 by Mekonnen and Hoekstra (2011) available in a 5 by 5 ARC minute raster grid and spatially explicit data pertaining to maize production modelled for 2005 by You et al. (2014), also available at the same resolution. We then classified each pixel, also referred to here as production units, as smallholder (<2 ton/ha), intermediate (2 -6 ton/ha) and intensive (> 6 ton/ha), using the data on maize yield for each pixel. In all instances, we deleted cases with absolute zeros for green water and maize production.

To obtain total grey water in cubic meters, we multiplied the millimeters of grey water by the area of each pixel in square meters and divided the resulting number by 1000. To estimate the cost of grey water per maize system, we used the mean of the deflated cost (USD 1.144/m^3) of irrigation water in the USA in 2005, which was priced at USD $1.53/$m^3$ (Agricultural Resources and Environmental Indicators, 2006). For Ecuador, we used the deflated market price of pumped irrigation water (2015: USD $0.25/$m^3$, 2005: USD $0.165/$m^3$) (Y. Cartagena Ayala, pers. comm.) and for Mexico, we used the shadow price of water (2015: USD $0.274/$m^3$, 2005: USD $0.184; C. Cabrera Cedillo, pers. comm.). In order to put the calculated remediation costs in perspective, we compared the value of externalities to the value of maize production. For this, we used the producer prices of maize in the analyzed countries; USD $79 for the USA, USD $345 for Ecuador and USD $144.9 for Mexico (FAOSTAT, 2016b). These prices represent the income received by farmers for maize as earned at the farm-gate or at the first point of sale. As such, they accurately represent the output value.

In Ecuador, the partial remediation costs associated with nitrogen leaching represented 11.6% of the maize production revenues in low-yield units and 9.5% in the intermediate units. In México, these costs represented 99.7% of the production income of smallholders, 35.9% that of intermediate producers and 17.5% that of intensive units. Finally, the highest remediation costs calculated were for maize production units in USA were 2,630% of the maize income for smallholders, 430.5% of the income of intermediate producers and 233.9% of that of intensive producers would need to be paid if producers were to assume these costs.

The three countries generated grey water footprints that differed enormously. The total grey water generated by the three countries was of 24,703 million cubic meters per year, valued in USD $22,975 million, of which 77.7% was produced by the USA, 21.6% by Mexico and 0.7% by Ecuador. In the USA, intensive units were responsible for almost the entire grey water footprint of the country, while in Mexico, smallholders and intermediate producers were responsible for this mainly because they represent the predominant maize producers.

Using the cost of the quantity of water required to dilute nitrate levels in water to value the impact of eutrophication represents, without doubt, only a small part of the total economic cost that must be accounted for, given the negative impacts of nitrogen leaching on aquatic ecosystems and biodiversity. The total economic value of water eutrophication driven by maize production in particular and agriculture in general will certainly exceed by far the remediation costs of diluting nitrate levels in water.

6.4 The value of maize landraces: a shadow price analysis to support decision making related to the protection of the centers of origin and genetic diversity of maize in Mexico in 2011

The cultural value of maize in Mexico is tightly linked to the biological, geographical and historical context, since the country is located in a region where agriculture originated and is considered the center of origin and a center of diversity of this crop. Centers of origin and genetic diversity have been recognized as being of "crucial importance to humankind" (Cartagena Protocol on Biosafety to the Convention on Biological Diversity) and protection measures have been fostered by some countries. The Mexican Biosafety Law considers that, within the countries where centers of origin and genetic diversity of native crops are located, areas should be officially established so these crops can be protected. In order to comply with the cost-benefit obligations previously required to decree these areas for maize, in 2011, the Mexican Environment Ministry (SEMARNAT by its Spanish acronym) developed an economic study in which it applied the methodology of shadow prices to elucidate and apply other values (such as characteristics related to physiochemical aspects, cropping, culture, diet and cuisine) of maize landraces in order to more clearly demonstrate the benefits of preserving the areas where these are grown. Arslan and Taylor (2009) produced an assessment of the cultural values underlying maize landrace production by traditional maize farmers in Mexico through a shadow price approach using *The National Survey to Rural Households in Mexico* (ENHRUM by its initials in Spanish).

We used the parameters found in the econometric estimation of Arslan and Taylor (2009) to estimate the value of subsistence rainfed maize in Mexico. We found that the shadow price of rainfed maize grown for self-consumption in 2011 is around nineteen times higher than the market price for white maize grain. The difference in valuation between the price given by the mainstream market and the traditional rainfed maize market can be explained by several factors, including their adaptability to a variety of environments, improved management of pathogens and pests, and the cultural, spiritual, religious, culinary specificities resulting from the differentiated tastes, colors and rheology of the masa doughs of the great variety of these maize landraces.

7. Public Policy Recommendations on the Production of Maize

We suggest that policies should acknowledge the different types of maize production systems in existence. Indeed, each production system responds to different needs and implies different types and levels of dependencies and impacts on ecosystem services. Therefore, to ensure that the particularities, functions and necessities of each system are taken fully into account, policy formulation should be designed to fit each system. For this, policies should avoid the uniformity of maize production systems as a unique production model, which would make their different roles, objectives and outcomes vulnerable.

We highlight the need for public investment in scientific research and specific data generation regarding maize production systems. This would allow a broader knowledge on the genetic, ecological, agronomic and social elements that interact in complex ways within these systems. Moreover, all maize farmers worldwide should be able to benefit more directly from research and breeding efforts, and these should include a special focus on local landraces because of the option value they entail.

We also identified the necessity to support the valuation and conservation of on-farm maize genetic diversity, and of crop genetic resources in general. Efforts must be made to understand value and strengthen the processes through which genetic diversity is continuously evolving. A worldwide decisive effort is needed to strengthen *in situ* (*i.e.*, on-farm) conservation efforts to complement *ex situ* conservation in the public domain. This implies a re-evaluation of family and traditional small-scale agriculture.

All maize production systems must aim to be sustainable in their agricultural production approach. It is time - and urgently required- to incorporate environmental criteria in agriculture activities that aim to develop sustainable ways of food production, in our case maize. This includes policy-making, research and development and strategies of implementation and monitoring. In this regard, new indicators must be developed that go beyond measuring yield and focus on the sustainability of the maize production systems. Subsidies should be reconsidered, in order to correct their historical tendency to promote externalities. Subsidies must be redesigned to address each particular circumstance. The best way to use subsidies is to make them contingent on compliance with a set of rules and standards that lead to better practices, such as more efficient use of irrigation water and agrochemicals. At the same time, subsidies should not only abandon the prevailing goal of introducing commercial maize varieties into small-scale systems that manage landraces, but should in fact encourage the ecological and social processes that guarantee the reproduction of landraces.

1. INTRODUCTION

1. Introduction

This study is part of a larger effort by The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgFood), from the United Nations Environmental Programme (UNEP), which has been “designed to provide a comprehensive economic evaluation of the ‘ecoagri-food systems’ complex, and demonstrate that the economic environment in which farmers operate is distorted by significant externalities, both negative and positive, and a lack of awareness of dependency on natural capital”. The underlying goal of this study was to improve the understanding among policymakers and key stakeholders about the economic dependencies and interactions between the maize producing sector and ecosystem services, and their value to society.

The National Commission on Knowledge and Use of Biodiversity (CONABIO), Mexico, decided to bid for the call made by TEEB on maize production systems valuation mainly because of its interest of making the case that it is indispensable for the present and future of food security in the world to safeguard agrobiodiversity. This implies a coordinated international effort to conserve the *in situ* socio-ecological processes and conditions of agricultural genetic resources in those places where crop wild relatives are found as well as where traditional agriculture is still being practiced. For the past twelve years, CONABIO has been supporting research projects to generate information on crops that have originated in Mexico through the domestication of wild plants that resulted interesting to human use. One of the crops that were domesticated in Mexico is maize. Native maize landraces are still grown today mainly in traditional agricultural settings throughout the whole territory in a diverse realm of agro-ecological conditions by at least two million farmers. Learning and understanding the processes behind this might help us conserve and use maize genetic diversity in ways which are favorable for sustainable development. It is under this perspective that CONABIO has undergone the TEEB study and presents the current report.

CONABIO has also approached the valuation of maize production systems by paying special attention to agrobiodiversity as a key component of agroecosystems and as a key provider of evolutionary services, which are seldom mentioned or evaluated in the ecosystems services literature. In the Millenium Ecosystem Assesment framework, genetic resources are considered mere provision services (MEA, 2005). Others, like Zhang et al. (2007, p.256) categorized genetic diversity as a support service to agriculture. Our perspective on the service provided by genetic diversity is more in line with the concept proposed by Faith et al. who coined the term of evosystem services to encompass “the contributions of nature to people that result from past, present, and future evolutionary processes” (Faith et al. 2010; 2017). In the context of agroecosystems, evosystemic or evolutionary services can be seen as a complementary aspect of ecosystem services, which specifically refers to the crucial role of biological diversity (at all levels) in favouring the adaptation of crops to present and future conditions. Adaptation and evolution are not possible without variation; for this reason, we argue against its conceptualization as a mere provision service and in favor of its role in providing evolutionary services.

The academic and political focus on the services provided by ecosystems to human societies has been usually paired with their economic valuation (Lele et al., 2013). However, we believe that valuing ecosystem services does not necessarily have to transit towards an economic valuation of these. Not only because economic valuation methods are most of the time unable to capture the total economic value of a ES, but because using the anthropocentric view upon which the ecosystems services concept is constructed, is not always adequate to safeguard ecosystems, species or genes that do not provide any direct (or recognized) benefit to humans. Therefore, performing economic valuations is not always possible nor recommendable which is why many scholars have argued that economic valuation should be only one component of ecosystem services valuation (Gómez-Baggethun and Ruiz-Pérez 2011; Jax et al., 2013; Boeraeve et al., 2015). This report reflects this later perspective as we provide both types of approaches (see below).

Conceptual framework of the report

Ecosystem services (ES) have been defined as the biophysical conditions and ecosystem processes through which natural ecosystems and biodiversity conform, sustain and nourish human existence (Daily, 1997; Gordon et al., 2008) (Fig. 1.1). The concept of "environmental services" by which scholars formally recognized these benefits provided by "nature" to human societies was developed in the 1970s and gained momentum from 1997 onwards (Lele et al., 2013). Based on this common parting point, slightly different conceptual frameworks on ecosystem services have been developed which Lele et al., (2013) summarizes as follows: 1) the 'conservation biology approach´ in which "*ES-related benefits are seen as distinct from and in addition to the value of biodiversity conservation for its own sake*" (p. 344); 2) the 'environmental economics approach' advanced by environmental economists who developed the term of natural capital to refer to the different "*kinds of benefit flows from nature that included products or goods, indirect benefits or services, and pure conservation (existence or aesthetic) values."* (p. 344); and 3) *Millenium Ecosystem Assessment* framework, which derived from the former but extended its conceptual framework to include provisioning and cultural services while excluding all abiotic resources as sources of ecosystem services. Another conspicuous feature that came along this formal recognition of the services provided by ecosystems to human societies was the sometimes implicit and sometimes explicit focus on the economic valuation of these (Lele et al., 2013). The justification behind the focus on economic valuation is that societies, and more specifically policy makers and decision makers, have failed to acknowledge the importance of these services because these lack a recognizable value that captures their importance for human wellbeing. Evidently, the emphasis put on pricing the services that ecosystems provide to humans societies has become a matter of heated debate (Schröter et al., 2014). Moreover, the critiques to the ecosystem services approach are not only based on its economic focus but also on their anthropocentric perspective, as it only considers those processes, services and goods that provide a benefit to human societies (Schröter et al., 2014).

In spite of the potential shortcomings of this approach, the ecosystem services concept has achieved to reach sectors of the society for whom the environment was but a mere source of directly exploitable resources. Nonetheless, while ecosystem services research originally focused on natural ecosystems, greater interest has also built on understanding the ecosystem services provided by and altered by man-made ecosystems such as agricultural land, land transformed by livestock and managed forests (MEA, 2005). In particular, there is increased interest in identifying the ecosystem services underlying agriculture that are recognized as pivotal for the production of food for human societies and to deepen our understanding about how different types of agriculture, characterized by different management practices, erode, maintain or enhance the ecosystem services upon which they depend (Bommarco et al., 2013).

Below we provide the conceptual framework that guided our particular perspective for the elaboration of this report.

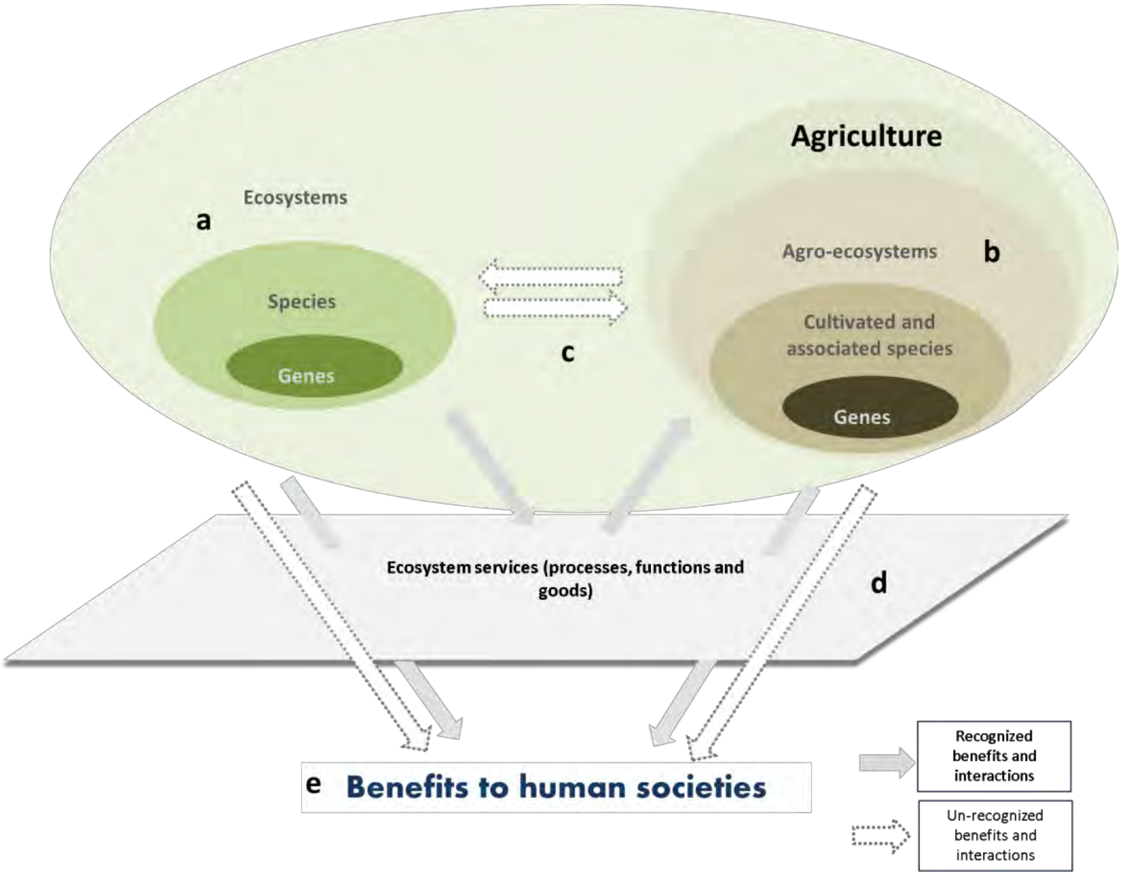


Figure 1.1 Framework for the CONABIO-TEEB report. (Note: Ecosystems and Agro-ecosystems actually could be represented as the same ensemble. They are separated in this diagram for the sake of clarity, so that dependencies and impacts of agriculture can be visually represented)

We consider that, such as ecosystems represent the most global level of biodiversity (Fig. 1.1 a), agroecosystems are the "human managed" equivalent of these, which are specifically devoted to agricultural production (and other associated benefits) (Fig. 1.1 b). Agro-ecosystems have been defined as "*a site or integrated region of agricultural production understood as an ecosystem*" (Gliesman, 2000: p. 17) or as "*a complex of air, water, soil, plants, animals, micro-organisms, and everything else in a bounded area that people have modified for the purposes of agricultural production*" (Marten, 1988: p. 294). These systems (ecosystems and agro-ecosystems) are continuously interacting and generating new conditions that impact each other in a dynamic fashion (Fig. 1.1 c). Take for the example the case of pollination services. Garibaldi et al. (2011) found that the productivity of pollinator-dependent crops is increased by the the closeness of agricultural fields from natural habitats that serve as refuges for wild pollinators. In this review, changes in closeby natural habitats were found to affect pollination services with a direct impact on provision services.

As in the case of ecosystems, agroecosystems are composed of the same three levels: genes represented here as maize genetic diversity, species or maize in its varied forms as well as its wild relatives, teosintles and tripsacum and the species that interact with these and, finally, the agroecosystems which include the diverse processes that occur in these maize production systems, including the interactions between the biotic, abiotic and human components of the system (Fig. 1.1 b).

Agricultural production (Fig. 1.1 e) depends on multiple ecosystem services (Fig. 1.1 d) provided by both natural ecosystems and agroecosystems. These include evolutionary services, as those provided by crop genetic diversity; supporting services as those underlying the structure and fertility of soil and the nutrient cycle; regulation services, as pest and disease control, water purification, weather regulation; and provisioning services, such as water supply (Zhang et al., 2007; Power, 2010); without these services agricultural production systems simply could not exist. Paradoxically, agricultural activity is undermining these same services on which their production relies (MEA, 2005).

The impacts of agriculture on ecosystem services greatly depend on the particular management practices followed. These practices are somehow determined by the environmental context in which they are inserted, the aim and cultural context of the production systems (*i.e.* typology), and by the level of recognition and value given by human societies (*i.e.* producers) to the ecosystems services on which agriculture depend. From our particular perspective, the concept of ecosystems services defines those services provided by ecosystems that are recognized by a variety of sectors (academia, political decision makers, producers, consumers, etc.) (Fig. 1.1 grey arrows). We assume that there is a wealth of services provided by ecosystems and agroecosystems that might not be recognized and which still provide a wealth of benefits but escape our recognition (Fig. 1.1 dashed arrows). What is important is that this recognition acts as a filter that guides human behavior and decision making with regards to human activities that will ultimately have an impact on all spheres (Fig. 1.1 a, b, c, d, e).

Valuing the externalities of agriculture on ecosystem services

Ecosystem services provide outputs or outcomes that affect human wellbeing and that can be quantified from an economic perspective. Environmental and ecological economists have been designing and applying non-market valuation techniques in order to value ecosystem services (*e.g.* Pearce and Turner, 1990; Adamowicz et al., 1994; Costanza et al., 1997; De Groot et al., 2002; Fisher et al., 2008; Bateman et al., 2011). Ecosystem service literature and the accompanying economic analyses can be divided roughly into three types: i) biodiversity and ecosystem functioning research that is typically focused on understanding and testing different aspects of biodiversity and ecosystem functioning and does not provide an economic valuation (*e.g*. Cardinale et al., 2006, Balvanera et al., 2012); ii) “how-to” economic evaluation manuals or guidelines for assessing the role of economic analysis in ecosystem service evaluation (*e.g.* Christie et al., 2008; Bateman et al., 2009; Kumar, 2010; Atkinson et al. 2012); and iii) applied case studies that have produced values for at least one ES (for a thorough review see Christie et al., 2008 and Balvanera et al. 2012). Our report falls in this last category.

Total economic value (TEV) is an important concept in environmental economics and offers a useful framework for analysis. The TEV provides a comprehensive measure of the economic value of any environmental good or service (Fig. 1.2). As can be appreciated in the schema presented below, TEV is mainly divided into use and non-use values. Use values "*can be associated with private or quasi-private goods, for which market prices usually exist, while non-use value are those that do not involve direct or indirect uses of ecosystem service in question*" (Pascual et al., 2010: p. 15). Use values are further subdivided into direct use (usually provision services) indirect use (usually regulating services) and future option values. Direct use values include marketed outputs (*i.e.* products or services that have a price in the market) and unpriced or non-consumptive benefits provided by ecosystems like recreation, aesthetic appreciation, spiritual or cultural benefits, etc. (*ibid*). Future option values, on the other hand, "*relates to the importance that people give to the future availability of ecosystem services for personal benefit*" (Pascual et al. 2010: p. 14). Thus, the TEV is the sum of all the relevant use and non-use values for a good or service (EFTEC, 2005). Below we use the TEV scheme to show the services that were evaluated in this report as well as the type of valuation used.

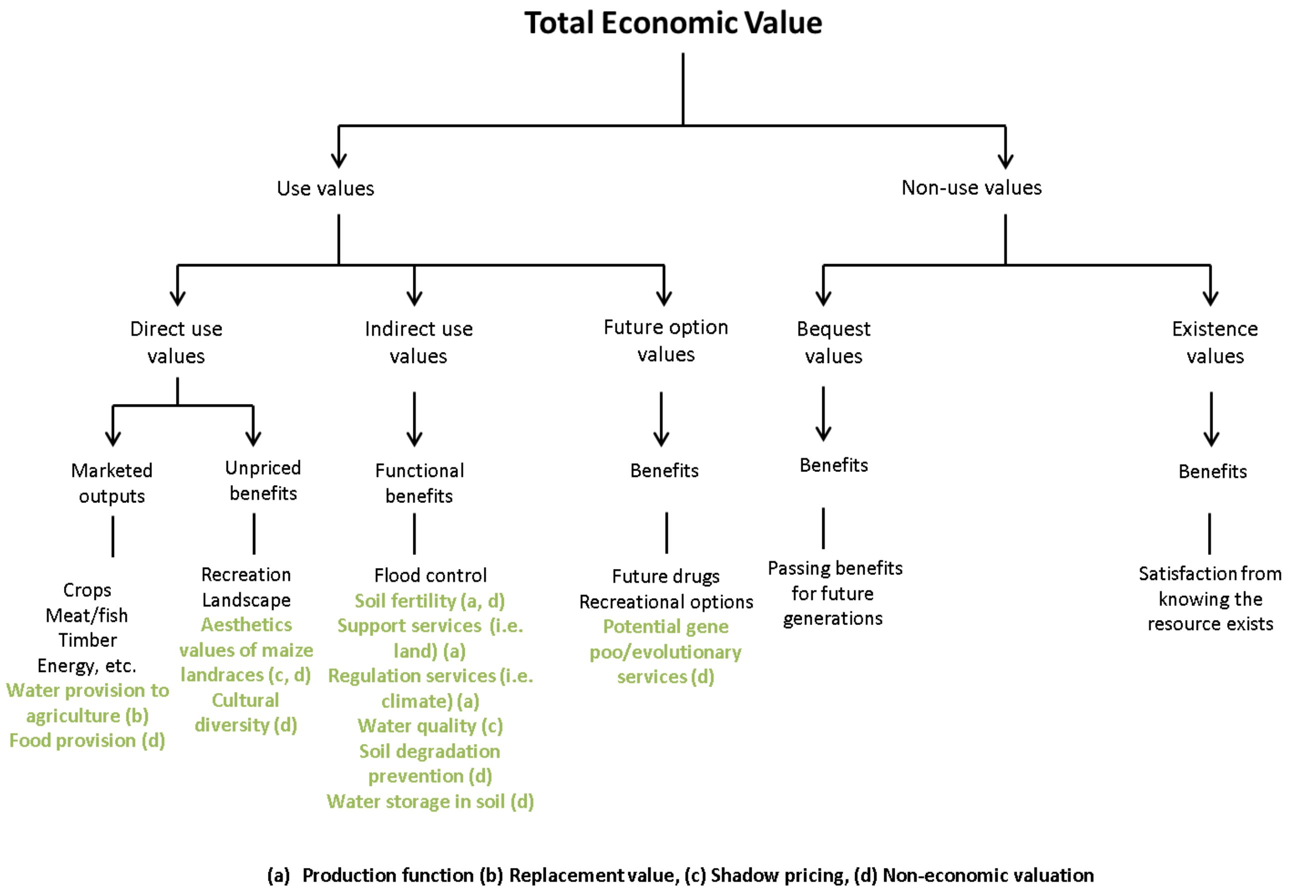


Figure 1.2 Ecosystems services assessed in the Maize TEEB project. Source: adapted from Pascual et al. 2010. Note: Ecosystem services highlighted in green are those valued in this report.

In figure 1.2 we show the environmental services valuated in this report as well as the valuation methods used. As stated above, agricultural production depends on multiple ecosystem services, which are rarely valued as a whole, that is, ecosystem services influencing agricultural production are not evaluated together, neither are they evaluated on the basis of their total economic value. Therefore, any existing evaluation approach that monetizes the ecosystem services underlying agricultural production will be necessarily narrow and represent a gross underestimation of the true economic value of those services. The following exercises will be no exception to this.

Roadmap for the reader

The report of the study is structured in eight sections. The first section includes the present introduction, framework of the report and roadmap for the reader.

The second section addresses the historical expansion of maize production and its uses, the importance of smallholders for food production and the conservation of agrobiodiversity, the socioeconomic contexts of maize production and the influence of regional and global agricultural policies on maize production. The aim of this section is to provide the reader with a broad perspective of maize production and consumption around the world.

In the third section we map and describe the geo-climatic conditions characterizing the distribution of some of the main maize production systems identified as part of this study. In order to map these systems we use yield as proxy for production intensity. Even though this approach might have some caveats, it provides a useful starting point to understand the limiting factors that, to a certain extent, shape maize systems.

The fourth section introduces the case study countries and regions of interest of the study. The three countries selected as case studies represent a mosaic of maize genetic diversity, agricultural systems and maize consumption patterns. Mexico was selected because it is center of origin and diversity of maize. Here, maize is produced in a wide variety of settings and using a wide variety of management practices and represents a staple food that has a significant contribution to the food security of the population, especially for the portion of the population that is more economically vulnerable. Ecuador also possesses a great diversity of maize landraces, but the greatest portion of maize produced is destined to the poultry industry. USA, on the other hand, is the main maize producer worldwide; maize is mainly produced in intensive agricultural units that are characterized by a low genetic diversity and the intensive use of agricultural inputs.

The fifth section includes the non-monetized valuation approaches undergone in this study, while section six contains the valuation exercises that generated results expressed in monetary terms. We titled these two main sections "*Externalities of maize systems*" because we mostly deal with services provided by maize systems or impacted by them, which are not visible for markets and are therefore not reflected in the prices charged for the goods provided by these systems (*i.e.* maize). According to Braat and de Groot, the definition of externality has become increasingly less rigorous. The concept of externality, initially refered to the "unintended consequences on one agent of an economic activity carried out by another agent, for which no compensation occurred" (Braat and de Groot, 2012: p. 6). Nowadays both the unaccounted effects of the production and consumption of goods on ecosystems, as well as the provision of ecosystem services by natural ecosystems are considered as such (*ibid*). We adhere to the later, more flexible use of the concept of externality.

We start section five (5.1) with a review the dependency of two extremely different production systems (*i.e.*, intensive maize production systems and small-holders using traditional practices) on maize genetic diversity, and describe the way in which intensive systems rely on traditional ones as a source of genetic diversity. In section 5.2 we review the negative consequences of the erosion of genetic diversity of maize in intensive maize production systems as well as the positive impacts of the conservation of maize genetic diversity by small-holder farmers in Mexico and Ecuador. Section 5.3 is divided into two subsections. In the first subsection (5.3.1), we focus on the effect of minimal or no soil disturbance through reduced or no-tillage, permanent organic soil cover by retaining crop residues and crop rotation. The ecosystem services assessed are food provision, soil erosion prevention, soil fertility and water regulation. In the second subsection (5.3.2), we compare the provisioning and regulating services provided by both organic and conventional maize systems. In section 5.4 we provide a review on the cultural importance of maize and maize landrace diversity in Mexico, Ecuador and USA, and point to the link between the maintenance of this diversity to the cultural values associated with it.

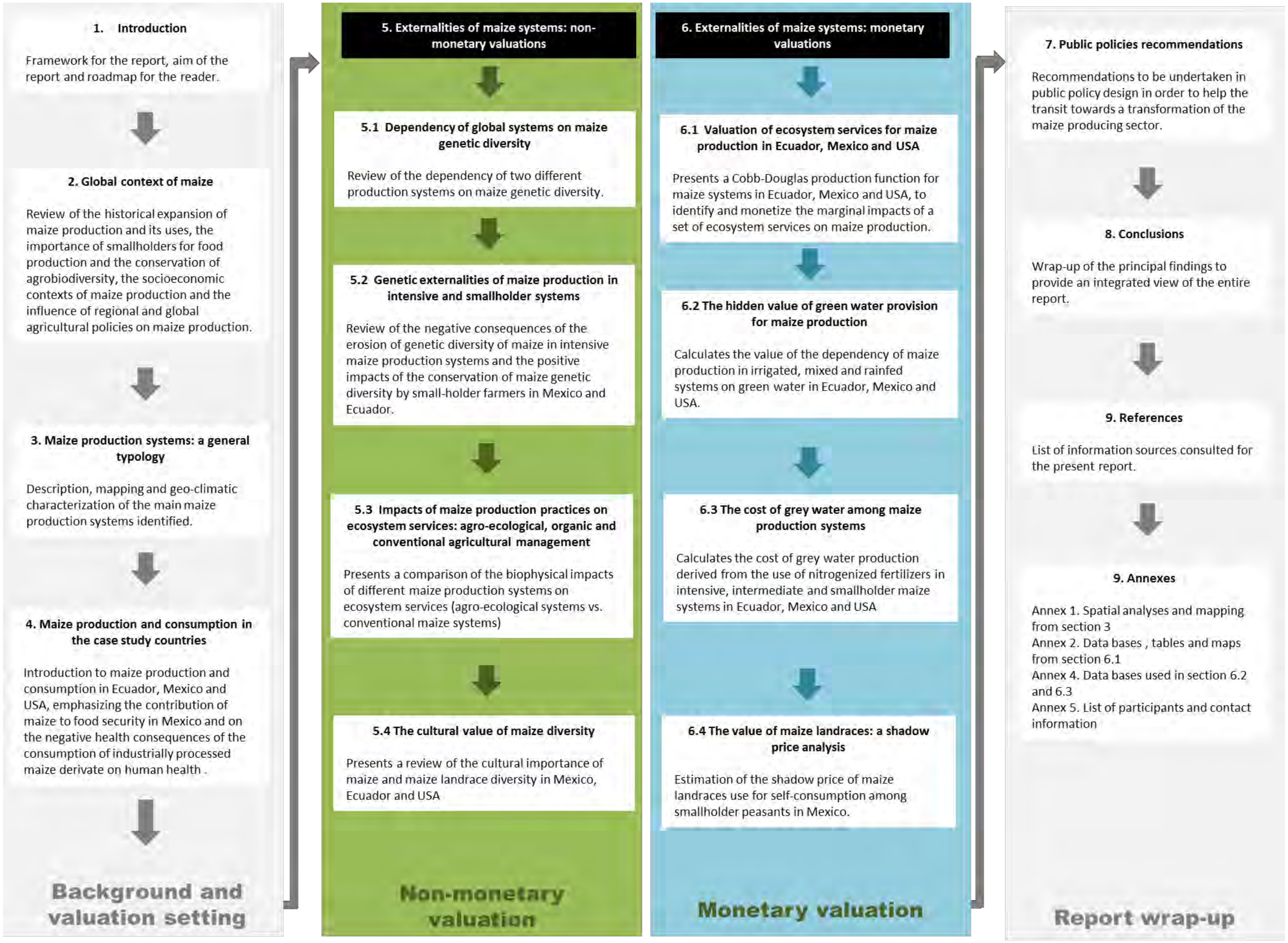
In section 6.1 we develop a Cobb-Douglas production function for maize systems in Ecuador, Mexico and USA, to identify and monetize the marginal impact of a set of ecosystem services on maize production. In section 6.2 we monetize the dependency of irrigated, mixed and rainfed systems on green water for maize production using data from Mekonnen and Hoeckstra (2010). Section 6.3 assesses the cost of grey water production derived from the use of nitrogenized fertilizers in intensive, intermediate and smallholder maize systems in Ecuador, Mexico and USA. For this we use the data of grey water from maize production calculated by Mekonnen and Hoeckstra (2010). In the last subsection (6.4) of section 6 we analyze the value of traditional landraces in Mexico by using a shadow price approach.

In section seven we provide a series of recommendations to be undertaken in public policy design in order to help the transit towards a transformation of the maize producing sector. We base these recommendations both on the results of this study but also on the lessons learnt of previous work. These recommendations highlight the importance of recognizing the relevance of the different maize production systems and the need to tailor agricultural policies taking into account the particular requirement of these systems. Additionally, it also points to the need to invest in research and data generation, the development of public policies to support the valuation and conservation of on-farm crop genetic resources in relation to smallholder systems, and the transition to more sustainable practices in large scale agriculture.

In the last section we try to summarize our principal findings and provide an integrated view of the entire report.

Additionally we provide a series of annexes which include tables with the description of the data and variables used in the various analysis included in this report, data bases and maps.

The following roadmap (Fig. 1.3) was devised to provide a global view on the present report:



1. Introduction

Framework for the report, aim of the report and roadmap for the reader.

2. Global context of maize

Review of the historical expansion of maize production and its uses, the importance of smallholders for food production and the conservation of agrobiodiversity, the socioeconomic contexts of maize production and the influence of regional and global agricultural policies on maize production.

3. Maize production systems: a general typology

Description, mapping and geo-climatic characterization of the main maize production systems identified.

4. Maize production and consumption in the case study countries

Introduction to maize production and consumption in Ecuador, Mexico and USA, emphasizing the contribution of maize to food security in Mexico and on the negative health consequences of the consumption of industrially processed maize derivate on human health .

Background and valuation setting

5. Externalities of maize systems: non-monetary valuations

5.1 Dependency of global systems on maize genetic diversity

Review of the dependency of two different production systems on maize genetic diversity.

5.2 Genetic externalities of maize production in intensive and smallholder systems

Review of the negative consequences of the erosion of genetic diversity of maize in intensive maize production systems and the positive impacts of the conservation of maize genetic diversity by small-holder farmers in Mexico and Ecuador.

5.3 Impacts of maize production practices on ecosystem services: agro-ecological, organic and conventional agricultural management

Presents a comparison of the biophysical impacts of different maize production systems on ecosystem services (agro-ecological systems vs. conventional maize systems)

5.4 The cultural value of maize diversity

Presents a review of the cultural importance of maize and maize landrace diversity in Mexico, Ecuador and USA

Non-monetary valuation

6. Externalities of maize systems: monetary valuations

6.1 Valuation of ecosystem services for maize production in Ecuador, Mexico and USA

Presents a Cobb-Douglas production function for maize systems in Ecuador, Mexico and USA, to identify and monetize the marginal impacts of a set of ecosystem services on maize production.

6.2 The hidden value of green water provision for maize production

Calculates the value of the dependency of maize production in irrigated, mixed and rainfed systems on green water in Ecuador, Mexico and USA.

6.3 The cost of grey water among maize production systems

Calculates the cost of grey water production derived from the use of nitrogenized fertilizers in intensive, intermediate and smallholder maize systems in Ecuador, Mexico and USA

6.4 The value of maize landraces: a shadow price analysis

Estimation of the shadow price of maize landraces use for self-consumption among smallholder peasants in Mexico.

Monetary valuation

7. Public policies recommendations

Recommendations to be undertaken in public policy design in order to help the transit towards a transformation of the maize producing sector.

8. Conclusions

Wrap-up of the principal findings to provide an integrated view of the entire report.

9. References

List of information sources consulted for the present report.

9. Annexes

Annex 1. Spatial analyses and mapping from section 3
Annex 2. Data bases , tables and maps from section 6.1
Annex 4. Data bases used in section 6.2 and 6.3
Annex 5. List of participants and contact information

Report wrap-up

Figure 1.3 Roadmap for the reader

Along the report we work at different geographical scales, owed mainly to the aim of each valuation exercise and the availability of data (Tab. 1.1). The sections of the global context of maize (section 2) and maize production systems (3) were developed at the global scale. The dependency of global systems on maize genetic diversity (5.1), and the genetic consequences of the large-scale production systems and continuity of the evolutionary process by on-farm cultivation of maize landraces (5.2) are reviews mainly focused on Mexico and USA. The rest of the report is focused on the three case study countries.

Table 1.1 Information about ecosystem services assessed**,** maize systems compared, type of valuation used and scale of the analyses

Sections	Ecosystem services addressed	Maize systems	Type of valuation	Scale
5.1	Evolutionary services (dependency)	Smallholder and intensive systems	Qualitative assessment	General but focused on Mexico and USA
5.2	Evolutionary services (externalities)	Smallholder and intensive systems	Qualitative assessment	General but focused on Mexico and USA
5.3.1	Soil erosion prevention Soil fertility Water storage Food provision	Conservation vs. Conventional agriculture	Qualtitative assessment	Case studies in semi-arid Mexico
5.3.2	Water storage Climate regulation Food provision	Organic vs. conventional agriculture	Qualtitative assessment	Focused in USA
5.4	Cultural services Aesthetic services	Not focused on systems	Qualitative assessment	Case study countries
6.1	Regulation services Provision services Support services	In Mexico and USA: High-yield irrigated and rainfed, mixed and low-yield rainfed systems. In Ecuador: Amazonia, Andes, Costa.	Monetary valuation	Case study countries: subnational level (cantons, municipalities and counties)
6.2	Water consumption for maize production	Irrigated, mixed and rainfed systems	Monetary valuation	Case study countries, 5x5 min ARC (10 km resolution)
6.3	Water quality	Smallholder, intermediate and intensive systems	Monetary valuation	Case study countries, 5x5 min ARC (10 km resolution)
6.4	Provisioning, cultural and evolutionary services	Smallholders	Monetary valuation	Mexico

2. A GLOBAL CONTEXT ON MAIZE

2. A Global Context on Maize

Authors: Gabriel Tamariz, Esmeralda Urquiza-Haas, Yatziri Zepeda, Daniela Torres Mendoza and Francisca Acevedo

2.1 The expansion of agriculture and maize

Key Message 1: Agricultural ecosystems have expanded worldwide and now cover half of the non-frozen land on Earth. *Half of the potentially productive land surface of the planet is under agricultural use. Intensive agricultural management has doubled the production of cereals in four decades. While the availability of calories per capita has also increased, food poverty persists mainly because of unequal food distribution and inefficient resource allocation. The contemporary diet and the level of food waste across the supply chain contribute to the inefficient expansion of agriculture and an increased use of intensive inputs.*

Over 75% of the non-frozen land on Earth can no longer be considered wild land (Ellis and Ramankutty, 2008). It is now estimated that more than 80% of this territory has already been affected by one or another type of human activity (Sanderson et al., 2002). The cultivated area of the Earth amounts to approximately 4,922 million hectares, representing almost 40% of the area of the Earth (FAOSTAT, 2015). This percentage is even higher (close to 50%) when ice covered frozen areas, unfit for cultivation, are excluded (Tilman et al., 2001; Hooke and Martín-Duque, 2012). A large portion of the Earth´s area is not suitable for cultivation due to inadequate rainfall or unsuitable topography, soil type and temperature (Fischer et al., 2000; Ramankutty et al., 2002). It has been calculated that half of the Earth´s area that is potentially productive is already in use while most of the remaining half is covered by tropical forests which capture CO_2 and comprise vast areas containing biodiversity (Hooke and Martín-Duque, 2012). Some of the results of the Millennium Ecosystem Assessment confirm that 42% of forest areas (mild forests: 67%; tropical forests: 34% and boreal forests: 25%) have been transformed into cultivated and urban areas, along with 18% of the arid zones (dry sub-humid: 35%; semi-arid: 25%; arid: 5%; hyper-arid: 1%): 12% of the mountain ranges, and 17% of the islands (MEA, 2005).

The area devoted to permanent farming is relatively small; however, in relative terms, agricultural use has shown the highest growth between 1961 and 2013 (83.5%). The area covered with weeds and prairies amounts to almost three quarters of the total area for agricultural use. In absolute terms, during this same period, this area was showing larger growth: 284 million ha. *vs.* 106 million ha of annual crops and 74 million ha in permanent crops (FAOSTAT, 2015).

The highest proportion of area under annual crops is found in Europe, whereas Oceania contains the largest percentage of permanent grasses and prairies (Fig. 2.1). At a regional level, Asia appears to be the region with the largest increase in agricultural area (i.e., 570 million ha: 53.7%) between 1961 and 2013, while Europe and Oceania present reductions in agricultural area of 314 million ha (-40.2%) and 59 million ha (-12.5%), respectively (FAOSTAT, 2015).

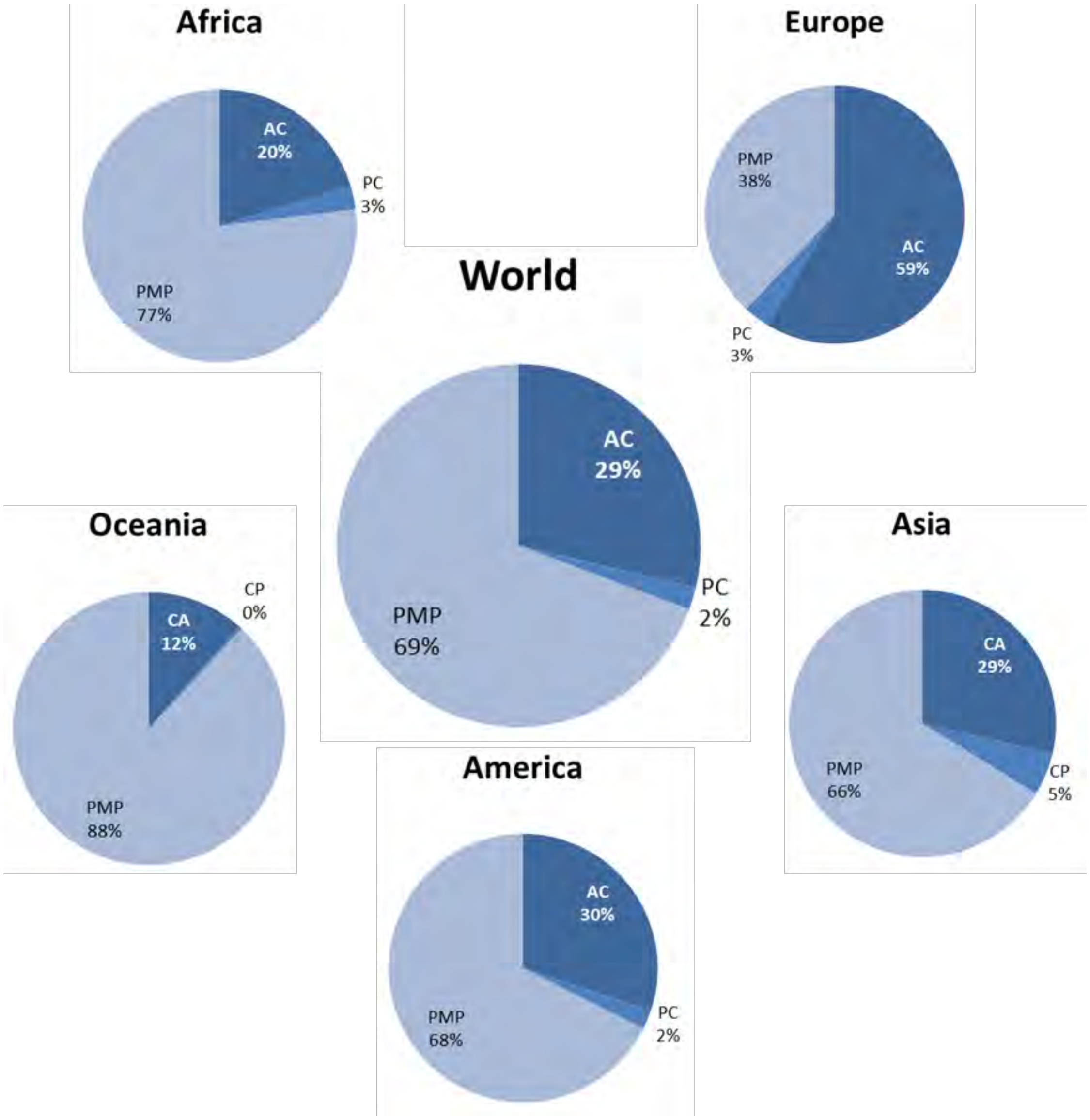


Figure 2.1 Global and regional distribution of the area of annual crops (AC), permanent crops (PC), and permanent meadows and prairies (PMP). Source: Own elaboration with data from FAOSTAT, 2015.

Together with the increase in agricultural area, the increase in areas under irrigation (70%: Alexandratos, 1999; Postel, 1999 , quoted in Foley et al., 2005) and use of fertilizers (700%: Tilman et al., 2001), as well as the use of a variety of modern seeds, have all contributed to a duplication in cereal production over four decades (1960-2000) (Foley et al., 2005). The availability[4] of calories *per capita* has increased from 2,250 (1961) to 2,750 kcal/person/day (2007) (Kastner et al., 2012). The increase in caloric availability derived from cereals was higher in absolute terms, but the highest increase in relative terms occurred in those products associated with the dietary habits of the well-off sector of the population, i.e. vegetables, fruits, vegetable oils, and animal products (*ibid*). The increase in the availability of foodstuffs has not been homogeneous. In the Eastern and central parts of Africa, throughout the four decades (1961-2007), caloric availability has remained at a low level

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[4] Referring only to the production, and not to its access or distribution.

(approximately 2,000 kcal/person/day), while in Northern Europe and Oceania, a higher level (approximately 3,000 kcal/person/day) has been maintained within the same period (*ibid.*).

The agricultural area required to feed a single person depends on the number of inhabitants, type of diet, and agricultural yield (*i.e*., the production of food per area/unit). In 1963, 2,650 m2/person/year were required; in 2005, the required area decreased to 950 m2/person/year (Kastner et al., 2012). The area required to feed a person presents important inter-regional contrasts: in Southeast Asia, 1,300 m2/person/year were required; in Oceania and Southern Europe, more than 3,000 m2/person/year, and in the Northern Europe and West Africa, 2,350 m2/person/year (*ibid*.). This increase in the production of food had important consequences for the improvement of food security for many people around the world (World Bank, 2007). Nevertheless, famine and malnutrition still prevail around the world: 12% of the world´s population is undernourished; 24.8% of the population of Sub-Saharan Africa, 13.5% in Asia, 7.9% in Latin America and the Caribbean and 12.1% in Oceania (FAO et al., 2013).

It is therefore argued that food poverty is less a problem of production than a matter of distribution and access to foodstuffs. In 1993, an evaluation was conducted on the capacity of productive systems to provide enough food for the 6.3 billion inhabitants of Earth and it was concluded that there was enough food to feed 115% of the global population with a basic diet of almost exclusively vegetable origins (FAO, 1993a). Worldwide production could have fed 77% of the population under a regime where 15% came from animal origins, and only 59% under a regime where 24% of the calories came from animal origin (*ibid).*

Waste constitutes another serious problem. It is estimated that between 30 and 50% of the food produced worldwide is wasted (IMECHE, 2013). The United Nations Food and Agriculture Organization (FAO), estimates that between 95 and 115 kg/person/year are wasted in Europe and the USA, whereas in Sub-Saharan Africa and Southern and South-eastern Asia, food waste is around 6 and 11 kg/person/year, respectively (Gustavsson et al., 2011). While in higher income countries 40% of food wastage occurs in retailing and consumption, in developing countries, 40% of the waste occurs in the post-crop and processing stages (Gustavsson et al., 2011). This problem is even more serious because of its environmental as well as ethical implications, considering that the wasted food is of animal origin. It is estimated that in the USA only 46% of beef and lamb and 42% of fish, chicken and pork is actually consumed; the rest (38 and 31%, respectively) is lost at retailing points and at home (20 and 23%, respectively) (ERS/USA, quoted in http:/shrinkthatfootprint.com). It has been argued that, to cover the requirements of a growing population, an increased production of foodstuffs from 70% to 100% (World Bank, 2007) is required. However, waste reduction could increase food availability to the point where there was no need to increase either the farming area or the use of agricultural inputs; both of which are environmentally deleterious actions.

Key message 2: Maize has become one of the most important crops for humanity, mostly because of its great environmental adaptability and high productivity. *The harvested area of maize has expanded to and within all continents and has gained ground over other grains and cereals because of its adaptability to wide latitudinal, altitudinal and rainfall ranges.*

Humanity depends on approximately 150 plant species for food, but only three of these (rice, wheat and maize) provide more than half of its caloric energy (IDRC, 2015). In 2013, the cultivated area for these three cereals together amounted to more than 570 million ha, equivalent to a little less than the Indian and Argentinian territories put together. While wheat is the cereal that occupies the largest area (38.4% of the total area), maize (32.6%) is the crop with the most extended distribution. Maize is cultivated in 166 countries; i.e., in 49 countries more than rice and 44 countries more than wheat. This pattern can be explained by the adaptability of maize to wide latitudinal, altitudinal and rainfall ranges (Tab. 2.1). Maize is grown from sea level to 3,800 meters above sea level, from desert oases to regions with more than 11,000 mm of rainfall per year, and from 42° latitude South to 50° latitude North (Timothy et al., 1988).

Table 2.1 Maize mega-environments.

ME*	Description	Altitude (masl)	Proportion of total (%)	Potential yield (t/ha)	Principal regions
1	Highland tropical >350 mm, 18–24 °C	>2,000	3	11	Ethiopia, Mexico, Andean zone
2	Wet upper mid-altitude subtropical >600 mm, 24–28°C	1,600–2,000	3	13	Ethiopia, Kenya, South Africa, central America
3	Wet lower mid-altitude subtropical >600 mm, 28–30°C	1,200–1,600	5	13	Uganda, Kenya, South Asia (winter plantings), central Brazil
4	Dry mid-altitude subtropical 350–600 mm, 24–30 °C	1,200–2,000	8	9[b]	Tanzania, eastern Kenya, central Mexico, Nepal
5	Wet lowland tropical >800 mm, 30–34 °C	0–1,200	15	9	Thailand, Nigeria, coastal central America
6	Dry lowland tropical 350–600 mm, 30–36 °C	0–1,200	14	6[b]	Coastal eastern Africa, central America, India, North-East Brazil
7	Wet temperate >600 mm, 26–34 °C	0–1,500	35	14	US Corn Belt, Western Europe, Argentina
8	Dry temperate 300–600 mm, 26–36 °C	0–1,500	17	9[b]	Eastern Great Plains USA, eastern Europe, north-western China

Source: http://aciar.gov.au/files/mn-158/s5_1-world-maize.html *ME: Maize mega environments.

The hypothetical reconstruction of the diffusion of maize outside the American Continent by Mir et al. (2013) shows how maize varieties were introduced into Europe, Asia and Africa at different times. Tropical lowland maize grains were the first to leave the American Continent. These were transported from the Caribbean region towards Southern Portugal in 1493 and from there were taken to Northern India, Pakistan and Afghanistan in the 17th century. Mexican highland varieties were introduced by the Portuguese into South-eastern Asia in 1496 and by the Spaniards in the 16th century. A diversity of native/flint corn was introduced by the French, Spaniards and possibly Portuguese to Northern France and, independently, by Portuguese expeditions to Northern Portugal (Mir et al., 2013). Varieties from the Northern part of South America were introduced by the Portuguese to West Africa in 1534 and by the Spaniards to Italy in the 16th century. Varieties from the central part of South America arrived to West Africa in the 17th century (*ibid*.). For centuries, maize was established around the world, adapting to the new environmental conditions and evolving as a result of local management and uses.

There has been a particularly rapid diffusion of maize in Africa. The area that is cultivated for maize in Africa currently exceeds that for sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*), although these two cereals were both domesticated on this continent (FAO, 1995). There are several reasons for this rapid diffusion: maize has a higher yield per person/hour labour; it is of easy harvest handling and transportation; it has a long storage life (provided it is stored properly) and it can be harvested over a relatively long period of time, according to its different maturity periods (Pingali and Heisey, 1999, quoted by Verheye, 2010).

At the global level, the expansion of maize can be explained by these and other reasons, such as its diversity of uses. In 2013, the total cultivated area of maize worldwide covered an area equivalent to the Mexican territory, and almost half of this area was found on the American continent (42%), almost a third in Asia (32.7%), 19% in Africa and 10% in Europe (FAOSTAT, 2015). From 1961 to 2013, the area of maize cultivated in the world grew by 48.8%. The area cultivated for grain maize grew by 75.4% (+79,561,635 ha), while that for green maize (corn in the cob) grew by 45% (+342,663 ha) and maize-fodder presented a 53.7% reduction (-14,478,622 ha). In 1961, maize-fodder accounted for 20% of the total maize harvest, but by 2013 this proportion had fallen to 6.6%. The reduction in area for maize-fodder and increased area for maize grain can be explained by the increased use of grain to feed livestock.

The area of maize cultivation in the world had an ascending trend between 1990 and 2013 but, in some sub-regions, there was an opposite trend. Such was the case of the Northern and Southern regions of Africa (-23.4% and -20.3%, respectively); central Asia (-82.2%); Eastern Europe (-36.6%) and Southern Europe (-10.6%), where the contraction of this area was significant. The rest of the sub-regions in the world showed a trend of increase that ranged from 5.1 to 758.6% (Tab. 2.2).

Table 2.2 Maize harvested area at a sub-regional level

Region	Harvested area of maize		% growth	Annual growth rate (%)	Intercept	Coeff	t	p
	(1990)	(2013)						
East Africa	9,756,310	15,443,643	58.3	2.27	-34.258	0.025	13.331	0.000
Central Africa	2,214,627	4,652,980	110.1	3.66	-37.64	0.026	10.801	0.000
Northern Africa	1,264,014	967,808	-23.4	-0.86	29.316	-0.008	-3.736	0.001
South Africa	4,488,399	3,575,083	-20.3	0.11	56.084	-0.02	-5.545	0.000
West Africa	7,700,469	10,822,693	40.5	1.66	-5.819	0.011	3.078	0.006
Central Asia	2,970,680	528,015	-82.2	-6.29	151.766	-0.069	-5.035	0.000
East Asia	22,230,169	36,919,263	66.1	2.32	-25.892	0.021	12.569	0.000
Southeast Asia	9,335,222	9,808,444	5.1	0.32	4.178	0.006	3.442	0.002
South Asia	7,885,299	12,401,926	57.3	2.03	-23.543	0.02	19.643	0.000
West Asia	725,719	1,194,808	64.6	2.5	-10.652	0.012	5.511	0.000
Caribbean	309,524	609,051	96.8	3.79	-30.046	0.022	6.336	0.000
Central America	9,134,866	9,663,931	5.8	0.51	18.17	-0.001	-0.732	0.472
North America	31,120,585	39,987,492	28.5	1.3	-2.475	0.01	7.32	0.000
South America	16,883,506	24,832,575	47.1	1.94	-0.77	0.009	4.071	0.001
East Europe	26,082,853	16,541,728	-36.6	-1.57	73.325	-0.028	-5.39	0.000
Northern Europe	52,750	452,927	758.6	11.01	-140.706	0.076	15.367	0.000
South Europe	4,643,386	4,150,822	-10.6	-0.43	24.172	-0.004	-4.449	0.000
West Europe	5,654,796	6,749,763	19.4	0.83	4.777	0.005	3.844	0.001
Australia and New Zealand	81,842	112,719	37.7	2.22	-11.275	0.011	3.388	0.003
Melanesia	21,238	27,909	31.4	1.26	-15.103	0.013	9.653	0.000
Micronesia	52	80	53.8	22.58	-140.259	0.072	4.055	0.001

Source: Own elaboration with data from FAOSTAT, 2015.

In the year 1990, the harvested area of maize covered 17% of the total area of grain and cereals. By 2013, this proportion had increased to 21.3%. The regions in which the maize harvested area has gained ground over other grain and cereal areas are Africa (from 30.6% in 1990 to 31% in 2013), America (from 28.8% to 31.8%) Asia (from 3.7% to 4.8%), and Europe (from 7.6 to 15.6%).

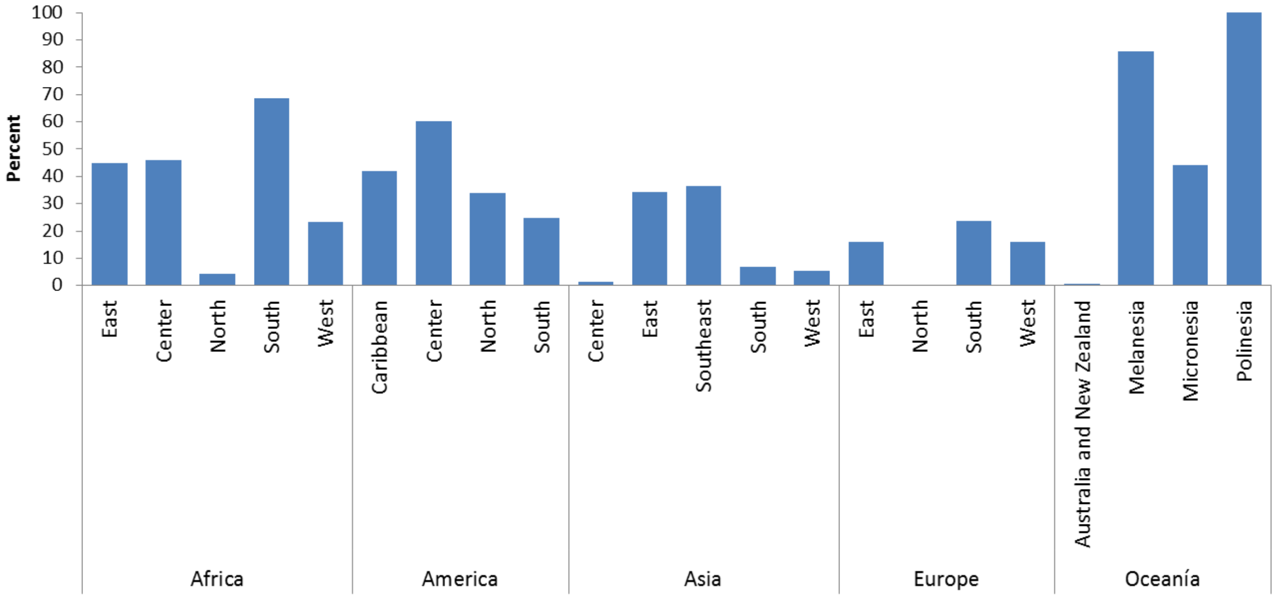


Figure 2.2. Maize harvested area in relation to total grains and cereals area at a regional and sub-regional level, 2013. Source: Own elaboration with data from FAOSTAT, 2015.

Trends show that this growth in maize area will persist in the next decades. It is estimated that by 2030 growth of all cereals will increase by 56% compared to their levels in the year 2000 and that almost half of this growth shall correspond to maize (45%), 25% to wheat and 8% to rice (Hubert et al., 2010). Half of this increase will be due to the increasing demand for cereals to feed livestock.

Key message 3: Maize production has increased twice as much as its harvested area since the year 1990. *This is the result of a generalized yield increase due to increasingly wider adoption of hybrid seeds and other modern inputs such as fertilizers, herbicides, pesticides, and mechanization. The average current maize yield is 5.5 tons/ha and is expected to reach 6.5 ton/ha by the year 2025 and 8.6 ton/ha by 2050.*

The area of maize grain cultivation in the world grew by 41% between 1990 and 2013, while its production grew 111% over the same period. This difference between area and production is the result of an overall yield increase of around 49%: from 3.7 to 5.5 ton/ha (FAOSTAT, 2015). Latin America and the Caribbean show the highest yield increase (129%: from 1.9 to 4.6 ton/ha), whereas Africa (34.5%), North America (34.2%) and the Far and Near East (28.3%) show the lowest increases. Although the latter three regions present similar relative growth, in absolute terms they are quite different: from 1.5 to 2 ton/ha in Africa; and from 7.4 to 9.95 ton/ha in North America, over the same period (FAOSTAT, 2015).

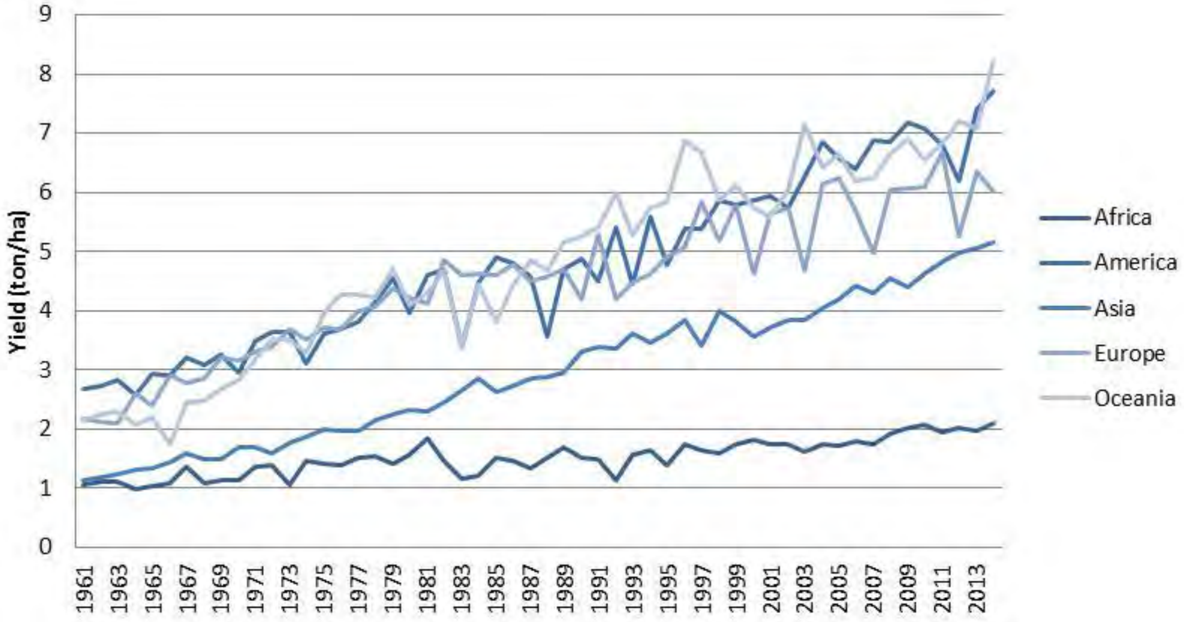


Figure 2.3 Historical maize yield (1961-2013). Source: Own elaboration with data from FAOSTAT, 2015.

The historic evolution of maize yield has followed a rather heterogeneous path in the different regions of the world (Fig. 2.3). While global maize yield in 1961 ranged between 1 and 3 ton/ha, in 2013 it had increased to between 2 and 7.3 ton/ha (FAOSTAT, 2015). Considering that there is still potential for increase, maize yield in the world is expected to reach an average of 6.5 ton/ha in 2025 and 8.6 ton/ha in 2050 (Ray et al., 2013).

Although global maize yield shows an upward trend, in some countries it has reduced substantially. For example, four of the main maize consumer countries, all of which are in the African continent, have experienced important reductions. This is the case of Lesotho, where yields have declined by 21.8% (from 1.1 to 0.9 ton/ha), as well as in Swaziland (-6.8%: from 1.2 ton/ha to 1.1 ton/ha), Tanzania (-12.3%: from 1.5 to 1.3 ton/ha) and

Zimbabwe (-48.4%: from 1.7 to 0.9 ton/ha) (FAOSTAT, 2015). However, despite these negative trends, the tendency at global, regional and sub-regional levels continues upwards (Tab. 2.3).

Table 2.3 Maize yield and its tendencies at a sub-regional level

Region	Sub-region	Mean (1990-2013)	Standard deviation	Annual growth rate (%)	Coefficient	t	P
Africa	East	1.45	0.21	2.48	0.013	3.774	<0.01
	Central	0.93	0.11	1.96	0.015	6.97	<0.001
	North	5.41	0.97	2.06	0.025	11.132	<0.001
	South	2.79	0.9	10.33	0.041	5.452	<0.001
	West	1.45	0.22	2.38	0.02	12.369	<0.001
Asia	Central	4.39	1.17	3.09	0.039	9.336	<0.001
	East	5.07	0.45	1.44	0.01	6.424	<0.001
	Southeast	2.84	0.76	3.76	0.038	86.415	<0.001
	South	2.08	0.46	2.99	0.03	19.779	<0.001
	West	4.34	1.03	2.85	0.027	7.774	<0.001
America	Caribbean	1.14	0.21	2.24	0.019	4.788	<0.001
	Central	2.5	0.35	1.93	0.019	12.869	<0.001
	North	8.57	1.04	2.15	0.013	5.275	<0.001
	South	3.49	0.87	4.66	0.035	17.404	<0.001
Europe	East	3.87	0.84	5.49	0.02	4.002	<0.01
	North	4.11	1.84	19.4	0.132	5.05	<0.001
	South	6.55	0.86	2.88	0.014	4.786	<0.001
	West	8.64	0.91	1.64	0.011	5.021	<0.001
	Australia and New Zealand	6.45	0.62	1.43	0.01	5.15	<0.001

Source: Own elaboration with data from FAOSTAT, 2015.

There are several reasons behind the increasing yield and its differential development in each region. It is recognized that the agricultural sector has experienced a significant growth in yield as a result of the so-called Green Revolution. This new agricultural approach began in the United States in the 1940s and spread to the rest of the world at the end of the 1950s, with the development of modern varieties of wheat, rice and maize grains and the concomitant use of fertilizers, herbicides and agricultural and irrigation infrastructure (Evenson and Gollin, 2003).

It has been estimated that between 50 and 60% of the growth in crop yields can be attributed to the development of high yield varieties of maize (Duvick, 2005). The other 40 to 60% of the yield increase can be attributed to the use of fertilizers (Stewart et al., 2005). According to data published by CIMMYT, between 1966 and 1998, the public sector released a total of 708 modern varieties (MV) of maize grain in Latin America and the Caribbean, 98 in Eastern and Southern Africa and 366 in Southern, Eastern and South-eastern Asia (Duvick, 2005; Morris, 2002). The maize grain MVs released by the public sector in each region respond not only to local ecological conditions but also to the uses and goals of maize production that guide consumption preferences such as the particular colour or texture of the grain (Tab. 2.4).

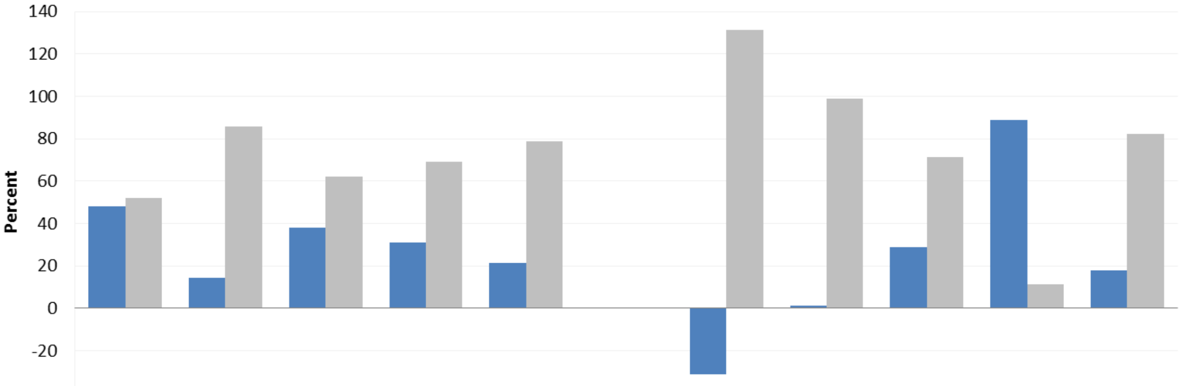
Table 2.4 Modern varieties' release from the public sector in America, Africa and Asia.

Released varieties from the public sector (1966-1998)		**Latin America and the Caribbean**	**East and South of Africa**	**South, east and southeast Asia**
	Total (number of varieties)	708	98	366
Type of material	Hybrid varieties (%)	37	48	59
	Open pollinating varieties (%)	63	52	41
Ecological adaptation	Lowland tropical (%)	61	20	74
	Subtropical median altitude (%)	23	69	26
	Highlands (%)	8	8	0
	Temperate zones (%)	8	3	0
Grain color	White (%)	55	96	24
	Yellow (%)	45	4	76
Grain texture	Flint/semi-flint (%)	44	46	72
	Dent/semi-dent (%)	23	40	12
	Others (%)	33	15	17
Maturation	Very early/early (%)	11	9	58
	Intermediate (%)	35	26	21
	Extra late/late (%)	54	65	21

Source: adapted from Morris, 2002.

It has been stated that the use of MVs affects yield by improving the tolerance of the plant to several types of stress (Duvick, 2005). Greater resistance to lodging, higher tolerance to abiotic and biotic stresses and increased yield rate per plant under conditions of high plant density, are amongst the characteristics that MVs are designed to present (*ibid).*

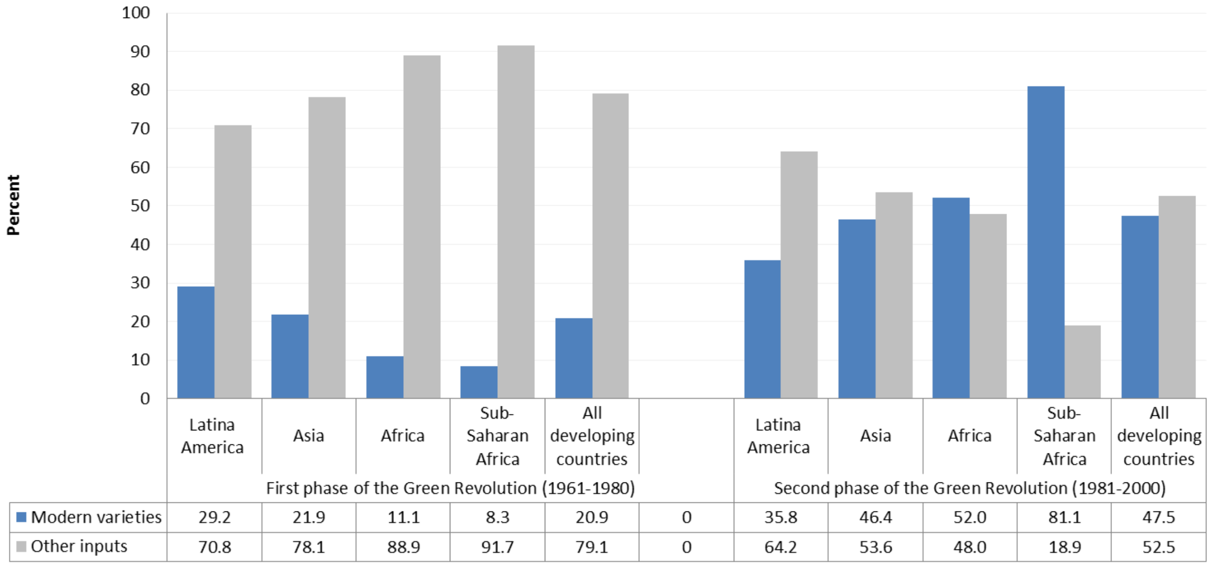
According to Evenson and Gollin (2003), during the first phase of the Green Revolution (1961-1980) cereal production growth rates in Latin America, Asia and Africa were more a consequence of yield improvement than of area expansion. As shown in figure 2.4, the contributions of yield and area increase, respectively, differ between regions. In Asia, only 14% of the increase of cereal production was due to the expansion of cultivated area, whereas in Latin America the expansion of the cultivated area was responsible for almost half of the cereal production. In the second phase of the Green Revolution (1981-2000), yield increase was responsible for most of the production increase in all regions of the world (86%) except for Sub-Saharan Africa (Evenson and Gollin, 2003). There was a drastic change in Latin America, where area expansion became negative.



	Latina America	Asia	Africa	Sub-Saharan Africa	All developing countries		Latina America	Asia	Africa	Sub-Saharan Africa	All developing countries
	First phase of the Green Revolution (1961-1980)						Second phase of the Green Revolution (1981-2000)				
■ Area	48.1	14.1	37.9	31.0	21.4	0	-31.2	0.9	28.7	88.6	17.6
■ Yield	51.9	85.9	62.1	69.0	78.6	0	131.2	99.1	71.3	11.4	82.4

Figure 2.4 Contribution of area and yield to the growth rate of cereals production. Source: adapted from Evenson and Golling, 2003.

The use of MVs had a lesser influence on yield annual growth rate in the first phase of the Green Revolution than in the second (*ibid*.); other inputs were more influential in the former phase (Fig. 2.5). The concept of *yield gap* refers to the difference between potential and actual yield. *Potential yield* refers to unlimited water and nutrient conditions and effectively controlled stress sources (van Ittersum and Rabbinge, 1997). Some factors directly affect the yield gap, such as nutritional deficiencies or imbalances, lack or excess of water, inadequate soil, overgrowing weeds, damage by insects or illnesses, lodging and low quality seeds. With respect to maize, there is a wide difference in yield gap production regions of the world (Lobell et al., 2009), as shown in Fig. 2.6. However, the yield gap in maize is much larger than in other cereals such as rice and wheat. In fact, the actual yield of maize represents 35% of the potential yield, whereas in rice and wheat the actual yields account for 60% and 65%, respectively. This can be attributed to the fact that a large proportion of maize is grown under seasonal conditions, thus increasing its vulnerability to abiotic stress (*ibid*.). Other possible explanations for the large yield gap in maize are that human population density is lower in maize production areas than in those of rice and wheat, and that a greater availability of labour and arable land exists for maize, which may act to limit the adoption of more efficient technologies. Finally, it is also likely that estimates for the yield gap in rainfed systems are inaccurate, and that there is a consequent overestimation of potential yield for these systems (*ibid).*



	Latina America	Asia	Africa	Sub-Saharan Africa	All developing countries		Latina America	Asia	Africa	Sub-Saharan Africa	All developing countries
	First phase of the Green Revolution (1961-1980)						Second phase of the Green Revolution (1981-2000)				
■ Modern varieties	29.2	21.9	11.1	8.3	20.9	0	35.8	46.4	52.0	81.1	47.5
■ Other inputs	70.8	78.1	88.9	91.7	79.1	0	64.2	53.6	48.0	18.9	52.5

Figure 2.5 Contribution of MV's and other inputs in cereals yield growth rates. Source: adapted from Evenson and Gollin, 2003.

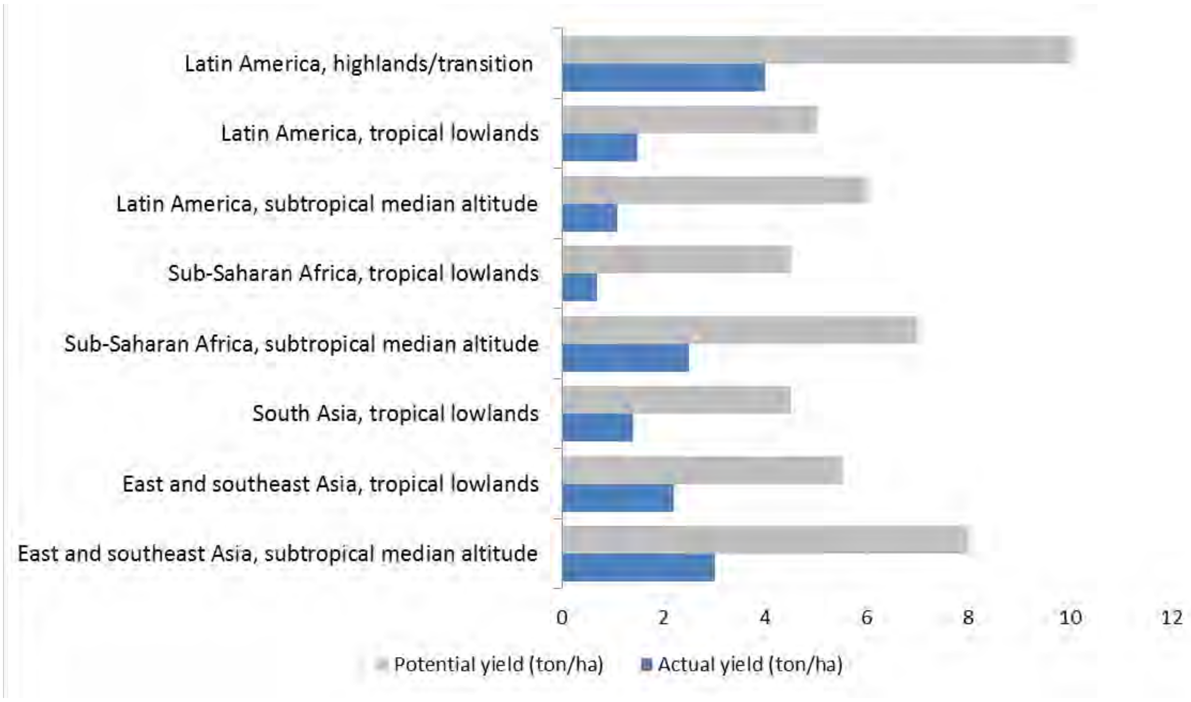


Figure 2.6 Maize actual yield and potential yield in Sub-Saharan Africa, Latin America and Asia. Source: adapted from Lobell et al., 2009.

Data from CIMMYT (2002, quoted in Schreinemachers, 2006) shows that Mexico is one of the countries with greater yield potential, but also has the highest yield gap. MVs have existed for 40 years in Mexico but their adoption has been limited. In 1996, only 20% of the cultivated area of maize (most of it comprised of commercial plantations) made use of MVs of grains (*ibid.).* In Mexico, central America, the Caribbean, the Andean region, Eastern, Western, and central Africa, more than half the maize area is cultivated with seeds that come from the previous crop (Morris, 2002).

According to Schreinemachers (2006), farmers resist the use of alternative methods (*e.g.* MVs and agrochemicals) designed to maximize the production of any crop. There are different reasons for this resistance: 1) an increase in the yield of a given crop reduces the yield of another of equal value (e.g. maize and beans), 2) high yield varieties have a lower cost in the market, 3) the costs of climate change are greater than the benefits of a higher production to a certain scale, 4) risk aversion and 5) cultural landrace preferences. There are a number of reasons that explain the conservation of landraces in the field: greater adaptability to prevailing environmental conditions, cultural preferences, handling of risk factors in the face of climatic and phytosanitary contingencies and the socioeconomic conditions of the producers (Perales et al., 2003; Bellon, 2006; Perales and Golicher, 2014). On the other hand, the adoption of MVs mainly involves economic factors: government support for the production of maize, a lower seed price compared to the price of grain, greater access to the market and availability of germplasm under modern public programs, among others (Kosarek et al., 2001). In a region of Chiapas, Mexico, Bellon and Hellin (2011) found that governmental subsidies providing MVs, farm size and the relationship between the price of fertilizer and the price of grain are three factors that are positively associated to the adoption of MVs.

2.2 Maize and its uses

Key message 4: There is no crop with such a wide variety of uses as maize. *In addition to its high environmental adaptability and productivity, maize has become the most abundant crop globally because of this versatility. Since the 1940s, its high starch content, high yields, and low price have made maize not only a source of food but mainly a raw material for edible and non-edible industrially processed products, sold in markets worldwide.*

Although maize has had multiple uses historically, some of them closely linked to the cultural development of both producers and consumers of this cereal, for thousands of years and up to the beginning of the 20th century it was mainly used for food. However, this changed in the 1940s when the so-called Green Revolution began. Since then, most of the maize grain worldwide is used by new mass production industries and international commerce in processed products, both edible and non-edible. Thus, as well as being directly consumed as food, maize is now used at large-scale mainly in the production of feed, but also in that of fructose/glucose, flour and oils. These first-stage industrial products are used in secondary products that are found in markets worldwide, including soaps, insecticides, ceramics, adhesives, plastics, tyres, paper, carton, textiles, cosmetics, paints, diapers, pharmaceutical products, antibiotics, serum, nitro-glycerine for explosives, tooth pastes, ice cream, marmalades, soft drinks, juices, chips and snacks, cold meat, baby food, chewing gum, frostings, chocolate and milk powder, candies, dressings, cooking oil, flour and other baking powders, sweeteners, alcoholic drinks and ethanol, as well as feed mainly for cattle, pork and poultry, in order to produce meat, eggs and dairy products.

Maize is grown mainly for the production of dry grain. This is the purpose of around 94% of its cultivated area, with the remaining 6% dedicated to the production of sweet corn, forage and silage (FAOSTAT, 2015). As shown in figure 2.7, from the year 1961, the FAO kept a register of the different uses of maize grain, grouped into six groups: food, manufactured food, feed, seed, waste and others. The latter group includes the production of ethanol. For more than half a century, the production of maize grain for feed has constantly been more than four times higher than that for food (Fig. 2.7). The quantity of maize grain used in the production of ethanol also exceeds, since 2006, the production of *food*. All of these six groups of maize use have presented a positive mean annual growth from 1961, *i.e.*, no group has grown at the expense of another (FAOSTAT, 2015). Between 1992 and 2011, the AMG of feed and others (ethanol) amounted to 12% each: a value well above that for food (2%) and processed food (3%). This positive AMG in all groups at global level also appears in each of the 19 sub-regions into which the FAO divides the world.[5] In all these sub-regions, the main use of the grain is as a *feed*, except in Central America and Mexico, Sub-Saharan Africa and Southern Asia, where maize is primarily used as food, and in Northern Europe, where its principal use is in processed food (FAOSTAT, 2015).

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[5] The 19 sub-regions, analyzed in this study, according to the regionalization adopted by the FAO, are: North America, central America (including Mexico), Caribbean, South America, Western Europe, Southern Europe, Northern Europe, Eastern Europe, North Africa, West Africa, Central Africa, East Africa, Southern Africa, Western Asia, central Asia, Eastern Asia, Southeast Asia, Southern Asia and Oceania.

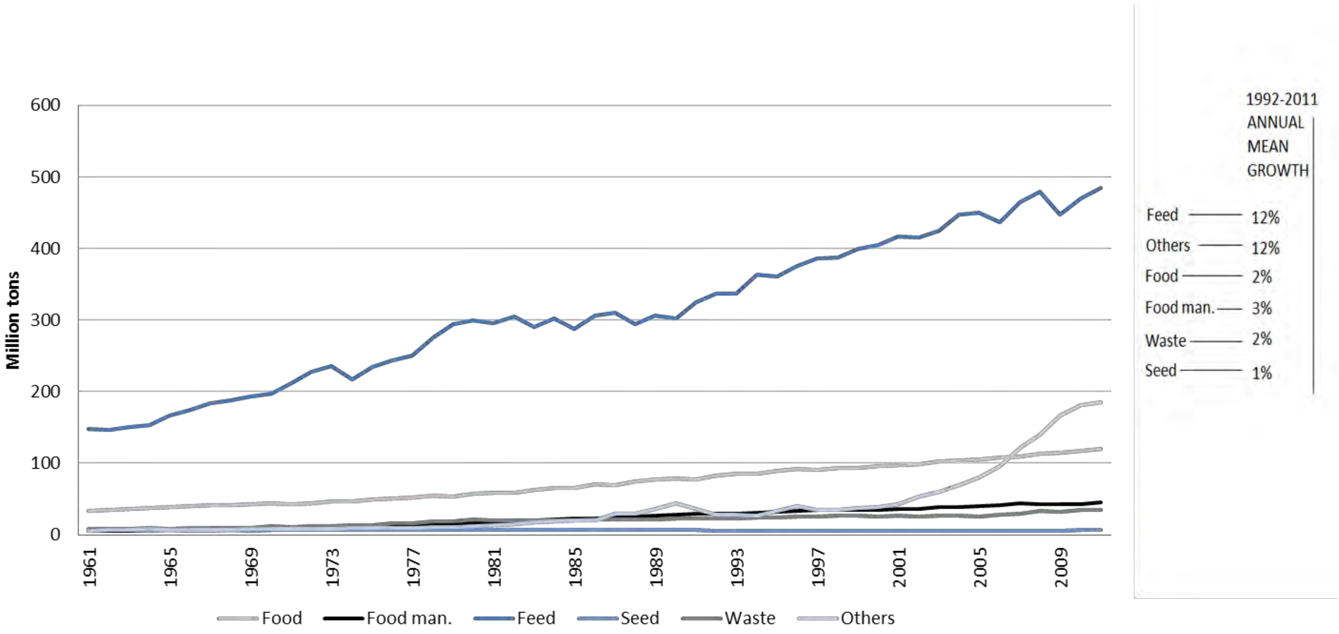

Figure 2.7 Historic evolution of different maize-grain uses in the world. Source: Own elaboration with data from FAOSTAT, 2015.

The use of maize is related to the variety of the plant, i.e., to the kind of grain that is produced (Fig.2.8). Commercially, maize is classified into three broad types: yellow, white and native/flint[6]. Yellow and white MVs come from similar landraces. At least from the second half of the 20th century, the greatest quantity of white and yellow maize seed are industrially produced MVs that are also known as *dent*[7] or *field corn*. From each of these two industrial types of maize (white and yellow), many varieties have been created but all of these maintain a very high starch content, present high yields and are cultivated using high modern technological and energy inputs, as well as financial capital. Yellow maize is chiefly used in the production of feed (either grain or fodder and silage), edible oil and ethanol, whereas white maize is used in the production of dough, snacks, cereals and high fructose syrup. In Mexico, unlike in the USA, white maize is also used in the production of edible oil. Finally, flint or native maize presents a wide variety of colours, including white and yellow. These landraces have a limited access to non-local markets and are mainly consumed as non-industrially processed food in a wide variety of forms, which represent diverse cultural values, mainly in the centres of domestication and diversity of this plant (see message #8, 9 and 10).

The contents and nutritional properties of the white varieties are practically the same as the yellow ones. "There is no proof of a better digestibility or nutritional value" between them (FAO and CIMMYT, 1997). What actually transforms the chemical composition of the grain, and thus its nutritional value, is the type of processing it goes through prior to consumption (FAO, 1993b). On the other hand, the different varieties of these two commercial types of maize do not, on average, differ in terms of yield. Their different uses are mainly the result of cultural

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[6] The term 'flint' refers to flint-stone, because of the hardness of the outer layer of this grain variety.

[7] The term 'dent' is related to the fact that once the grain dries, it contracts because of the absence of humidity, creating a small indentation at the crown of the grain.

preferences. In general terms, the white maize food consumer prefers white grain because the yellow colour is associated with feed and (in the case of Sub-Saharan Africa) this maize is given away to the poorest sectors as humanitarian aid. Yellow maize is used as feed for poultry, giving the meat a yellow colour that is preferred by the consumer (FAO and CIMMYT, 1997). The market value of both white and yellow grains is not subject to much variation. In general, the price of white grain is slightly higher than that of yellow grain due to the extra cost implied by legal issues in the handling of a grain destined for human consumption (*ibid*.). Margins vary constantly due to factors of supply and demand in the international markets, speculation on future commercial value and on the fluctuations in the exchange rate. Oil price also has a bearing on the price of maize. Higher oil prices tend to raise the demand and production of agro-fuel supplies. This, added to the high subsidies paid for maize – particularly in the United States – have contributed to the increases in the price of yellow maize, especially since the year 2006 (Babcock and Fabiosa, 2011; IICA, 2014), which have led to the substitution of food crops (including white maize) for the yellow maize and, as a consequence, supply has declined and thus prices have increased for such food crops.

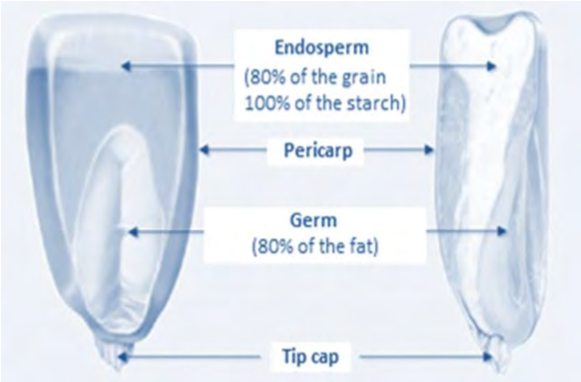

Figure 2.8 Description of the parts of a maize kernel**.** Source: Own elaboration.

The high starch content in maize, as well as its high yield and (subsidized) low price (see message #14), give this cereal an advantage over other crops or industrial raw materials that are used to process starch to produce ethanol or high fructose syrup. It also offers an advantage to the livestock industry, which seeks to maximize efficiency in the process of increasing livestock weight. Uses of maize differ from those of wheat and rice, which have been used primarily for non-industrially processed food since 1961. Table 2.5 details the differences in use among these three basic cereals, showing that 80% of rice and 67% of wheat are used for food. Unlike with maize, the use of wheat for feed is low (21%) and is even lower for rice (7%). In terms of the total harvest weight of these three grains, at a global level, maize has the highest production (43%), followed by wheat (32%) and then rice (25%). Despite this statistic, there is a lower production of food from maize than from either wheat or rice.

Table 2.5 Maize, wheat, and rice uses and (total and food) production in 2011.

			Uses				**Production**	
	Food	Man. food	Feed	Seed	Waste	Others	Total	For food
MAIZE	14%	5%	55%	1%	4%	21%	43%	11%
WHEAT	67%	1%	21%	5%	4%	3%	32%	47%
RICE	80%	1%	7%	3%	6%	3%	25%	42%

Source: Own elaboration with data from FAOSTAT, 2015[8]

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[8] The most updated information from FAOSTAT for maize uses for all countries is from the year 2011. This information was accessed in May, 2015.

Key message 5: The vast majority of maize in the world is produced as a raw material for the livestock, sweetener and oil industries, as well as for the production of ethanol and other non-edible products. *The production of maize grain for feed is four times greater than for food, while the production of maize for ethanol is also much larger. The supply chain of maize is heterogeneous and defined by its ultimate use.*

As mentioned previously, industrial livestock and ethanol production (recent) predominate in the use of maize grain worldwide and show the highest mean annual growth over recent decades. Most cattle, pork and poultry are currently given grain-based feed, mainly derived from maize. Since the 1960s, maize has superseded wheat as the main grain-based feed worldwide. The demand for maize in 2013 (one million tons) was twice that of the other feed grains put together, excluding wheat – i.e., it duplicated the added demand of feed made with soybean, rye, sorghum, barley oats and rye. Around 60% of the maize grain produced in the world over the last fifty years has been used for feed. Besides grain, maize offers three other sources of feed: the entire plant, silage, and dry distillers grains (DDG). The whole plant is harvested, cut and served, or stored in a silo. Silage is the process of converting the whole plant into a fermented and high-humidity fodder with which to feed ruminants. On the other hand, the DDG are derived from the production of ethanol: the solid leftovers of the distillation process of grain. These have high protein content and are used in feeding livestock. More than 1400 million tons of DDG were produced in the United States (US) in the commercial year 2014/2015, accounting for 10% of the weight of the maize grain used in that country (USDA-WASDE, 2015).

Ethanol is the newest industrial use for maize. It is produced through fermentation of the starch. Practically all maize ethanol in the world is produced in the US, which accounts for 67% of worldwide ethanol production –the rest is mainly produced in Brazil from sugarcane (USDE, 2014). Figs. 2.9 and 2.10 show the steady increase in the production of ethanol from maize since 1980 and its distribution in the US, respectively. More than 75% has been produced in the *Corn Belt* of the USA (USDA, 2014b). Yellow maize No. 2 is the variety used for the production of this alcohol (Fuentes et al., 2005). During the first decade of this century, total production of maize ethanol has reached an outstanding AMG of 26.6%. Following the market trends, a constant increase is expected over the coming decades (Shiferaw et al., 2011), particularly if the prices of fossil fuels increase (Cassman et al., 2005). In the USA, maize ethanol has been replacing the use of fossil fuels to a significant extent, as demonstrated by the reduced importation of oil into that country as a consequence of the availability of this new source of energy (USDA, 2014a). Maize demand for ethanol production in the US has grown since 2008, when a national project was created with the intention to replace gasoline with ethanol in that country, even though this may not have been the most efficient decision. In the 2011/2012 cycle, one quarter of the production of maize in the US was used for the production of ethanol (IICA, 2014).

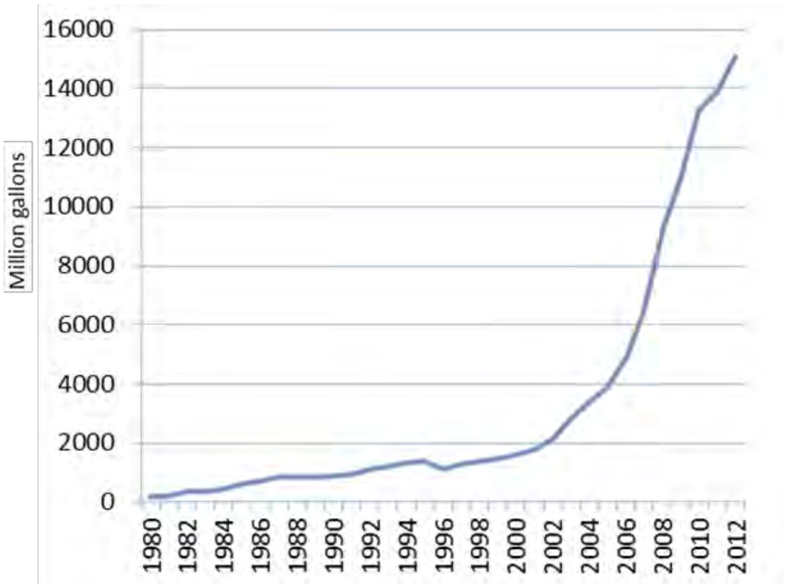


Figure 2.9 Maize ethanol production in USA. Source: Own elaboration with data from the USDE, 2014.

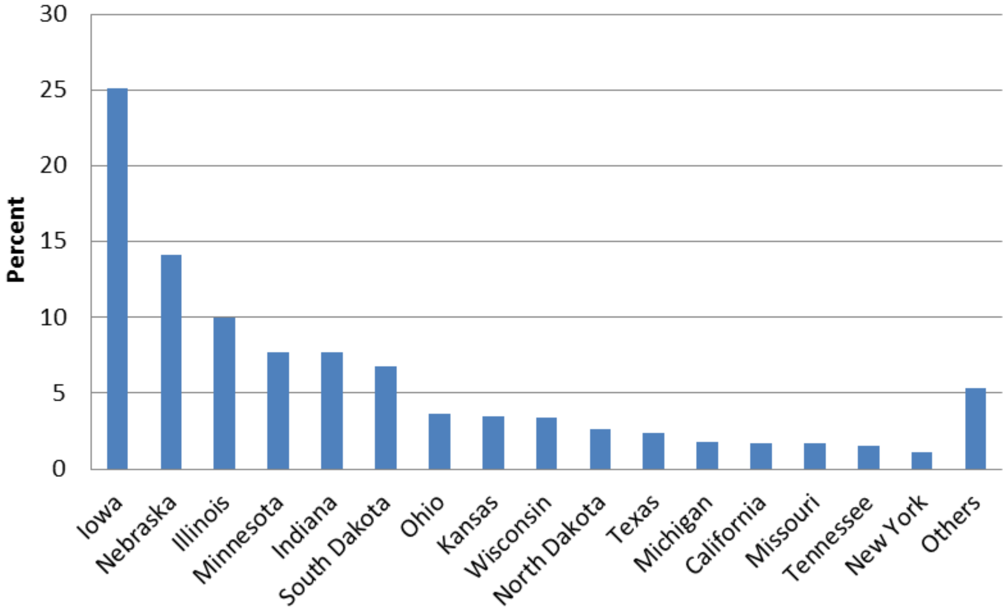


Figure 2.10 State level distribution of maize ethanol production in USA. Source: Own elaboration with data from the USDE, 2014.

Ethanol is only one of a series of derivatives of maize starch. Starch is extracted from the endosperm of the grain and transformed into sugar. This starch is, in turn, fermented or transformed into fructose, glucose, maltose, dextrose, syrup solids or maltodextrins for the manufacture of a wide variety of alcohols, sweeteners, papers and textiles. Maize starch is also used by the pharmaceutical industry as an adhesive or disintegrator. This latter item allows tablets or capsules to dissolve in order to facilitate absorption by the body. After ethanol, the most important industrial use given to maize starch is the production of high fructose syrup, known as high fructose corn syrup (HFCS). This product has gained ground over sucrose because of its easier storage, handling and transportation (its liquid state takes up less space than sugar grains), because the price of HFCS is more stable than that of sucrose given high governmental subsidies for the production of maize, and finally because maize has a wider base production than sugarcane globally. HFCS has become the main sweetener of soft drinks and is used in fruit juices, breads, confectionery, marmalades, cereals, yoghurts and other dairy products, condiments and canned and packed products. Maize entered the industrial market at the end of the 1960s and has since then achieved high production and distribution growth rates. The consumption of maize is still nine times smaller than sucrose but, in the USA, it is already found in 40% of all sweeteners. Its nutritional value and possible contribution to an increase of diabetes and hypertension in countries that use more HFCS than sucrose has been the subject of debate (Tordoff and Alleva, 1990; Bray et al., 2004; Stanhope and Havel, 2008; White, 2008).

Maize has also become one of the main sources for edible oil production, with constant growth recorded over recent decades. Its grain germ, which contains around 80% of the grain's fat, is mainly used to produce cooking oil, but is also used in other industrial products such as soaps, ointments, paints, colourings, textiles, nitroglycerine, insecticides, and anticorrosives. Its production is currently concentrated in the US and Canada (58%), the Eastern Asia (13%), the European Union (11%) and South America (7%); almost all of the rest is produced in East Africa (3%), South Africa (3%), Western Asia (3%) and Mexico (1%) (FAOSTAT, 2015). Compared to other cooking vegetable oils, maize oil is still in the minority considering that, from the 1960s to the present, it has constantly represented only around 2% of the total production of vegetable oil in the world and currently holds ninth place after African oil-palm, soybean, rapeseed, sunflower, peanut, cotton, olive, and coconut (FAOSTAT, 2015). Nevertheless, the demand for maize oil has been constantly increasing: 720% between 1961 and 2013, to reach a total of approximately 3 million tons a year, as shown in the following figure.

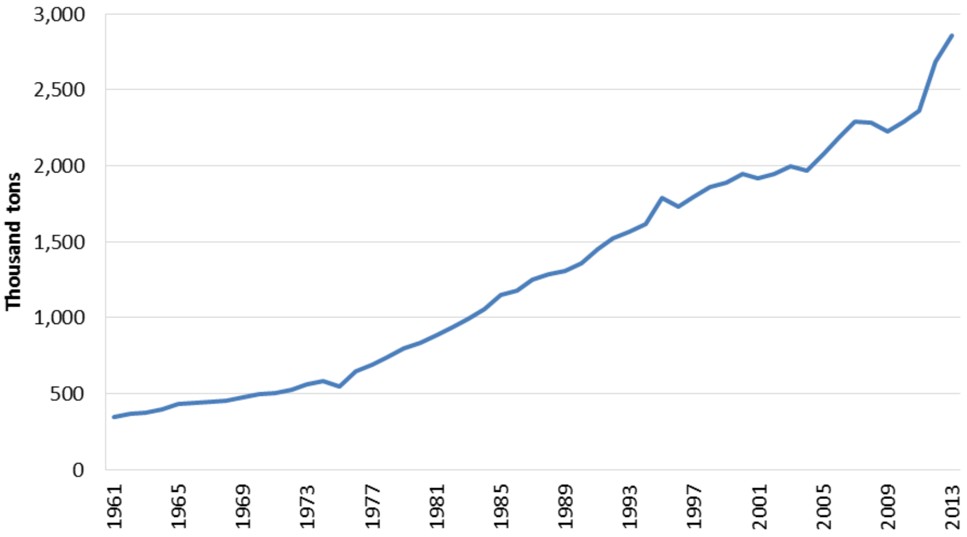


Figure 2.11 Production of maize edible oil in the world (1961-2013). Source: Own elaboration with data from FAOSTAT, 2015.

The great variety of maize products and ingredients described above implies a highly heterogeneous supply/value chain. The type and quantity of inputs, processing, distribution and outputs in the maize supply /value chain are all defined by the ultimate consumption goal. Whether this ultimate goal is, for example, providing food for the farmer’s household, raw material for the national soft drink or ethanol industries or for the livestock and fast-food industries in a distant country, a high contrast exists in terms of labour, land, materials, equipment and other financial, technological and energetic resources involved in the different stages of the chain. To analyse this chain, an initial division can be made between small and large-scale systems (Fig. 2.12). In fact, in a prototypical smallholder system, on the one hand, there is a direct link between production and consumption, *i.e.,* the farmer and his/her family consume their own production and, therefore, the whole cradle-to-grave process involves the same agricultural landscape. Consumption and production decisions are linked in these smallholder low-input rainfed systems (Bellon et al., 2015). A second link of the chain typically appears in these systems whenever there is a production surplus, which is then sold in local markets (Bellon and Berthaud, 2004). In the opposite extreme case, however, such as a prototypical intensive irrigated system, high external inputs that are invested in extensive lands represent only the first link of a large chain of transformation and distribution of products. There is of course no direct link between the producer and the consumer in such a system. As shown in the following figure (2.12), the entire maize grain production in large-scale systems is first transported to three major industries: refiners, dry millers and distillers (CRA, 2006). The various by-products of each of these industries are directed to other domestic and foreign industries and markets.

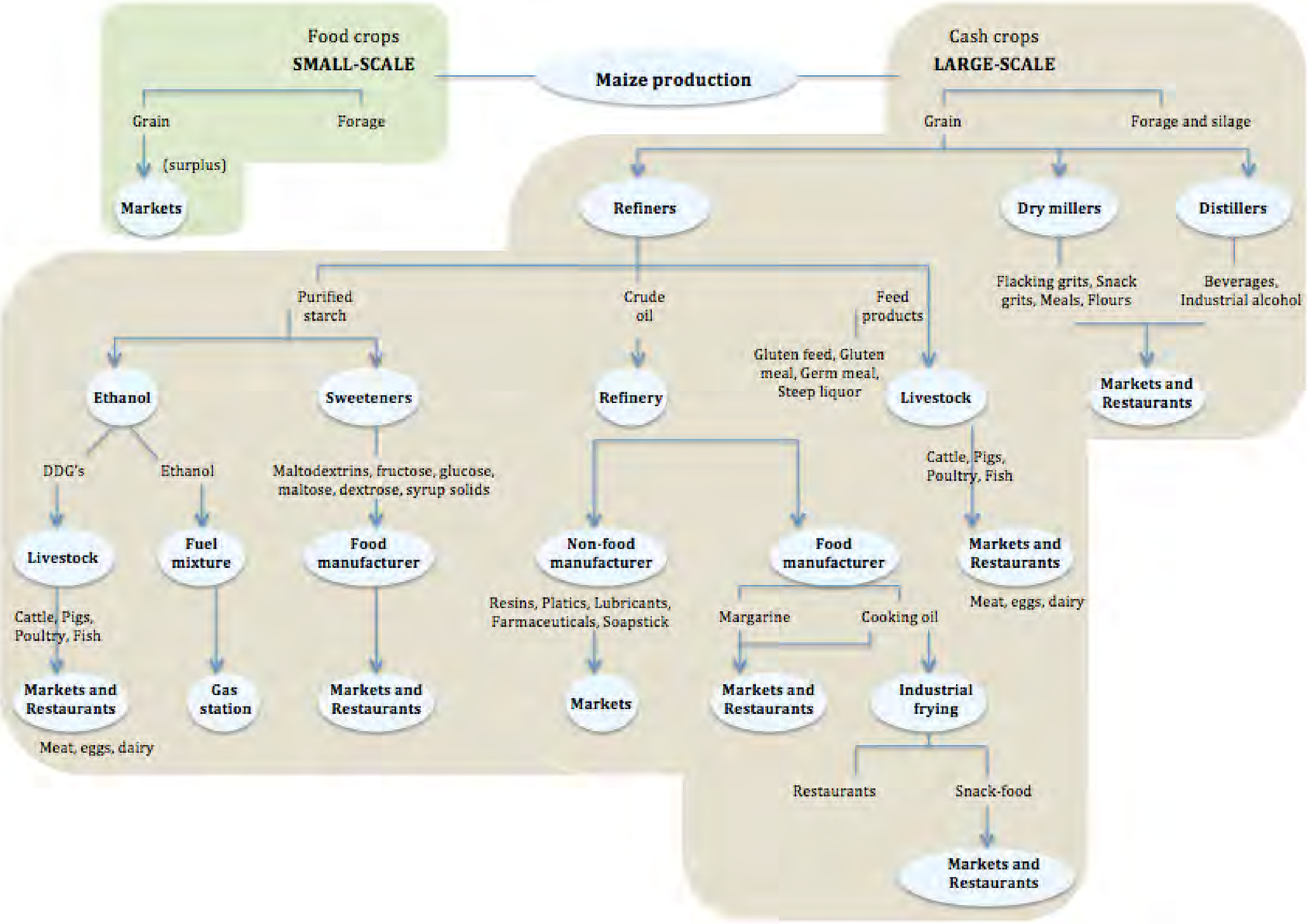


Figure 2.12 Maize supply chain in small and large-scale systems. Source: adapted from CRA, 2006.

Key message 6: In contrast with maize produced for industrial purposes, non-manufactured maize (direct food-maize) is geographically restricted in terms of its consumption, production and commerce. *With exceptions such as Mexico and Central America, the production and consumption of direct food-maize is concentrated in societies with high poverty rates that depend on this cereal as a staple food, i.e., as a main nutrient source. Besides landraces, practically all direct food-maize comes from white varieties, which represent only 4% of the total quantity of internationally traded maize.*

The large majority of maize produced for non-industrially processed food is consumed within the boundaries of the country where it was produced, i.e., its exportation is limited. Together with native maize, nearly all maize that is consumed as food is of the white variety. White maize represents only 4% of internationally traded maize (Shiferaw et al., 2011); the other 96% is yellow maize, which (as described above) is mainly destined for the livestock, ethanol and edible oil industries. The volume of white maize that is internationally traded is just over two million tons a year, which accounts for only 0.002% of the total production of this food variety (Fuentes et al., 2005; IICA, 2014). Native maize is produced above all for (family and community) self-consumption, which implies that nearly all maize that is internationally traded for food is of a (high yield) white variety. However, a recent tendency has favoured the exportation and consumption of native maize varieties for the gourmet market (Shiferaw et al., 2011; Burnet, 2016).

The main exporter of white maize is South Africa (1.5 million tons in 2012/13). South African maize is exported principally to neighbouring countries of Sub-Saharan region such as Botswana, Namibia, Zimbabwe, Mozambique, Lesotho and Swaziland. The second most important exporter of white maize is the USA, particularly the states of Texas, Nebraska, Indiana, Illinois and Iowa (USDA, 2015b). This represents 1% of US maize production and also 1% of its exportations, mainly heading to Mexico, Colombia, Honduras, El Salvador, Japan, Guatemala and Costa Rica. South Africa and the USA jointly account for nearly three quarters of the international exportations of white maize (USDA, 2015b).

Since the 1970s, white maize has mainly been produced in Africa (47%), Latin America (31%) and Southeast Asia (11%), i.e., in countries with low and medium incomes (see Fig. 2.13). In Europe, this type of maize is produced at a small-scale in Portugal, Italy and France. Mexico is by far the leader of the ten main white maize producers, with 26% of the production for the 2004/2005 cycle, followed by Egypt (8%), Nigeria (6%), South Africa (6%) and the USA (4%) (Fuentes et al., 2005). This is a limited production and distribution compared to that of yellow maize, which is produced both intensively and extensively on all continents. White maize represents only 12% of global maize production (Fuentes et al., 2005).

The main maize producing countries in the world contribute little to the production of food maize, with the exception of Mexico, South Africa and Egypt. For example, the USA, China, Brazil, France, India and Argentina together produce around 75% of the maize in the world, but contribute only 11% of the production of white maize. Within each of these six countries, yellow maize accounts for between 91% and 99% of their total production.

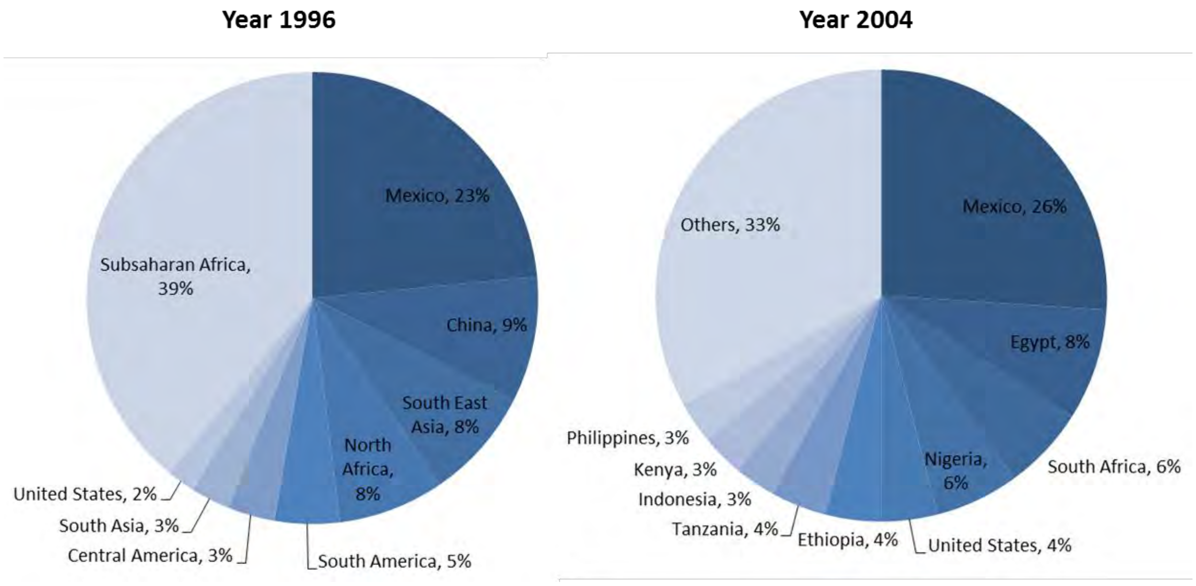
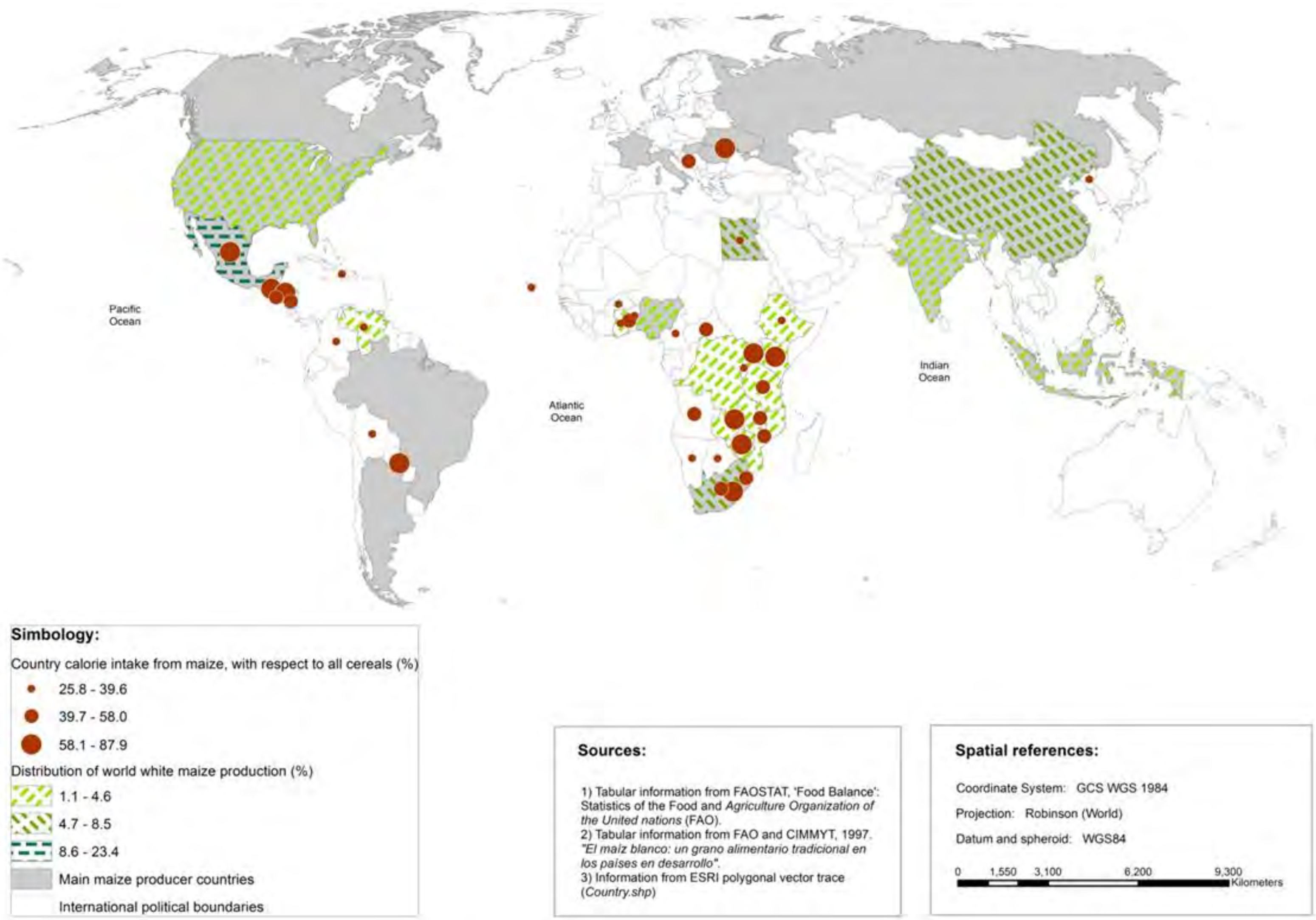


Figure 2.13 World distribution of white maize production for the years 1996 and 2004. Source 1996 data: FAO and CIMMYT, 1997; Source 2004 data: Fuentes et al., 2005.

White maize production regions happen to coincide with the regions where people have adopted this maize as a staple crop (Fig. 2.14). In nearly all countries of the world, maize is consumed as food, but only in one third of these countries is food its main use. In other words, in more than 65% of the countries, maize has a predominantly industrial use. The countries that consume maize mainly for food are located almost entirely in the Sub-Saharan Africa, Latin America and Southern Asia. For 900 million poor people, this cereal constitutes their main food source (Shiferaw et al., 2011). In 21 countries, maize contributes to more than 20% of the total calorie intake, with extreme cases such as Zambia (51%), Lesotho (56%) and Malawi (88%). With respect to all cereal types, calorie intake from maize consumption is greater than 25% in 37 countries, almost all of which are located in Sub-Saharan Africa and Latin America. Prominent among these countries are Zambia, Mexico, Lesotho, Guatemala and Zimbabwe. In the 37 countries that have adopted maize as a staple crop –19% of all countries in the world and 12% of the world population–, an average of 84 kg per capita per year are consumed; that is, nearly four times the global average (FAOSTAT, 2015)



Sources:

1) Tabular information from FAOSTAT, 'Food Balance': Statistics of the Food and *Agriculture Organization of the United nations* (FAO).
2) Tabular information from FAO and CIMMYT, 1997. *"El maíz blanco: un grano alimentario tradicional en los países en desarrollo"*.
3) Information from ESRI polygonal vector trace (*Country.shp*)

Figure 2.14 Relationship between: a) maize staple crop countries, b) the distribution of world white maize production, and c) main maize producer countries. Source: Own elaboration with data from FAO and CIMMYT, 1997; and FAOSTAT, 2015.

Compared to other staple crops, maize has a medium nutritional value, in terms of carbohydrates, proteins and fats, as shown in Table 2.6. The amount of carbohydrates within a portion of maize is very similar to wheat and rice –although the latter slightly supersedes the others. Wheat is superior to its two counterparts for protein supply, and maize is superior in fats. In absolute terms, wheat is the most important source of vegetable protein in the world and rice is the most important source of calories. This is due not only to the amount of protein and calories offered by each one of these two grains per portion, respectively, but also and chiefly to the quantity of grain of each of these crops that is used for food. Both wheat and rice are superior to maize in relative (*i.e.*, the percentage of grain used for food, in relation to other uses) and absolute (*i.e.*, tons used for food) terms.

Table 2.6 Comparison of the nutritional value of maize and other seven staple crops.

	For every 100 grams							
	MAIZE	RICE	WHEAT	SOY	SORGHUM	POTATO	CASSAVA	BANANA
Energy (kJ)	**1528**	**1528**	1369	615	1419	322	494	511
Carb.(g)	74	**80**	71	30.16	75	71	28	32
Prot.(g)	9.4	7.1	12.61	**36.5**	11.3	2.0	1.5	1.3
Fat (g)	4.74	0.66	1.54	**19.94**	3.3	0.09	0.17	0.37

Source: Own elaboration with data from Nutrient data laboratory, USDA, 2015b.

The supply of calories, proteins and fats from maize used directly for food is important mainly in Mexico, Central America and Sub-Saharan Africa, unlike other regions of the world, as shown in the following table.

Table 2.7 Direct food consumption of maize and its calorie, protein, and fat contribution, by region (in red first place, and in bold second), in 2011.

Region	**Direct food consumption**		**Calories**		**Proteins**		**Fat**	
	Related to other uses	Total	Maize / Total	Maize / Cereals	Maize / Total	Maize / Cereals	Maize / Total	Maize / Cereals
	%	kg/per capita/year	**%**	**%**	**%**	**%**	**%**	**%**
AFRICA	56	44	15	30	14	29	7	7
Sub-Saharan Africa	61	54	18	40	18	39	7	7
Northern Africa	34	33	10	17	9	16	6	6
AMERICA	8	34	9	30	7	27	2	2
Central America	48	103	30	70	28	70	12	12
Caribbean	21	16	5	16	6	18	2	2
South America	14	26	7	22	6	21	1	1
North America	2	13	3	12	2	8	0	0
EUROPE	5	7	2	5	1	4	0	0
Western Europe	8	7	2	7	1	5	0	0
Southern Europe	4	8	2	7	1	5	0	0
Northern Europe	16	3	1	3	1	2	0	0
Eastern Europe	5	9	2	5	1	4	0	0
ASIA	14	10	3	5	2	5	1	1
Western Asia	25	13	3	7	3	6	1	1
Eastern Asia	6	8	2	5	1	4	0	0
Central Asia	26	6	2	3	1	3	0	0
Southern Asia	38	7	2	4	2	4	1	1
South-eastern Asia	29	21	5	9	5	11	2	2
OCEANIA	20	5	1	5	1	4	0	0

Source: Own elaboration with data from FAOSTAT (2015)

Key message 7: Although the planted area of maize is distributed around the world, only 17 countries account for almost 90% of its production. These main production countries differ from those that consume maize as a staple crop, in terms of production, commerce, inputs, socio-economical conditions, and uses. *While the main maize production countries offer manufactured food and raw material for non-edible products to the growing urban populations, staple crop countries produce food-maize and act to shelter the agrobiodiversity of this crop. The harvested area of the main production countries is 10 times larger than that of the staple crop countries, and their production is 27 times larger.*

Maize production is widely distributed around the world. The production percentage in America is 56%, in Asia 29%, in Europe it accounts for 12% of maize around the world and in Africa and Oceania it represents 7.4% and 0.08%, respectively. Even though maize is grown in 166 countries, about a quarter of the entire production worldwide originates in only 7 countries (FAOSTAT, 2015). In the period from 1989 to 2013, 17 countries were highlighted as main maize producers at global level. These countries are distributed in all the regions of the world and accounted for 88% of the whole production in 2013. On the other hand, there are countries that produce a relatively low quantity of maize; however, their population depends directly on maize as a staple crop[9]. These countries are mainly located in Central America and Africa (Fig. 2.15). Mexico and South Africa are unusual cases, since both are simultaneously large maize producers and main food consumers. More than 50% of the energy intake of the populations of Mexico and South Africa comes from maize and grain consumption, as well as 32.4% and 28.6%, respectively, of the total amount of calories in their diet (FAOSTAT, 2015).

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[9] This includes countries where maize represents more than 50% of energy intake in the diet of cereals (FAOSTAT, 2015). Mexico and South Africa were excluded from this group, as we consider that they play an important role as maize producers. Therefore, these countries were analyzed within the scope of that group.
In order for both groups to have the same amount of countries, we included Nicaragua and Malawi, countries where maize represents 49.5% and 48.9%, respectively, of the energy intake from cereals.

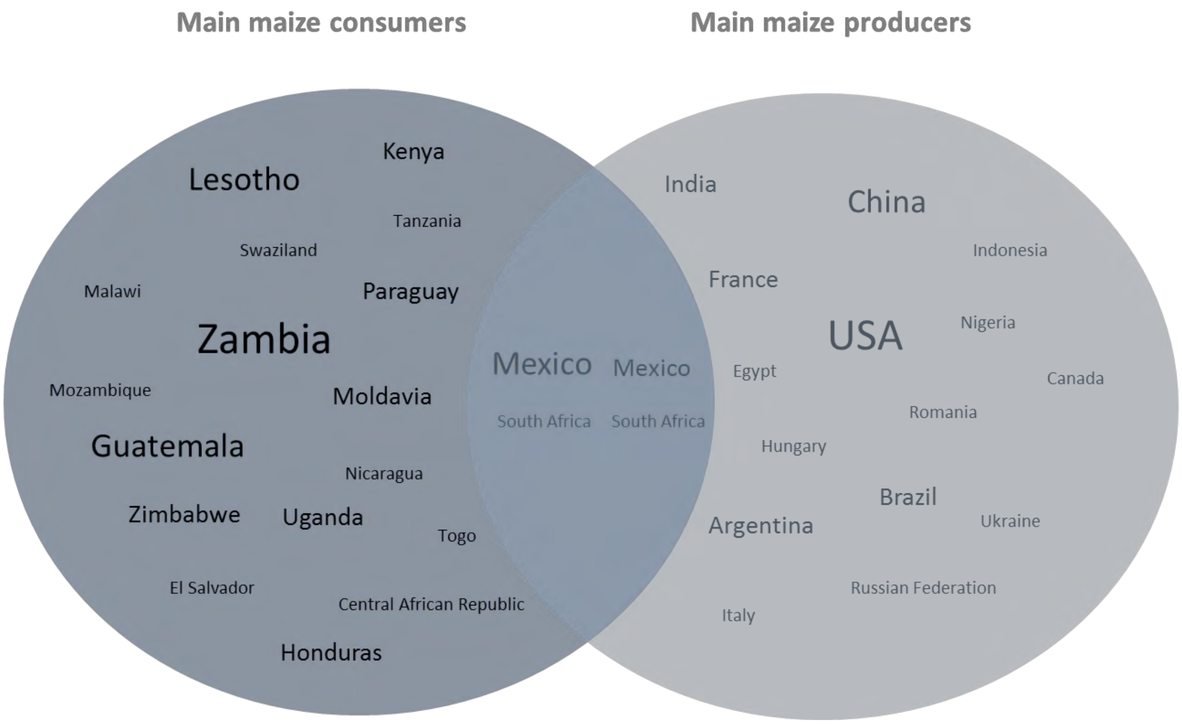

Figure 2.15 Main maize *producing* countries and main maize *consuming* countries. Source: Own elaboration with data from FAOSTAT, 2015. Note: The size of the letter represents the level of consumption and production of maize. 1) Among main maize consuming countries, the percentage of calories from maize, in relation to calories from all cereals: a) 80-90%, b) 70-80%, c) 60-70%, and d) 48-60%. 2) Among main maize producing countries, percentage distribution of production within this group: a) 40-100%, b) 20-39%, c) 2-20% and d) 0.1-1.9%.

While the harvested area of maize[10] among the main producing countries is 10 times larger than that of the consumer countries, production[11] is 27 times larger (FAOSTAT, 2015). Producer countries were responsible for 88.8% of the cultivated area, 96.5% of production, 98.5% of exports and 90.1% of maize-grain imports between 1990 and 2013[12](Fig. 2.16, 2.17, 2.18, and 2.19). It should be noted that there are major differences in the inside area of both groups. For example, only China and the United States (US) accounted for more than 50% of the harvested maize area and 68% of the total production among the main 17 producing countries (Fig. 2.16 and 2.17).

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[10] This refers to the average of maize-grain harvested surface between 1990 and 2013.

[11] This refers to the sum of the total maize-grain production between 1990 and 2013.

[12] This represents the sum of the cultivated area, the production, exports and imports of the set of producer and consumer countries (FAOSTAT, 2015).

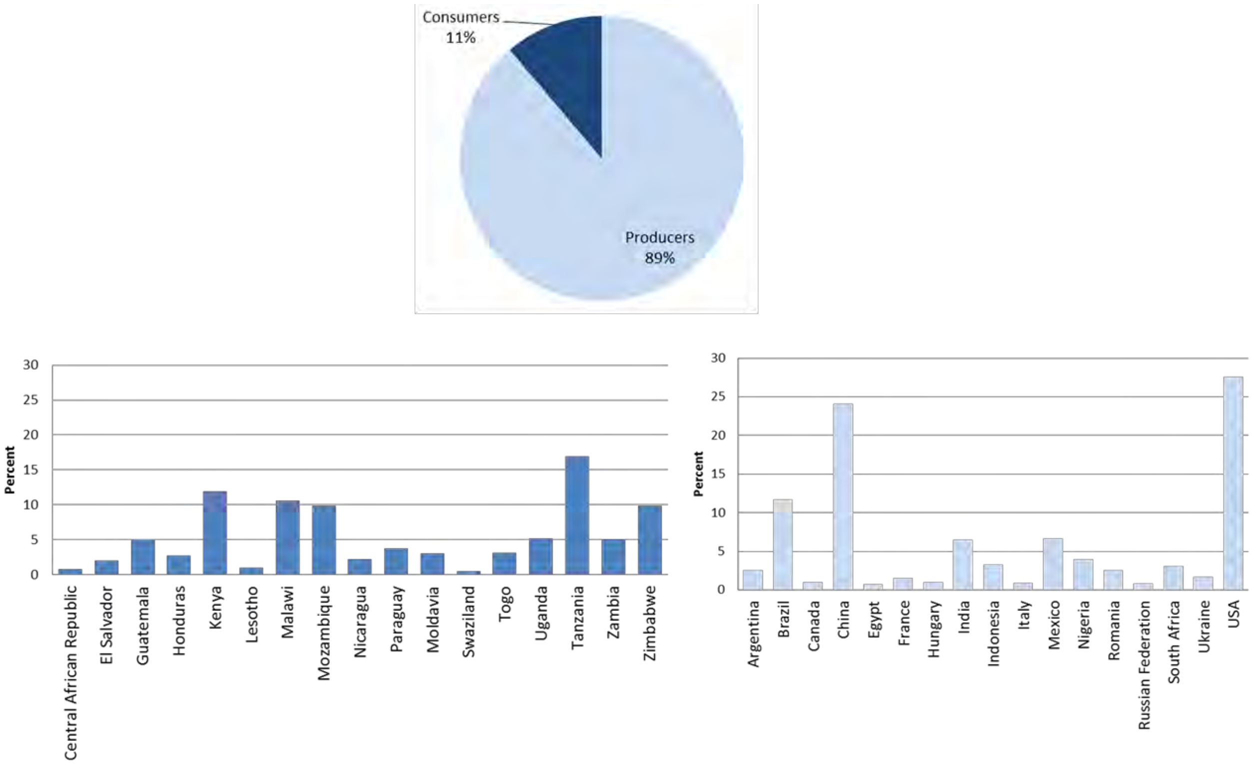

Figure 2.16 Distribution of maize harvested area between main maize producing and consuming countries. Source: Own elaboration with data from FAOSTAT, 2015.

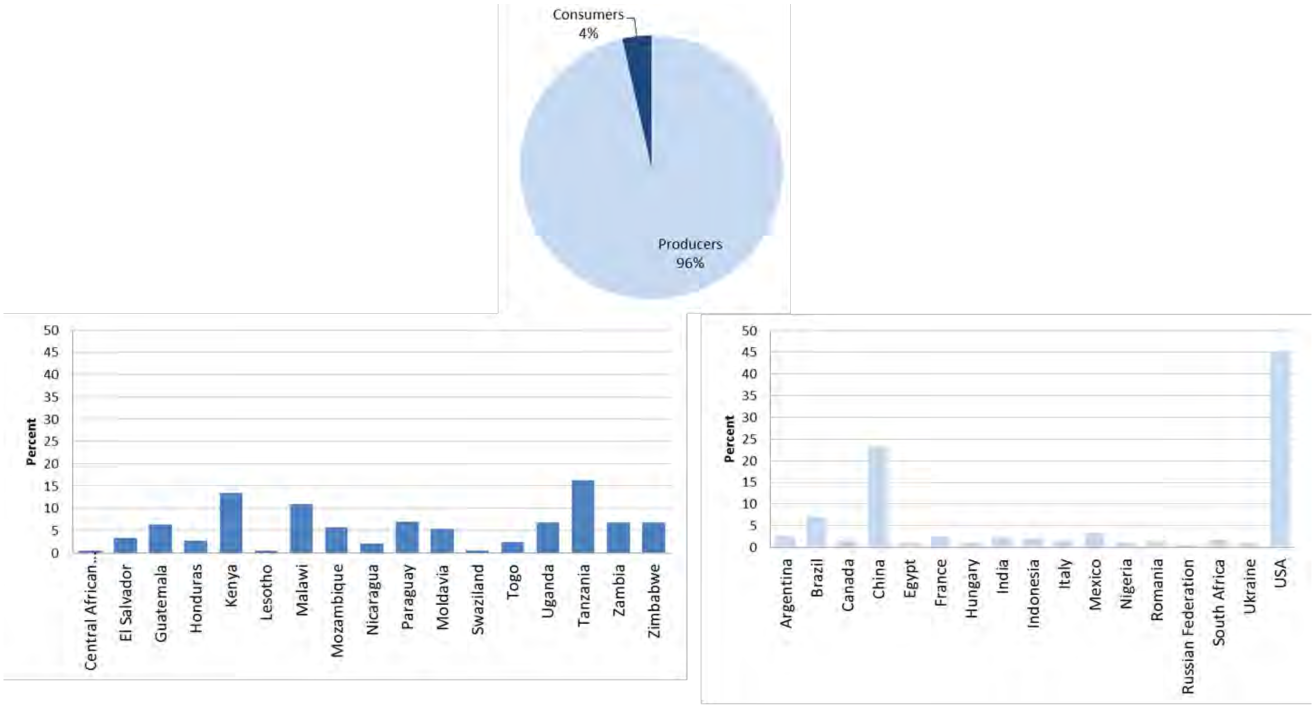

Figure 2.17 Distribution of maize production between main maize producing and consuming countries. Source: Own elaboration with data from FAOSTAT, 2015.

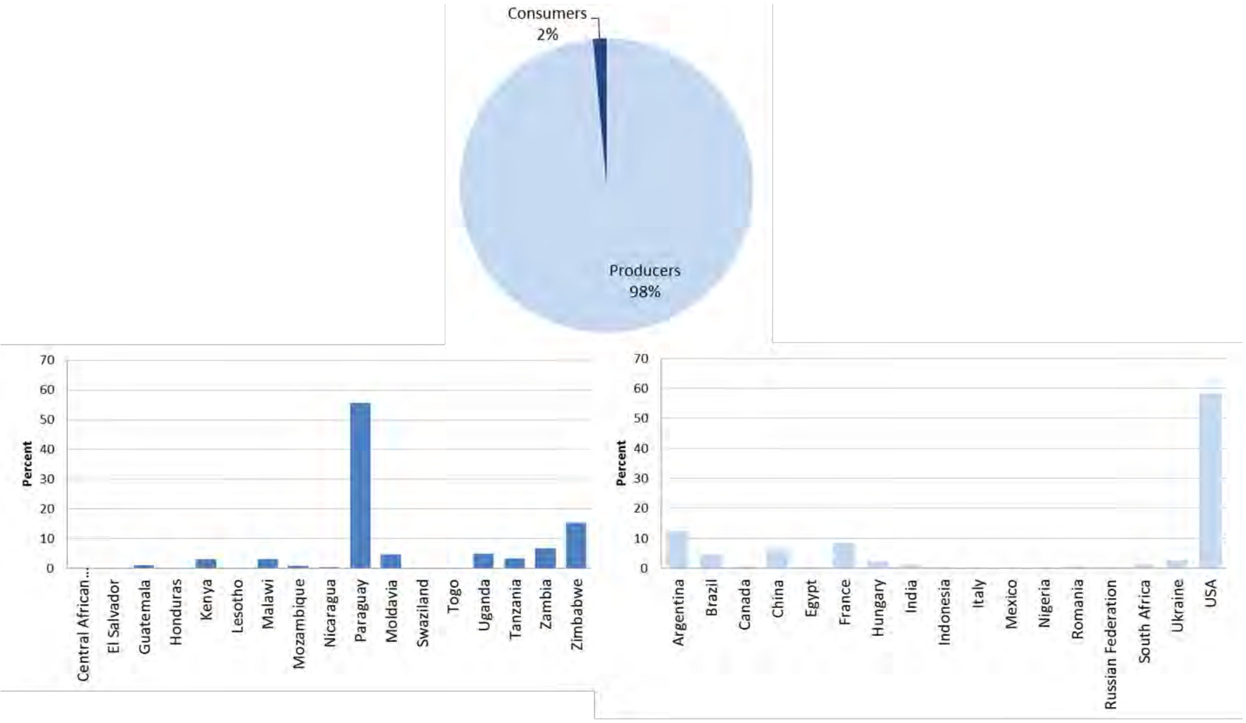

Figure 2.18 Distribution of maize exports among main maize producing and consuming countries. Source: Own elaboration with data from FAOSTAT, 2015.

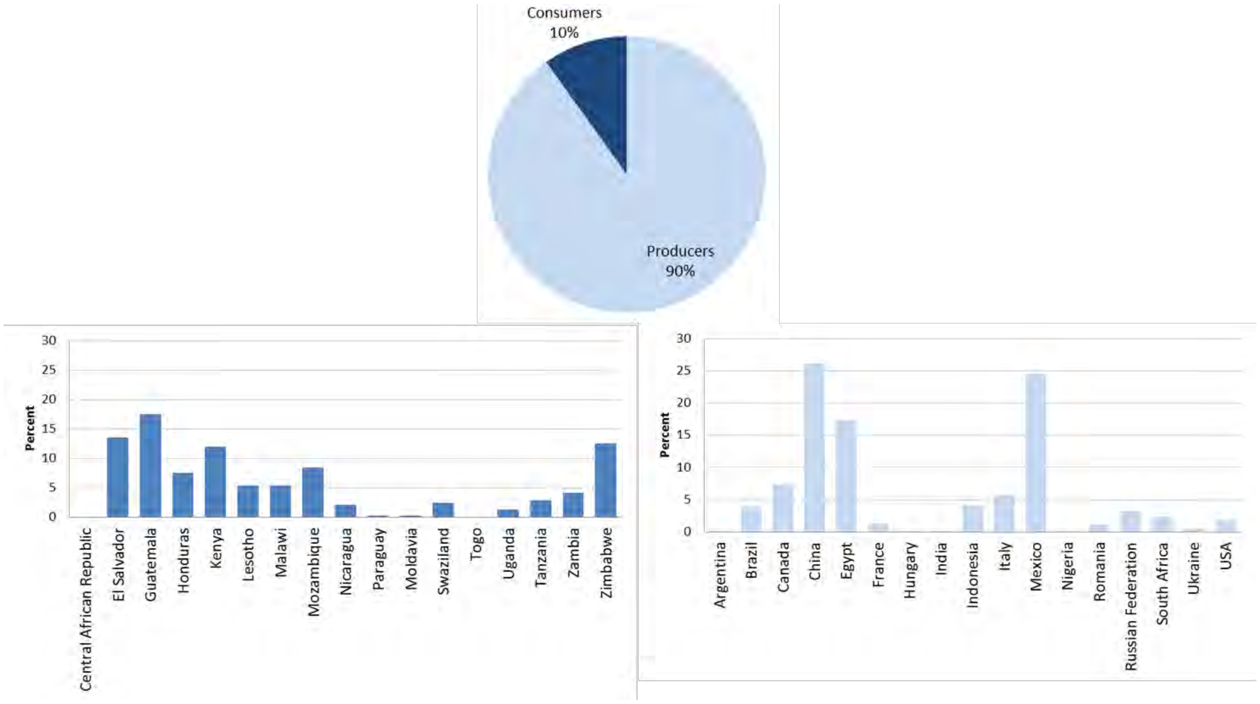

Figure 2.19 Distribution of maize imports among main maize producing and consuming countries. Source: Own elaboration with data from FAOSTAT, 2015.

Even when the main producing countries have a larger maize harvested area, the area of maize relative to that of other cereals is larger among main consumer countries. In this sense, Mexico and South Africa stand out within the group of producers that already have a relative high area of maize (Fig. 2.20). This is probably a reflection of the importance of this grain in the diet of the populations of these countries. Within the group of consumer countries, Paraguay stands out, since it has a very limited relative maize area (21%) when compared to other grains and cereals, especially soy.

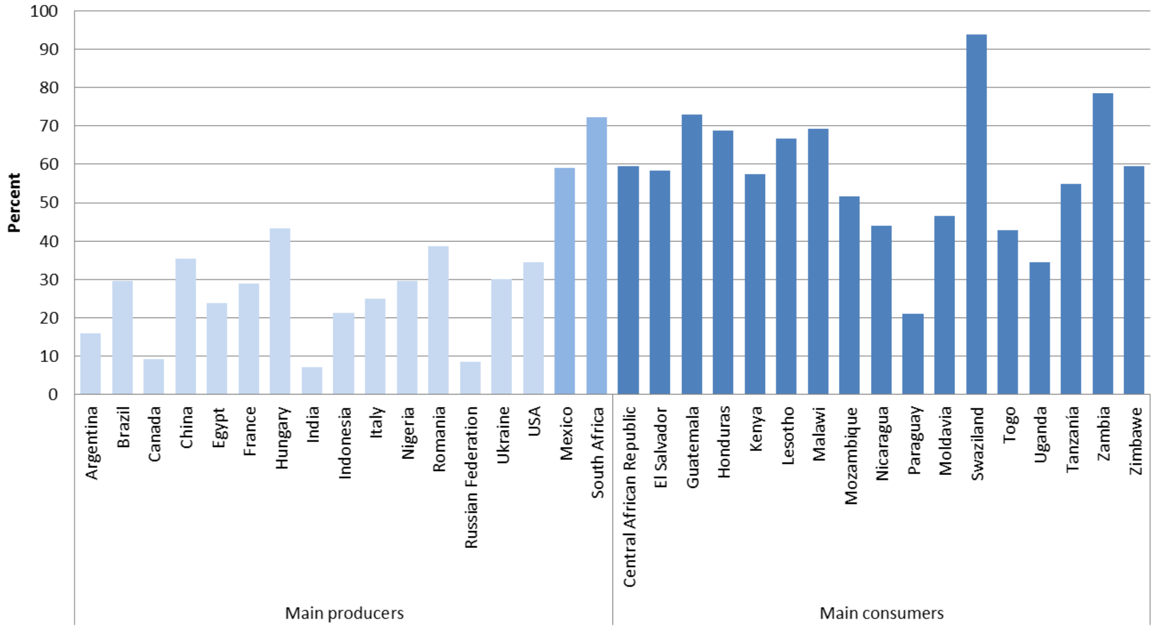

Figure 2.20 Harvested area of maize in relation to all grains and cereals. Source: Own elaboration with data FAOSTAT, 2015.

The average yield of maize is also different in both groups (4.9 ton/ha within the main producing countries, and 1.6 ton/ha within the main consuming countries). As mentioned previously (Message #3), this is due to the presence of MVs and other modern inputs such as chemical fertilizers. Both the use of MVs and other inputs are important indicators of maize production intensity.

Even when the main producing and consuming countries have a similar amount of small-size farming units and a similar distribution of the agricultural lands in the hands of such producers, they differ in terms of the importance of the agricultural inputs used (Fig. 2.21a). Producing countries have larger irrigation farming and irrigation-equipped areas, as well as a higher consumption of fertilizers per unit area, which indicates a larger proportion of intensive agricultural units (Fig. 2.21a and 2.21b). In this respect, China and Egypt stand out, since fertilizer consumption in these countries is considerably higher than their group average in these agricultural intensification indicators. Furthermore, there are consuming countries that consume similar amounts of fertilizers as producing countries. Fertilizer use per hectare in Guatemala, Honduras and Kenya is similar to that of the USA (Fig. 2.21a). The irrigation-equipped agricultural area is very restricted in both consuming and producing countries; except for countries such as Egypt, India, Italy and Romania, where irrigation-equipped agricultural areas represent 100, 38, 24 and 20% of their respective agricultural areas (Fig. 21b)

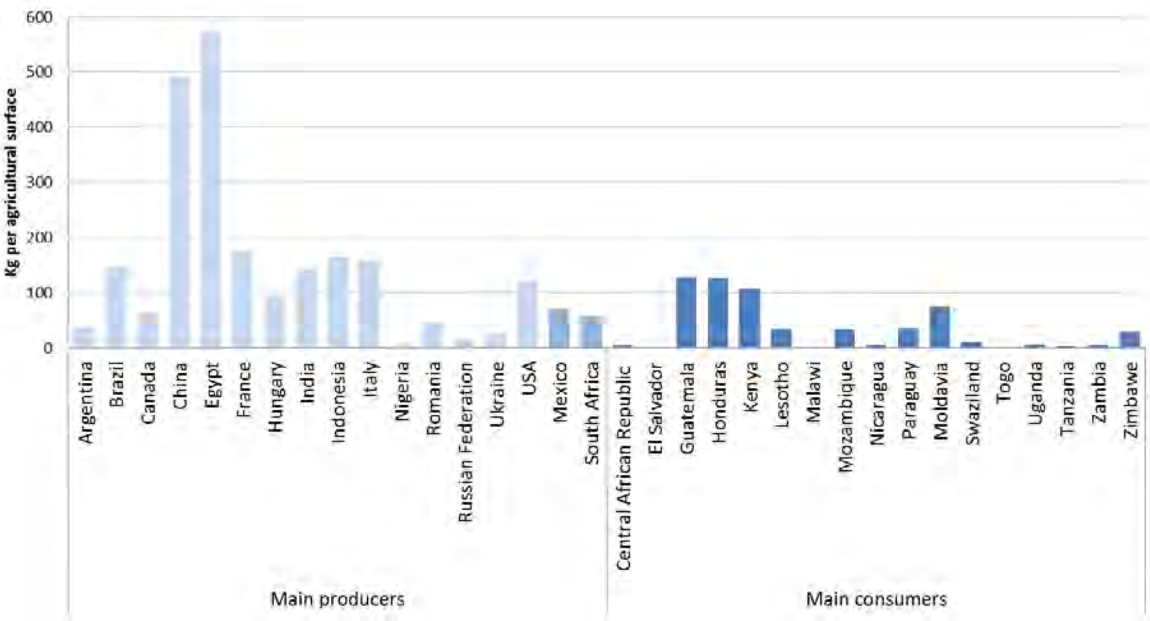

Figure 2.21a Average fertilizer consumption (2002-2012). Source: Own elaboration with data from World Bank, 2015.

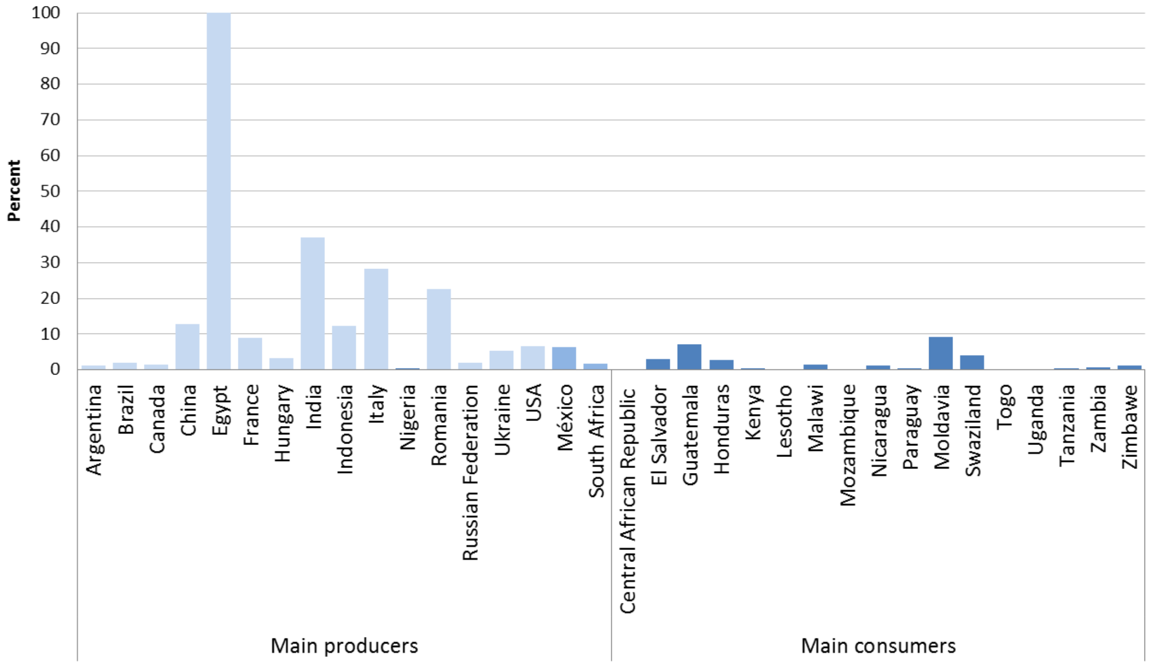

Figure 2.21b Percentage of maize production area with irrigation (2002-2012). Source: Own elaboration with data from World Bank, 2015.

Besides irrigation and fertilizers, the use of MV seeds is a key indicator of agricultural intensification (Abdoulaye and Lowenberg-DeBoer, 2000). In consuming countries, 61.5% of the area cultivated with maize uses local seed, i.e., seeds that are generated, selected and used by the farmers or acquired in the informal seed system (Pingali, 2001; Morris, 2002). MVs are acquired for each cultivation period through public or private genetic enhancement institutions. Among producing countries, only 17.2% of the area of maize production is cultivated with local seed. Mexico is the only exception in this group; more than half of the area devoted to maize in this country is cultivated with local seeds (Morris, 2002).

The different conditions and production modes between producing and consuming countries reflect not only different levels in the use of inputs that typify intensive and extensive production systems, but also the different goals associated with maize production. In fact, 60.5% of the total national maize supply of the producing countries is destined for feed, 22.4% for direct human consumption and 5.4% for the production of processed food. In contrast, in consuming countries, 16.4% is intended for feed, 67.3% for direct human consumption and 3% for processed food production. The use of maize in these groups is also reflected in the type of maize that is produced. Most consumer countries predominantly produce white maize; in accordance with gastronomic use (see message #6). In contrast, white maize accounts for more than 8% of total production only in 5 of the 17 main producing countries (Fig. 2.22).

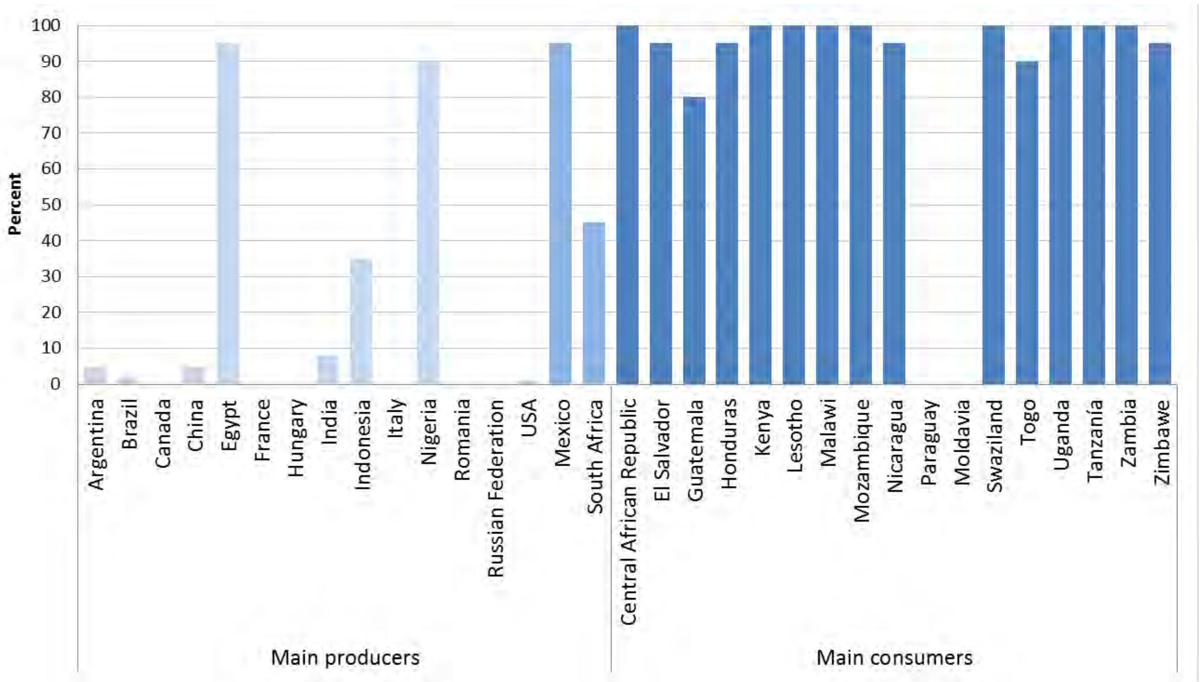

Figure 2.22 Percentage of white maize production, from total maize production in main producing and main consuming countries. Source: Own elaboration with data from FAO and CIMMYT, 1997.

In addition to the differences in the harvested area, production, commerce, quantity of external inputs and use of maize, there are important differences between the two groups in terms of the socioeconomic and agricultural production areas. Consumer countries are characterized by a low income level, lower Gross Domestic Product per capita, higher inequality level in terms of income, a higher percentage of the population below the poverty line, a higher percentage of rural population and a higher agricultural contribution to the Gross Domestic Product, as shown below (Tab. 2.8).

Table 2.8 Comparing main producing and main consuming countries for their socio-economic conditions. Source: Own elaboration with data from World Bank, 2015.

		Main production countries	**Main consumption countries**
Rural population (% of total)	Mean	33.5	61.5
	SD	16.6	15.5
	Min	8.4	15.5
	Max	67.6	84.2
GDP per capita (USD)	Mean	16,814.0	1,722.0
	SD	17,654.0	1,235.0
	Min	1,610.0	250.0
	Max	55,200.0	4,150.0
Income level	Mode	High income	Lower middle income
Gini index	Mean	36.8	48.2
	SD	7.6	7.6
	Min	7.6	7.6
	Max	52.7	57.5
Population under the national poverty line (%)	Mean	23.3	47.0
	SD	17.7	17.9
	Min	4.6	12.7
	Max	53.8	72.3
Rural population (% of total)	Mean	33.5	61.5
	SD	16.6	15.5
	Min	8.4	15.5
	Max	67.6	84.2
Agriculture, value added (% of GDP)	Mean	7.5	22.0
	SD	6.1	14.3
	Min	1.4	5.6
	Max	20.2	58.2

The economic and social reality of the main maize consuming and producing countries has a clear effect on the manner in which maize is produced. Maize production schemes with a high level of external inputs allow the high production and yield levels that characterize the main producing countries. Even when most of this maize is not destined for direct food consumption (see message #6), maize that is produced under low intensity systems would be insufficient to feed rising urban populations (Perales, pers. comm.), especially in those countries with a high direct consumption of this grain. Nevertheless, the genetic diversity of maize, which has an inestimable importance for the long-term sustainability of this crop (see message #8), is maintained on-farm and in a constant process of evolution in the production systems that characterize the consumer countries. Modern varieties used by producer countries have relied and will continue to rely on this on-farm genetic diversity.

2.3 The value of smallholders for food production and agrobiodiversity conservation

Key message 8: Smallholders provide most of the world´s direct food-maize and are the stewards of the genetic, agricultural and landscape diversity of this crop. *They depend on this activity since it contributes to their food security and accounts for a significant part of their income.*

Small agricultural units (SU) are the most numerous and contribute most of the food that is produced in the world (Dixon et al., 2001). The SU are usually managed by families (including one or more households) that use mostly or entirely family labour, and get most of their income and food from this work (Narayanan and Gulati, 2002; HLPE, 2013). These systems also stand out for having little energetic, technological, financial and land resources for agricultural production (Dixon et al., 2001). Around 94% of all production units in the world are of 5 hectares (ha) or less, and together amount to a total number of around 500 million units. However, they cover only 19% of the agricultural area worldwide (HLPE, 2013). It is estimated that there are 200 million SU in China, i.e., 40% of the total SU in the world, which cover 10% of the agricultural area and contribute 20% of the food production in the world (*ibid*.). These SU predominate in countries of low and medium-low income, where they account for 95% of the total number of agricultural units and "produce a substantial portion of food" (FAO, 2014a: p.3). On the other hand, large-scale units prevail in countries of high and high-medium income, with some exceptions such as Mexico where 84% of agricultural units are less than 5 ha in size (PROCAMPO, 2009).

Despite the fact that SU cover a minor part of the agricultural area on all continents and in most countries in the world (units of more than 50 ha account for two thirds of the agricultural area), some estimates based on surveys in different regions within low income countries[13] show that SU are responsible for around 75% of total agricultural production (FAO, 2014b; Rapsomanikis, 2015). This figure is even higher when non-manufactured food production is taken exclusively into account; i.e., production that is not destined for processed food factories (including meat and sweeteners) or non-edible products. Large and highly technified production units generate the raw material for these industries. In China, Africa and the Southern Asia (including India), SU provide the majority of their agricultural production (IFAD, 2011).

Maize is generally representative of agriculture in terms of the contribution of SU to the production of food. For example, the 25 million ha that are devoted to maize in sub-Saharan Africa are mostly cultivated by SU, with a production of 38 million tons of grain each year, mainly for food (Smale et al., 2011). South Africa is the exception within the Sub-Saharan region. Although 90% of the agricultural units of this country are SU, these cover only 15% of the harvesting area and generate a minor part of the maize production. Most maize production area in South Africa is managed by large-scale (commercial and intensive) systems for feed production (Shiferaw et al., 2011). In Mexico –the main producer of maize for food in the world and, together with South Africa, the major producer of high yield white maize–, small farmers contribute around 30% of the supply of maize grain at national level. This contribution comes mainly from landraces, which have a low yield and are managed under adverse environmental conditions and with limited production resources (PROCAMPO, 2009; SIAP, 2013).

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[13] Surveys conducted in Bangladesh, Bolivia, Ethiopia, Kenya, Nepal, Nicaragua, Tanzania and Vietnam.

Most smallholders producing maize in different regions of the world have developed and currently manage landraces of high genetic diversity, under a wide range of socio-ecological conditions. This diversity has been developed on the American continent over several millennia and in the rest of the world for 500 years with the introduction and subsequent adaptation of this cereal, mainly by smallholders (Matsuoka et al., 2002). Little has been written regarding the historic dispersion and the actual presence of maize landraces outside the centre of origin of this crop (Kato et al., 2009). However, some global estimates and studies about specific regions do exist. For example, with information pertaining to 799 maize landrace accessions from America (258), Africa (237), the Middle East (13), Europe (148) and Asia (143), Mir *et al* (2013) aimed to represent the global genetic pool of maize landraces and to analyse its genetic and historic relationship. Maize landraces from 50 countries were analysed in this study, exploring their presence and expansion in all continents. On the other hand, study cases have analysed maize landraces on the American continent (Vigouroux et al., 2008), Canada (Camus-Kulandaivelu et al., 2006; Falco and Chavas, 2006), South America (Vilaró, 2011; Bracco et al., 2012), Argentina (Bracco, 2012; Bracco et al., 2013), Brazil (Carvalho et al., 2004), Europe (Gouesnard et al., 2005), Switzerland (Eschholz et al., 2008) and Serbia (Knežević-Jarić, 2009; Knežević-Jarić et al., 2010).

In Mexico, the National Commission for the Knowledge and Use of Biodiversity (CONABIO) has developed a national project for the geographic location and morphological and physiological description of maize landraces and their wild relatives within the Mexican territory (CONABIO, 2010). This project confirmed that Mexico is the centre of origin and one of the centres of diversity of this species, and hosts 59 different maize landraces that are currently used throughout its territory, mostly in SU (Acevedo et al. 2011; CN-CONABIO, 2011; Kato *et al.,* 2009). On the other hand, although South America is not a centre of origin of maize, a wide genetic and morphological diversity of this crop exists in this region, particularly in the Andes, with a great cultural richness and diversity of uses (Kosarek et al., 2001; Bellon et al., 2015b; Bracco et al., 2012; Prasanna, 2012; Vilaró, 2011).

Field studies in different parts of the world have analysed the economic incentives that lead farmers and communities to allocate their land to the cultivation of maize landraces and/or MVs (*e.g.*, Bellon and Taylor, 1993; Smale et al., 2001; Arslan and Taylor, 2009). These are incentives for either the diversification or simplification of their crop, making use of one or several landraces or a combination of these and MVs (genetic or intra-specific diversity), or using different crop species simultaneously or in rotation (species or inter-specific diversity) (Smale, 2005). These studies show the non-market value of landraces for their stewards in several countries.

Another approach to the geographical location of maize landraces in the world is found in analysis of the percentage of area grown with local seeds, i.e., seeds that are generated, selected and used by the farmer or acquired through the traditional system of seed exchange. Local seed is generally native, as opposed to MVs, which are generated by public or private institutions involved in scientific genetic improvement, and which are acquired by the farmer in each seasonal period. Morris (2002) shows the ratio of native and MV cultivated area in countries of Africa, Asia, Europe and Latin America. This study demonstrates that, despite the fact that in Sub-Saharan Africa maize is cultivated primarily by smallholders and that, in this region, there is a high rate of food maize consumption *per capita*, with a significant dependence in terms of calorie intake, the source of maize seed in this region is primarily the formal system based on MVs. On average, only 8% of the maize cultivated area in Eastern and Southern Africa utilizes local seed. Mozambique depends almost entirely on local seed

(91%), but other countries of this region grow all or nearly all of their maize with MVs, e.g., Uganda (65%), Zambia (65%), Kenya (87%), Zimbabwe (100%) and South Africa (100%). Mexico, Central America and the Caribbean show the opposite trend. As in Africa, the national data differ in these regions; however, on average, 77% of the cultivated maize area uses local seed. This number increases to 83% when exclusively addressing Mexico, Guatemala, Honduras, Nicaragua and Haiti. In South America, local seed covers only 28% of the maize cultivated area. On the other hand, local seed covers 1%, 38% and 50% in Eastern, South-eastern and Southern Asia, respectively. Finally, according to the aforementioned CIMMYT studies, all of the main producers of maize in the world, except for Mexico, primarily use MVs: South Africa (100%), India (58%), Indonesia (80%), China (90%), Argentina (100%), Brazil (69%) and Italy (100%) (Fig. 2.23).

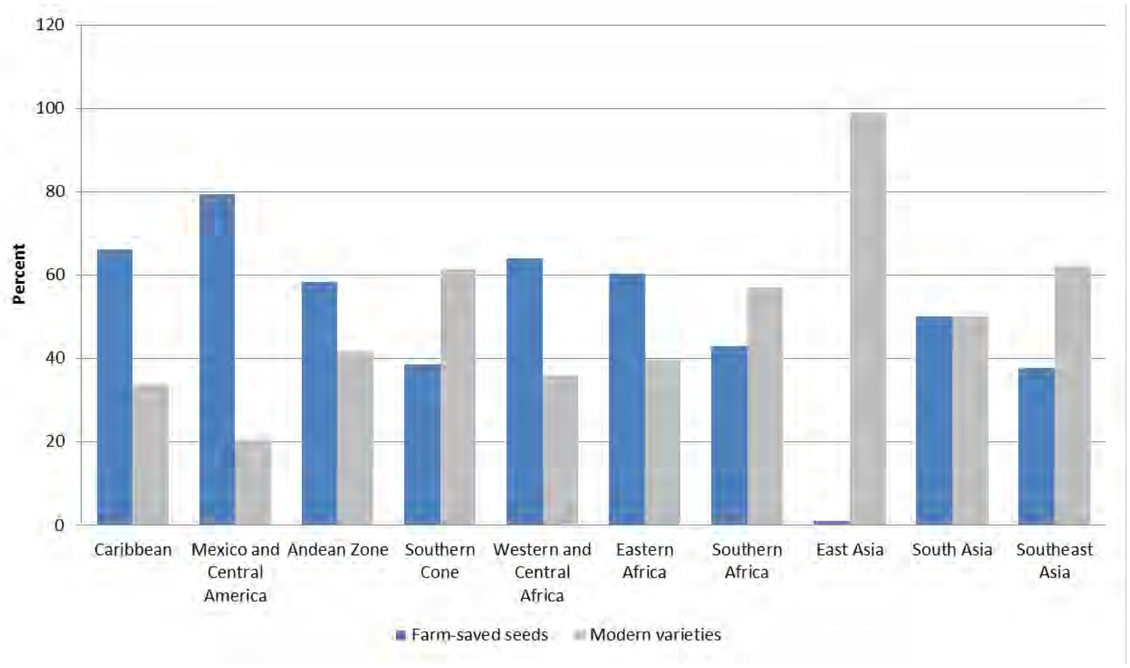

Figure 2.23 Percentage of maize cultivated area with local and modern seed. Source: adapted from Morris, 2002.

Intra-specific diversity generally happens to coincide, within the same production unit, with inter-specific diversity, *i.e.*, farmers who decide to use landraces tend to grow more than one species (Jarvis et al., 2008). Maize is a perfect example of this: most production systems that shelter maize landraces are multiple cropping systems. Also large-scale production systems with MVs are found in rotation, e.g., the maize-soybean rainfed system in the US (corn belt), Canada (Southeast), Brazil (South-central), and Argentina (Cassman et al., 2005; Lithourgidis et al., 2011). There are numerous different production systems growing maize, some as (non-rotating) monocultures but most of them rotating or mixing this cereal, as a primary or secondary crop, with legumes, tubers, vegetables, fruits, trees, nuts, non-edible crops (some illegal) or with other cereals, mainly for food or forage production (Tab. 2.9). No other species is grown together with such a variety of species as maize.

Table 2.9 Examples of maize polyculture in the world

Crops	**Country or region**	**Reference**
Cowpea (V*igna unguiculata*)	Zimbabwe, India, Philippines, Brazil, Tanzania, Sub-Saharan Africa savannas	1, 2, 3, 4, 5, 7, 8
Pigeon pea (C*ajanus cajan*)	Zimbabwe, India, South Africa, Indonesia, Malawi, Kenya	1, 2, 4, 9, 10, 11
Common bean (P*haseolus vulgaris*)	Latin America and the Caribbean, South Africa, Kenya, Cuba, Zambia, Uganda, Sub-Saharan Africa, East Asia and the Pacific, and Costa Rica	2, 4, 12, 13, 14, 15, 16, 17
Soybean (G*lycine max*)	India, Uganda, Nigeria	2, 16, 18
Broad bean (V*icia faba*)	China	19
Cassava (M*anihot esculenta*)	Amazon, Nigeria, Latin America and the Caribbean, el Sub-Saharan Africa, and Costa Rica	2, 13, 17, 20, 21, 22
Potato (S*olanum tuberosum*)	Andes, China, Uganda, Nepal	23, 24, 25, 26
Sweet potato (I*pomoea batatas*)		2, 4, 13, 14, 17, 27
Taro (C*olocasia esculenta*)	Cuba	4
Yautia (X*anthusoma sagittisaliun)*	Tropical forests of Central Africa	21
Beet (B*eta vulgaris*)	East Europe and Central Asia	13
Rice (O*ryza sativa*)	Sub-Saharan Africa, East Asia, and the Pacific	2
Wheat (T*riticum aestivum*)	China, East Europe, Central Asia	13, 19, 25
Barley (H*ordeum vulgare*)	East Europe, Central Asia	14
Green bean	India	2, 4
Tomatoe (S*olanum lycopersicum*)	Cuba	2, 28, 29
Okra (A*belmoschus esculentus*)	Nigeria	2, 29, 30, 31
Kale (B*rassica oleraces*)	Nepal	2, 26, 30
Squash (C*ucurbita*)	Mexico	3
Coriander (C*oriandrum sativum*)	India	2, 4
Chili (C*apsicum spp.*)	Central Africa tropical forests	
Banana (M*usa paradisiaca*)	Cuba	5
Melon (C*ucumis melo*)	Nigeria, Central Africa tropical forests	30, 32
Pineapple (A*nanas comosus*)	Central Africa tropical forests	32
Colocynth (C*itrullus colocynthis*)		29
Lemon (C*itrus limon*)	Central Africa tropical forests	32
Sesame (S*esamum indicum*)	Tanzania	33
Peanut (A*rachis hupogaea*)	Central Africa tropical forests, China, Nigeria, Uganda	13, 19, 21, 34
Coffee (C*offea arabica*)	Sub-Saharan Africa, Latin America and the Caribbean	14
Cacao (T*heobroma cacao*)	Sub-Saharan Africa, Central Africa tropical forests	13, 21
Oil palm (E*laeis guineensis*)	Sub-Saharan Africa, Central Africa tropical forests	13, 21

Date plam (P*hoenix dactylifera*)	Sub-Saharan Africa	13
Melina (G*melina arborea*)	Mexico	17
Pine *(Elliottii* and *caribaea*)	Argentina, Venezuela, Dominican Republic	17
Eucaliptus (E*ucalyptus*)	Brazil	17
Cedar (Cedrela odorata*)*	Colombia	17
Mombin (S*pondias mombin*)	Mexico	17
Mahogany (S*wietenia macrophylla*)	Mexico	17
Sudan grass (S*orghum drummondii*)	Kenya	11
Sesbania (S*esbania bispinosa*)	Kenya	11
Sunflower (H*elianthus annuus*)	Sub-Saharan Africa, East Europe, Central Asia	13
Wild cabbage (B*rassica oleracea*)		34
Runner bean (P*haseolus coccineus*)		35
Tobacco (N*icotiana tabacum*)	China, Sub-Saharan Africa	24, 13
Sugarcane (S*accharum officinarum*)	China, East Asia and the Pacific	24, 13
Cotton (G*ossypium*)	Sub-Saharan Africa	13
Rubber tree (H*evea brasiliensis*)	Sub-Saharan Africa	13
Marihuana (C*annabis sativa*)	Mexico	35, 36
Opium poppy (P*apaver somniferum*)	South-east Asia, Afghanistan, Thailand, Myanmar	37, 38, 39, 40, 41

[1]Lithourgidis et al., 2011 ; [2]Serán and Brintha, 2010; [3]Hugar and Palled, 2008; [4]van Wolfswinkel, 2010; [5]Eaglesham et al., 1981; [7]Blade, 1997; [8]Giller, 2001; [9]Mathews et al., 2001; [10]Makumba et al., 2009; [11]Mukhebi and Onim, 1985; [12]Siame, 1998; [13]Dixon et al., 2001; [14]Carlson et al., 2008; [15]Tsubo et al., 2005; [16]Sekamatte et al., 2003; [17]Altieri, 1999; [18]Ijoyah and Fanen, 2012; [19]Zhang and Li, 2003; [20]Mutsaers et al., 1993; [21]Komatsu, 2012; [22]Ikeorgu et al., 1990; [23]Saddam Aref Al-Dalain, 2009; [24]Li et al., 2009; [25]Ebwongu et al., 2001; [26]Khatiwada, 2000; [27]Amede and Nigatu, 2001; [28]Sharma and Tiwari, 1996; [29]Ijoyah, 2012; [30]Ijoyah and Jimba, 2012; [31]Ijoyah and Dzer, 2012; [32]Komatsu, 2012; [33]Mkamilo, 2004; [34]Jiao et al., 2008; [35]Dube et al., 2014; [36]Steinberg and Mathewson, 2005; [37]Hogshire, 2005; [38]Batugal et al., 2004; [39]Wiesmann et al., 2006; [40]Denslow and Padoch, 1988; [41]UN-ODC, 2007.

Multiple cropping systems are primarily managed by smallholders with low external inputs and limited access to markets. These limitations are not the only reason they maintain multiple cropping. Smallholders diversify their varieties, plant and animal species and, in general, their economic activities as part of a livelihood strategy of risk management in the face of potential production failures (Pascual et al., 2011). In fact, both intra and inter-specific diversity act to stabilize long term yields and maximize production with low levels of technology and resources, as well as promoting dietary diversity by offering different products for the food and the farmers' household income (Seran and Brintha*,* 2010).

The FAO and the World Bank (Dixon et al., 2001) designed a global typology of agricultural systems in poor rural regions, which shows the role that maize multiple cropping systems play within subsistence agriculture in nearly all regions of the world. According to this report, there are eight different systems in Sub-Saharan Africa where maize is mixed with other crops, representing 61% of the agricultural area and 58% of the farming population. In Latin America, four different multiple cropping systems of maize are described.[14] In this region, farmers grow between 70 and 90% of beans together with maize, potatoes and other crops, and the multiple cropping maize system covers 60% of the area devoted to the production of this cereal (Francis, 1986).

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[14] The four systems of multi-farming which include maize in Latin America, as described by Dixon *et al.,* (2001), are: 1) Maize-beans (Mesoamerica): maize, beans, coffee, horticulture and labour sourced on the property itself; 2) Intensive mixture in the highlands (North Andes): vegetables, maize, coffee, cattle; 3) Extensive mixtures (closed areas and prairies): cattle, oilseeds, grains (rice, soy and maize), coffee; and 4) dry land mixture: cattle, maize, cassava, paid labour, seasonal migration.

Key message 9: Agrobiodiversity that is managed in small-scale maize production systems has a strategic value for feeding both the societies that produce and those that consume this cereal. *Its evolving (on-farm) conservation represents an irreplaceable natural insurance because it offers farmers and plant breeders a wide array of adaptation options for unpredictable future conditions. Paradoxically, agrobiodiversity stewards are the most vulnerable to biotic and abiotic stress, being the poorest and having the highest levels of food insecurity. This paradox will persist as long as the local and global value of agrobiodiversity stewardship remains invisible to the markets, and to society overall, and is therefore not duly compensated.*

The value of agrobiodiversity as a natural insurance for food can be analysed over three geographic scales: local, ecosystem and global (Pascual et al., 2011). At the local level, the intra and inter-specific diversity of the crop reduces the risk of production failure or collapse for several reasons. Firstly, such diversity implies a lower scale of the host of pests and diseases. In fact, the distribution of pests and diseases does not only occur in an exogenous manner, but is mainly conditioned by the size and dispersion of the host (*i.e.*, the crop). For this reason, increasing the scale of the host (with plants of the same genetic base) increases the probability of pests and diseases evolving and spreading rapidly (Heal et al., 2003; Di Falco and Chavas, 2006). Secondly, cultivated biodiversity (also known as *planned* biodiversity) also reduces the risk of production failure or collapse because it increases the number of functional crop traits that favour resistance and resilience. Higher quantities of such functional traits increase the probability of the presence of at least one variety that is tolerant to temperature or humidity changes or extreme events, or is immune to a pest or disease. Different crops or varieties typically differ in susceptibility to environmental variations (Bellon, 1996; Heal, 2000; Sala et al., 2000; Zhu et al., 2000; Di Falco and Perrings, 2003). This is due not only to genetic diversity but also to phenotype adjustments that do not require changes in the genetic frequencies, which are known as the phenotypic *plasticity* of the plant (Mercer and Perales, 2010). Thirdly, different varieties of the same agricultural species may be adapted to different agro-ecological and micro-climatic conditions because they have evolved to fit them. Therefore, it is not only a matter of benefit (on account of risk) due to the *quantity* of varieties but also due to its *quality* in terms of attributes developed according to the particular environmental conditions that prevail in the ecosystem and to transformations it has suffered in the past (Di Falco and Chavas, 2006; Landis et al., 2008; Chavas and Di Falco, 2012).

Such features that are associated with crop diversity and that are characteristic of smallholder systems are part of the livelihood strategy for risk management employed by the farmers. At the same time, the farmers also take potential commercial fluctuations (*i.e.*, of grain prices and access to markets) into account as well as political fluctuations (*i.e.*, of governmental agricultural assistance), since these generally have an effect on their income. For that reason, the farmers' strategy is aimed at finding optimal levels of diversification of their intra- and inter-specific, agricultural (*i.e.*, crops and livestock) and non-agricultural resources, which tends to reduce the risk and thus their vulnerability in the face of contingencies (Pascual et al., 2011). Just as in financial investment portfolios, diversification spreads risk.

On the other hand, at local and agro-ecosystem levels, agro-diversity is a natural insurance due to the complimentary and facilitating interactions between planned and associated diversity. The latter accounts for biota that is not cultivated but cohabits the agro-ecosystem with the crop; it includes wild relatives, pollinators, soil and subsoil organisms, weeds, fungi, anthropods, herbivores and carnivores. These can be competitors, predators or pathogens holding back crop growth, or complementary and facilitator organisms living in symbiosis with cultivated plants (Altieri, 1999). Symbiotic interactions allow existence, improved development and temporal stability of certain ecosystem functions. For example, an increase in planned biodiversity contributes to the re-establishment and multiplication of organisms in the soil that are able to perform biological functions that buffer the agro-ecosystem from risk, thus helping to support productivity (Altieri, 1999; Giller et al., 1997). In addition, the associated diversity enhances efficiency in the use of resources, contributes to control of the local micro-climate, regulates hydrological processes, increases resistance of crops to abiotic stress, regulates pests, detoxifies the system of harmful chemicals, aids crop pollination and improves the dynamics of nutrient cycling, as well as representing alternative sources of food (Giller et al., 1997; Vandermeer et al., 1998; Heal, 2000). In short, associated biodiversity contributes to agricultural production through nutrient cycling, pest and disease control and pollination (Wood and Lenne, 1999; Cassman et al. 2005).

The productive function of agrobiodiversity has been analysed with field studies measuring its role in diminishing the long-term variance of production. These studies state that both genetic and species planned diversity increase the mean yield while reducing its variance (Hartell et al*.,* 1997; Altieri, 1999; Heal, 2000; Di Falco and Perrings, 2003; Tilman et al., 2005; Di Falco and Chavas, 2006; Baumgärtner and Quaas, 2008; Chavas and Di Falco, 2012; Di Falco, 2012). Such long-term production stabilization has been documented not only in small-scale, but also in large-scale intensive (Omer et al., 2007) and extensive (Li et al., 2009) systems. Moreover, it has been shown that agrobiodiversity is an element in the agro-ecosystem that has a positive influence on the mean income of farmers while exerting a negative influence on its variance (Di Falco and Perrings, 2005; Pascual and Perrings, 2007; Baumgärtner and Quaas, 2008).

The fact that agrobiodiversity represents a unique source of alternatives available to any production system, in the face of climate change and phytosanitary contingencies, has been confirmed by historical cases of agricultural production collapse. This phenomenon has occurred in different regions of the world, with devastating social and economic consequences. Widely known cases are the potato blight in Ireland (1845-1849) and Scotland (1846-1857) and also the fungal epidemics of coffee in Ceylon (1870s), wheat in the USA (1917-35), maize in the tropical region of Africa (1950s), tobacco in the USA and Europe (1960s) and maize in the USA (1969-70s). Another widely extended occurrence was that of the viral epidemics in rice that took place in Indonesia (1970-77), the Philippines (1973-77), India (1972-74), Japan (1978) and Vietnam (2000-2008). Agricultural production collapses are largely the consequence of vulnerability implied in the genetic homogeneity that characterizes large-scale agricultural systems. As mentioned previously, the genetic homogeneity of crops makes them susceptible to the rapid spread of pests and diseases. On the other hand, collapsed systems have been able to re-establish themselves through the availability of on-farm and wild genetic resources that are found elsewhere. For example, a wild relative of the potato (*Solanum demissum*) that is resistant to the fungus (*Phytophthora infestans*) that caused the epidemic (and famine) in Ireland and Scotland in the 19th century was found in the highlands of Mexico. Another example is the 1970s maize blight in the USA, which reduced "yield by 50% [causing] an economic loss of almost USD $1,000 million [… and] was resolved by blight resistant genes from *Tripsacum dactyloides L.*", a maize wild relative (Maxted et al., 1997).

In summary, agrobiodiversity prevents collapse and, at the same time, has been (and will continue to be) the source of genetic resources that serve to rescue collapsed systems.

Climate change and its negative effects on agriculture (see message #13) increase the value of agrobiodiversity as a wide and expedite source of resources for adaptation. Crop genetic diversity provides farmers and plant breeders with the capacity to adapt to changing and often unpredictable conditions associated with climate change (Bellon, 2009; Bellon and van Etten, 2014). The ability to respond in time (*i.e.,* the agility) to stress factors very much depends on adequate and available resources. On-farm agrobiodiversity has the potential to offer such availability of resources due to the large amount of genetic material in constant evolution. Agrobiodiversity therefore not only injects resistance and resilience to the system, but also gives the system the *agility* to transform and adapt itself adequately to inevitable changing conditions. This is the difference between the concept of *sustentagility* (Jackson et al., 2010) and that of sustainability: the latter is focused on maintaining conditions whereas the former refers to adaptation to new conditions. Accordingly, the term *sustentagility* is more appropriately applied to the global value of agro-diversity for food production systems (Pascual et al*.,* 2011).

The function of on-farm agrobiodiversity as an agile source of alternatives for future conditions cannot be substituted by the *ex situ* conservation of genetic resources– i.e. by germplasm banks. This is due to the fact that the seed accessions that supply germplasm banks capture only a sample, a fraction, of the diversity that exists in the field that is limited to given regions and moments in time. In contrast, the on-farm agrobiodiversity that is handled and reproduced forms part of a co-evolutionary process that constantly acts to enhance genetic diversity. It does so through the interaction between cultivated plants and the rest of the (biotic and abiotic) components of the agro-ecosystem, including wild relatives of the crop, farmers and their input and seed management. In this process, genes flow between agricultural individuals and populations and the genetic resources adapt themselves to the changing conditions (Brush, 1989; Perales et al., 2003; Pascual et al., 2011). In other words, as stated by Bellon and van Etten (2014: p.137): “on-farm conservation is about maintaining processes, while *ex situ* conservation is about maintaining specific results of these processes (specific genes and genotypes sampled at a particular point in time)”. Both types of conservation can be treated as complementary (Bretting and Duvick, 1997; Brush, 2004). The benefits offered by such processes represent the evolutionary (or evo-systemic) service of on-farm conservation (Faith et al., 2010; Bellon and van Etten, 2014), which has already been analysed experimentally and quantitatively in the field (Vigouroux et al., 2011).

On the other hand, the global value of on-farm genetic diversity includes its use as a raw material in seed improvement programs (Evenson and Gollin, 1994, 2003; Brush and Meng, 1998). This scientific improvement, which has taken place over the last century, has used genetic resources that were managed on-farm and evolved in the last millennia. For example, a single variety of wheat developed by CIMMYT was produced by 3,170 different crosses involving 51 wild relatives from 26 countries (Perrings, 2014; Moore and Tymowski, 2005).

Another conceptual approach to the value of agrobiodiversity is the difference between its private and public benefits, which can sometimes diverge (Smale and Bellon, 1999; Heal et al., 2003; Bellon and van Etten, 2014). The optimal level of agrobiodiversity for a farmer –*i.e.,* the private benefits this farmer obtains from such

diversity– does not necessarily match the optimal level this farmer should maintain in terms of the benefits it offers for other farmers and for consumers at wider spatial and temporal scales.
As stated by Bellon and van Etten (2014: p.140):

> "The problem is that the resources needed to generate these benefits, such as land, labour, capital and knowledge, are limited, whereas public and private benefits can often diverge, creating trade-offs for individuals and society (Heal et al., 2004; Smale and Bellon, 1999). For example, the conventional explanation for crop genetic erosion is that farmers increasingly specialize and replace their diverse sets of landraces with a few scientifically-bred varieties that provide them with higher yields and more income. Although farmers pursue their legitimate private interest (higher incomes), crop genetic diversity that may be central to ensure the adaptation of other farmers to changing conditions or the needs of future generations (public benefits) may be lost. Farmers as individuals may tend to under-invest in the conservation of landraces and associated genetic diversity relative to what might be considered optimal for society at large (Heal et al., 2004; Smale and Bellon, 1999)."

For private and public benefits alike, agrobiodiversity is a fundamental element for risk management and, for that reason, represents a natural insurance at different spatial and temporal scales, since it confers greater stability (resistance and resilience) and greater *sustentagility* to agricultural systems. This is the most important value of maintaining an evolving (on-farm) crop genetic diversity. It offers a wide array of adaptation options for unpredictable future conditions (Bellon and van Etten, 2014).

This is particularly relevant to maize for several reasons: its worldwide extent and distribution, the caloric dependency that societies of many regions have on this cereal, its great diversity of traditional and industrial uses, the close relationship between the genetic diversity of maize and its uses and its wide genetic diversity that is still conserved both on-farm and in the wild. Smallholders, who are the stewards of agrobiodiversity –and maize landraces in particular – and who therefore manage the key resources for the stability and the adaptation of agricultural systems for world food production, are paradoxically the most vulnerable to biotic and abiotic stress (Pascual et al., 2011). This vulnerability is because they are the poorest and suffer the highest levels of food insecurity (exceeding even the urban poor sectors) (Dixon et al., 2001). Their socio-economic marginalization is only partially compensated by the rich natural capital that they manage. This paradox will persist as long as the global value of agrobiodiversity stewardship –as described above– remains invisible to the markets and to society overall and, therefore, not duly compensated.

Key message 10: Despite the global expansion of modern maize varieties, landraces are still grown in several regions of the world. *This is partly due to economic drivers such as the lower market value of modern varieties and high technological transaction costs, but also to the close relationship that exists between cultural and crop diversity, particularly in Latin America. Gastronomic uses may be related to, and therefore have the potential to positively influence, the conservation of landraces since these have the appropriate characteristics for the preparation of traditional dishes and beverages. The same is true for certain spiritual ceremonies that include maize.*

Maize was domesticated about 9000 B.C. in the Balsas South-central region of Mexico (Matsuoka et al., 2002). This is why Mexico is considered a centre of origin, domestication and diversity of maize (Kato et al., 2009; CONABIO, 2010). Over thousands of years, maize slowly spread along the American Continent. Initially, it moved towards Mexico’s central high plateau and the South American lowlands, around 6,000 B.C., and later towards the South-western USA and South American highlands about 4,000 B.C. (Vigouroux et al., 2008). Once introduced into Europe in 1493, Western Africa in 1534, Asia in 1496 and the Middle East in 1534 (Mir et al., 2013), landraces continued to be adapted and modified as a result of the preferences and needs of local farmers. In the early 1930s, modern varieties (MVs) began to be developed, which replaced the landraces of almost all areas cultivated with maize in the USA in little more than three decades (Duvick, 2001). In Europe, MVs were introduced at the end of World War II, completely modifying the traditional agricultural systems typified by high biodiversity and low external inputs (Bertolini et al., 1998).

The hastened replacement of landraces with MVs triggered a concern over genetic diversity loss. This propelled the development of mainly *ex situ* strategies in order to conserve this diversity (Maxted et al., 1997). Given the need to preserve the genetic diversity of maize and other crops that are of profound importance to humankind, more than 100 germplasm banks have been established worldwide (Sachs, 2009). Nowadays, 27,000 maize accessions exist in the American Continent and 20,000 in the rest of the world (Ortiz et al., 2010). More than 27,000 maize accessions are safeguarded in the International Maize and Wheat Improvement Centre (CIMMYT, for its Spanish acronym) in *El Batan*, Mexico. The CIMMYT also has the most diverse landrace collection (Ortiz et al., 2010; Wen et al., 2011). In spite of these achievements, a series of gaps in the spatial end ecologic representations of the available accessions have been found at a worldwide level. The CGIAR organization carried out a gap analysis in order to determine the spatial[15] and ecological[16] representations of the available accessions at a worldwide level (Biodiversity International et al., 2009). Spatial gaps were found in central and Eastern Brazil, Northern Europe, the Western area of the Italian Peninsula, the Caucasus and Sub-Saharan Africa. Ecological gaps were found in Central America and the Northern region of South America, Southern Brazil and Nepal. Finally, both types of gaps were found in South-eastern USA, Sub-Saharan Africa, India, and Southern/South-eastern and Eastern Asia (*ibid*.).

Worldwide, there is little information regarding the regions where landraces are conserved on-farm (see message #8), except in the case of Mexico, where a national project of landrace morphological analysis and harvest was developed (CONABIO, 2010; Perales and Golicher, 2014). However, there is evidence suggesting

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[15] Based on geographical distances and densities of accessions.

[16] Based on the 19 Bioclimatic Indexes (Bioclim) available at Worldclim (http://www.worldclim.org/).

that farming areas are being progressively reduced (Barnhart, 2004; Knežević-Jarić et al., 2014). In the regions and countries where MVs have been extensively adopted, maize landraces are kept in marginal areas, as well as in small plots where traditional farming prevails, and where maize is grown for human consumption (Lucchin et al., 2003; Kneţević-Jarić et al., 2010). Statements have therefore been made affirming that there is a very close relationship between the maintenance of traditional agricultural systems and the on-farm conservation of local maize varieties (Lucchin et al., 2003).

As mentioned previously, specifically in the case of maize, a series of elements that are associated to the maintenance of landraces have been identified. Such varieties prevail around the world regardless of strong national and international pressure towards yield increases through the modernization of farming. These factors may be grouped into: 1) a greater adaptability to dominant environmental conditions, 2) cultural preferences and 3) socioeconomic factors associated to agricultural production (Fig. 2.24).

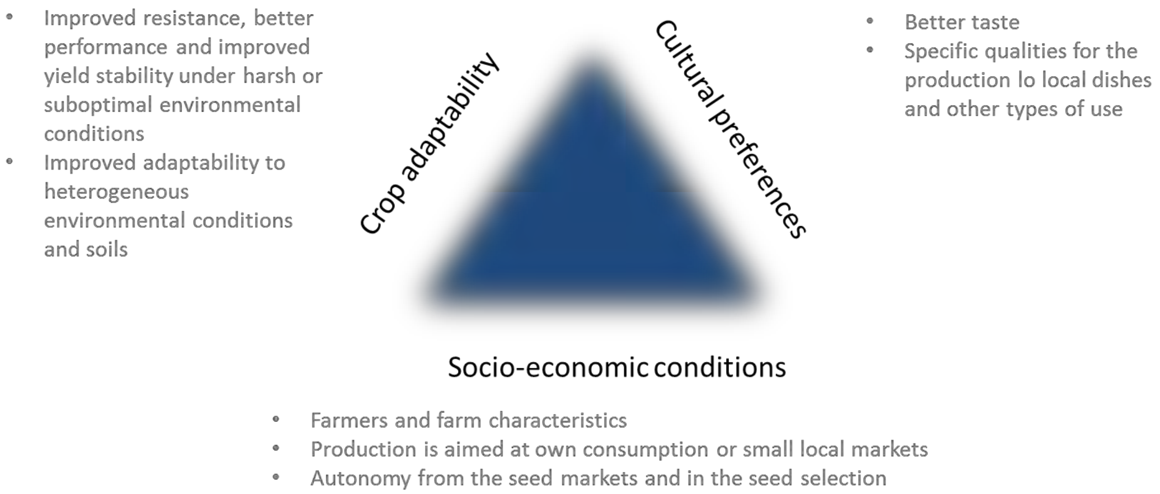


Figure 2.24 Factors associated with the use of maize landraces. Source: Own elaboration with information from Clawson (1985), Brush (1995), Bellon (1996), Bellon et al. (2003); Knezevic (2009); Vaz Patto et al. (2007).

The advantages of landraces over MVs have been documented. These include greater resistance to unfavourable environmental conditions (Bellon et al., 2006; Knežević-Jarić et al. 2014), better adjustment to soil heterogeneous conditions (Bellon, 1996) and greater stability in performance under biotic and abiotic stress conditions (Knežević-Jarić, 2009). For example, the Mexican maize varieties *Bolita* and *Tuxpeño Sequía* are tolerant to drought conditions, *Tuxpeño Crema* is resistant to tropical foliage disease, *Olotillo* is adapted to non-fertilized or poor soils, *Olotón* is tolerant to acid soils, the *Chalqueño/Ancho de Tehuacán* crossbreed is tolerant to alkalinity, and *Toluqueño* is resistant to the maize weevil (Benz, 1987; Arnason et al., 1993; Gutierrez-Rodriguez et al., 1998; quoted in Prasanna, 2012).

On the other hand, both the socioeconomic and cultural contexts where the production units are inserted affect the producers' decision in terms of maintaining or changing their production style (*e.g*. crop intra-specific and inter-specific diversity, external input usage, MV usage, etc.). Included among these factors are the personal and housing conditions of the farmers (land and workforce availability, socioeconomic situation, education and technology), agro-ecological conditions (topography, natural humidity, temperature and landscape heterogeneity), access to the market (proximity or isolation, supply and demand), access to external financial assistance (subsidies to grow certain varieties and financial insurance to cover market and environmental eventualities), as well as the ability to substitute the goods and services provided by diversity in the market (Bellon, 1996; Benin et al., 2004; van Dusen and Taylor, 2005; Hajjar et al., 2008). Financial insurance, for example, has been shown to discourage diversification, since it supersedes the function of agrobiodiversity as a natural insurance against climatic and phytosanitary changes (Di Falco and Perrings, 2005; Baumgärtner and Quaas, 2008). Furthermore, most government policies tend to produce the same effect by providing farmers with infrastructure, modern inputs and subsidies, all of which lead to specialization (Bellon, 1996).

Lastly, and undoubtedly, cultural preferences play a significant role in the maintenance of maize landraces, not only in countries with a high diversity of maize like Mexico, but also in regions where this crop does not hold central importance in terms of food production. Gastronomic uses are related to the conservation of landraces, since these present the correct flavours and textures for the preparation of traditional dishes (Bellon et al., 2003b; Magorokosho, 2006; Vaz Patto et al., 2007; Knežević-Jarić, 2009; Kneţević-Jarić et al., 2010). Hilgert et al., (2013) found a meaningful relationship between maize diversity and the gastronomic use diversity associated with maize in traditional communities of Argentina’s Northern region. Turrent et al. (2012) also emphasized the close relationship between landrace growth and food preparation: “*…e.g., Oaxacan cuisine’s special tortilla ‘tlayuda’ can only be prepared with the landrace ‘bolita’ grain; ‘totopos’ also from Oaxacan cuisine can only be prepared with the landrace ‘Zapalote chico’ grain [...]. ‘Pozole’ can only be prepared with ‘Cacahuacintle’ and ‘Maíz Pozolero’ landrace, rather than with the improved current varieties*”. In the East of Serbia, local maize is grown in reduced areas of less than 1 hectare in order to produce flour that is used to prepare several traditional dishes (Kneţević-Jarić et al., 2010). Among the Mayan people in Mopan, Guatemala, white varieties are grown unripe in order to prepare *tamales,* and ripe to prepare *‘tortillas’* or to feed animals (Steinberg, 1999). Black and red maize are not for sale, as these have religious and spiritual connotations and are preferentially consumed during festivities. Finally, black maize is believed to promote physical strength and resistance to hard labour or when people experience a long period of fasting (*ibid*.). Among the Yungas from Argentina, the *Culli* variety (black/red maize) is grown to protect lodging and plots, in the preparation of *chicha* (a fermented beverage) and for purifications (Hilgert et al., 2013).

For Steinberg (1999) and Chambers *et al* (2007), landrace diversity loss is not a direct result of the expansion of MVs, but rather of the social change related to generational replacement in the context of rising urbanization and industrialization. While replacing landraces implies not only a worsening of genetic diversity of crops, but also the diversity loss of associated crops, agro-ecological interrelations, the diversity of herbaceous and wild related species and the traditional knowledge that sustains and modifies these (Brush, 2000), there is an imperative to create public policies aimed at the preservation of such richness. At the international level, there is a growing acknowledgement of the importance of agrobiodiversity (FAO, 2011a).

2.4 Agricultural production and ecosystem services

Key message 11: Maize production systems, as with all agricultural systems, depend on multiple ecosystem services (ES), which at the same time are affected by management practices that can act to reduce, conserve or enhance these ES. *Intensification has limited expansion of the agricultural frontier in recent decades, but represents a source of ES degradation at different spatial scales.*

Maize production systems depend on multiple ecosystem services (ES). Among these, there are supporting services, such as those underlying the structure and fertility of the soil and the nutrient cycles; regulation services, such as pest and disease control, crop pollination, water purification and weather regulation; and provisioning services, such as water supply (Zhang et al., 2007; Power, 2010). Without these services, maize production systems simply could not exist. At the same time, agricultural practices (*e.g.*, soil management, input usage, irrigation and crop or livestock diversity) can either favour or downgrade these same services, creating new production conditions in subsequent agricultural cycles (Fig. 2.25).

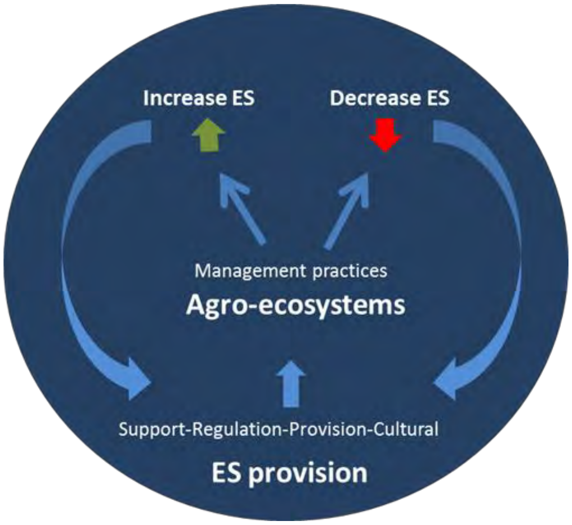


Figure 2.25 Dependencies and impacts of agricultural systems on ecosystem services

2.4.1 Soil fertility, Structure and Nutrient cycle

Soil fertility and structure, as well as nutrient cycling, are closely linked services and determine, to a great extent, the availability of nutrients and moisture for crops, thus affecting their quantity and quality (Zhang et al., 2007). Microorganisms and micro and macro invertebrates play a very important role in porosity, organic matter addition and decomposition and nutrient availability (Power, 2010). Macro invertebrates improve soil structure by creating channels and redistributing organic matter and minerals in the soil; micro fauna decompose plant detritus and add it to its biomass, thus retaining it within the system and micro- and macrofauna regulate the fungi and bacteria that fix atmospheric nitrogen and make it available to plants (Hendrix et al. 1990, Edwards, 2004, quoted in Garbach et al. 2014). Table 2.10 shows the management practices that act to degrade and maintain or enhance these supporting services:

Table 2.10 Management practices that reduce, conserve, or enhance soil structure and fertility services, and nutrient cycling

Support services: Nutrient cycling, structure and soil fertility	
Practices that reduce ES	
Conventional tillage and disking	Alters microorganisms, and communities of micro and macro-invertebrates (*e.g.* nematodes) in soil. Reduces microbial activity. Releases carbon stored in soil. Affects mycorrhizal activity. Breaks soil macro-aggregates (review in Hendrix et al., 1986).
Short fallow periods	Impedes the recovery of soil organic matter (review in Matson et al., 1997)
Use of irrigation in arid and semi-arid region	Waterlogging and soil salinization (review in Matson et al., 1997)
Vegetation burning in shifting systems	Volatilization of N and C (increased by intensity of fire) impacting soil fertility (dynamic of macronutrients) (review in Ribeiro et al., 2015). A study demonstrated that between 94-97% of carbon, 96-98% of nitrogen and 63% of phosphorus is lost during burning through its volatilization or particle-ash transfer (Sommer et al., 2004).
Practices that maintain or increase ES	
Organic management of the soil (use of green manure and cover crops)	Increases soil organic matter and available nutrients, favors the formation and stability of soil macro-agregates, water infiltration and humidity retention, reduces soil erosion (review in Matson el al., 1997 and Kremen and Miles, 2012).
Use of slash and mulch in shifting systems	Increases soil organic matter and availability of nutrients for crops (Sommer et al., 2004)
Use of animal and green manure	Promotes a the diversity of microorganisms and soil invertebrates that affect nutrient cycling (Mader et al., 2002, Reganold et al., 2010, quoted in Kremen and Miles, 2012)
Conservation tillage and use of cover crops	Prevents soil erosion, and increases carbon capture and storage (Caldeira et al., 2004). Increases microbial biomass, total nitrogen and arbuscular mycorrhizal fungus (Wang et al., 2012).
Mulching	Increases water infiltration, reduces water runoff and soil erosion (Jordan et al., 2010)
Riparian vegetation and hedgerows	Reduces water runoff and soil erosion (review in Power, 2010)

Management practices of both intensive and extensive systems negatively affect nutrient cycling and the structure and fertility of the soil, exhausting soil nutrients and affecting the micro- and macro-organisms that participate in the replenishment of such nutrients. In contrast, the use of cover crops, fallow lands, fertilizers and compost, efficient irrigation, agro-forestry, and forest recovery helps to maintain and avoid the degradation of such ecosystem services (Lal, 2004).

2.4.2. Pest control and regulation

Pest control and regulation is probably one of the services that is most affected by agricultural intensification. Approximately 8 to 15% of rice, maize, potato, soybean, wheat and cotton crops are ruined by pests (Oerke, 2005, quoted in Garbach et al., 2014). In the case of maize, around 30% of the crop is ruined by weeds and pests (Settle et al., 1996, quoted in Bommarco et al., 2013).

Management practices that characterize intensive production systems have a greater effect in terms of reducing pest control (Tab. 2.11). It has been documented that, in spite of the intensive use of pesticides, damage caused by pests and diseases has not diminished (Oerke, 2005, quoted in Garbach et al., 2014) and has even caused a pest resurgence as these organisms develop resistance to pesticides (Kenmore et al., 1984, quoted in Garbach et al., 2014). For instance, it has been reported that the cotton aphid (*Aphis gossypii*) that affects maize crops has presented an increase in its frequency of resistance to clothianidin, a pesticide extensively used on such crops in the USA (Herron and Wilson, 2011, quoted in The Task Force on Systemic Pesticides, 2015). Neonicotinoids and fipronil are the most commonly used insecticides worldwide. These insecticides are water-soluble and are usually sprayed over the crop seeds, which absorb these substances and the plant consequently incorporates them into its tissues during growth (Simon-Delso et al., 2014). The use of these insecticides not only affects crop pests, but also a great quantity of the natural enemies of these pests, pollinator species, communities of ground invertebrates, aquatic arthropods and even the birds that feed on the affected insects or treated seeds (see review in The Task Force on Systemic Pesticides, 2015).

Nevertheless, there are several strategies, that can be implemented to optimize the natural control of pests and diseases, which imply providing safeguards and reproduction and feeding spaces for the natural enemies of the most common pests of the harvested species (Tab. 2.11).

Table 2.11 Management practices that reduce, conserve, or enhance the natural control of pests and diseases

Regulation services: pest and disease control	
Practices that reduce ES	
Monocultures	Might increase the population of locally adapted weeds (Barberi, 2002, quoted in Kremen and Miles, 2012). Low intraspecific and intraspecific crop variety increases the risk of a quick spread of pests and diseases (review in Kremen and Miles, 2012). Reduces natural enemies and increase pest pressure (Poveda et al. 2008).
Use of pesticides	Enhances the emergence of secondary pests, plague resurgence and erodes the capacity of auto-regulation of the system (Krishna et al., 2003)
Excessive use of nitrogen fertilizers	Increases the abundance of fungus, pests, bacteria and viruses (Huber, 1981; Scriber, 1984, quoted in Matson et al., 1997)
Simplification of landscape structure	Reduces beneficial insects and other natural enemies of agricultural plagues (Brewer et al., 2008, Gardiner et al., 2009, quoted in Power, 2010)
Practices that maintain or enhance ES	
Crop genetic diversity	Provide an ample gene pool with potential resistance to pathogens (Hawtin, 2000)
Landscape complexity, diversified agricultural systems and polycultures	Associated with a lower density of pests, increase of natural enemies, higher mortality of herbivore insects and less damage to crops (Tonhasca and Byrne, 1994, Letourneau et al. 2011, quoted in Kremen and Miles, 2012)
Crop rotation	Interrupts the development of soil borne pathogens, disease vectors, and pests (review in Kremen and Miles, 2012)
Intercropping	Lower incidence of crop diseases given host dilution, allelopathy and microbial antagonists (Hiddink et al. 2010, quoted in Kremen and Miles, 2012)
Use of native vegetation as hedgerows	Provide food and refuge for natural enemies of agricultural pests (Landis et al. 2000, Tillman et al., 2012, quoted in Garbach et al. 2014; Tscharntke et al. 2005, quoted in Power, 2010)
Maintenance of natural habitats around agricultural fields	

2.4.3. Pollination

Management practices that favour the presence of insects that are good for pest control are also beneficial for the service of pollination (Tab. 2.12). Even when animal pollination is not relevant to maize - this species is wind pollinated - management practices of maize productive systems do affect this service, which is fundamental for almost a third of all the agricultural products upon which humankind relies (Dias et al., 1999). Based on data from 200 countries, an estimate has been made that 75% of the most important crops worldwide depend on this pollination service (Klein et al., 2007). The value of these services has been estimated at 11.9 billion Euros in the African countries, 89.4 billion in Asia, 22 billion in Europe, 14.4 billion in North America and 15.1 billion in Latin America and the Caribbean (Potts et al., 2010). While a wide diversity of pollinator species exists, bees are the most important pollinators for human crops, partly because they are handled to provide this service. In the USA alone, the estimated value of services provided by *Apis mellifera* is 5 to 14 million dollars per year

(Southwick and Southwick, 1992, Morse and Calderone, 2000, quoted in Kremen et al., 2002). *Apis mellifera* has been reported to be able to increase the performance of crops pollinated by animal species by up to 96% (see review in Klein et al., 2007).

Pollination services provided by bees and other insects are threatened by an interaction of factors that include land use change, fragmentation of natural habitats, use of pesticides and environmental pollution, invasive species, climate change and the reduction of the plant species diversity upon which they depend (review in Potts et al., 2010). The use of pesticides such as neonicotinoids and finopril represents a serious threat to a large variety of pollinator insects like the bees. Sub-lethal doses of neonicotinoids and finopril affect the olfactory learning, memory, feeding behaviour and locomotion of bees (Decourtye and Devillers, 2009, quoted in Sánchez-Bayo, 2014). Exposure to sub-lethal doses represents an important risk for pollinator insects, since it is possible to find traces of such substances in the pollen of such crops that have been treated (e.g. maize), in the land where these crops have been cultivated and in the soil and flowers located in the surroundings of treated crop fields (Krupke et al., 2012). It has even been documented that bees can be exposed to lethal or sub-lethal doses of pesticides through the dust produced by mechanical seed drills in the process of depositing maize seeds coated with clothianidin, imidacloprid, thiamethoxam and finopril (Sgolastra et al., 2012). In addition to the use of pesticides, the pollination service is affected by intensification, the increase of crop fields, reduction of crop diversity and suppression of natural habitats and vegetation strips surrounding the crop fields; among other factors (Tscharntke et al., 2005).

Table 2.12 Management practices that reduce, conserve, or enhance the pollination service

Regulation services: pollination	
Practices that reduce ES	
Use of pesticides	Affects not only target species but also beneficial insects like pollinations (Moradin and Winston, 2005, quoted in Kremen & Miles, 2012; Brittain et al., 2010)
Simplification of landscape structure and loss of plant diversity	Reduces the presence of pollinators due to the loss of floral resources and nesting sites (Klein et al., 2007, review in Potts et al., 2010)
Use of neonicotinoid insecticide coating on maize seed	Increased bee mortality due to exposure to atmospheric emission of particles containing the insecticide by drilling machines (Tapparo et al., 2012)
Use of herbicides	Reduced sensitivity to nectar reward and impaired associative learning in bees (Glyphosate: Herbert et al., 2014)
Practices that maintain or enhance ES	
Organic agriculture	Associated to an increase in richness and abundance of pollinators (Holzschuh et al., 2007, Gabriel et al. 2010, quoted in Kremen & Miles, 2012).
Plantation of hedgerows with perennial and floral native species; maintenance of natural habitats around agricultural fields	Provide food, refuge and reproduction sites for pollinator species (review in Potts et al. 2010 and Garibaldi et al., 2011)

2.4.4. Water supply: quality and quantity

The supply of water is a critical ecosystem service for agriculture. It is estimated that around 70% of the water extracted from water-bearings, rivers and lakes is used in agricultural production (FAO, 2011b). About 86% of the water extracted in Africa (215 km^3/year) is used in agriculture. This value is 49% in America (790 km^3/year), 82% in Asia (2, 451 km^3/year), 29% in Europe (374 km^3/year) and 70% (26 km^3/year) in Oceania (FAO, 2011b). Around 40% of crops are produced in areas with irrigation provision. Those areas represent 20% of the total agricultural area (UN Water, 2013; quoted in Garbach et al., 2014).

Water availability in agricultural ecosystems depends not only on infiltrated water, but also on moisture retained by the soil. In fact, it is estimated that around 80% of the water used by agricultural crops comes from this latter source (Molden 2007, quoted in Power, 2010). Soil moisture retention is regulated by factors such as organic matter content, coverage of plants and composition of the community of macro- and microorganisms in the soil (Molden, 2007, quoted in Power, 2010). The management of agricultural soil affects all of these factors. Harmful practices include ploughing, short fallow periods, monocultures and irrigation. Practices that act to increase infiltration and moisture retention in soil are those that directly increase soil organic matter and avoid erosion (Tab. 2.13).

In addition to supply, the quality of water must also be considered since this is severely affected by farming activities, especially by the intensive use of fertilizers and pesticides, which leach into the subsoil and enter water sources, creating a series of harmful effects on aquatic ecosystems and human health. The use of agrochemicals (including herbicides, insecticides, fungicides and fertilizers) has increased considerably worldwide. Irrigated areas and the use of farming machinery has doubled over four decades, while the consumption of fertilizers has increased four-fold over the same period (Pretty, 2008). It has been estimated that 50% of the nitrogen used in agricultural systems is used by plants, 2 to 5% remains in the soil, 25% is released as N_2O emissions, and 20% is leached into aquatic ecosystems (Galloway et al., 2004). The main consequence of the leaching of nitrogen-based fertilizers into water sources is that the excess of nutrients favours the growth of algae. On decomposition, these algae favour the reproduction of microbial communities. Such communities use up the available oxygen, provoking a significant decrease in the levels of oxygen dissolved in the water. Levels O_2 per litre falling below 0.5 (*i.e.* anoxia), cause the death of benthic species (Rabalais et al., 2002). One of the results of the hypoxia and anoxia generated by the boom of algae and aquatic plants is therefore the presence of 'death zones' in lakes, estuaries and coasts; in other words, zones that are temporarily devoid of marine fauna. Globally, more than 400 'death zones' have been identified (Diaz and Rosenberg, 2008). Some of these zones present periodical hypoxia or stationary hypoxia; however, in other cases, such hypoxia has been sustained, causing low secondary productivity, as well as the absence of benthic fauna. In the Gulf of Mexico, Cheakspeake Bay and on the coasts of Denmark, there have been cases that exemplify the latter (Kemp et al., 2005; Conley et al., 2009a). The 'death zone' of the Gulf of Mexico is largely the result of maize and soybean production in the so called Corn Belt, located in the states of Iowa, Illinois, Indiana, Nebraska, Kansas Minnesota and Missouri (Goolsby et al., 1999, quoted in McLellan et al., 2015).

Table 2.13 Management practices that reduce, conserve, or enhance water provision and water quality

Regulation services: quantity and quality of water	
Practices that reduce ES	
Irrigation (mostly laminar)	Increases soil erosion and siltation of water bodies (Sojka et al., 2007)
	Reduction of available water in low basins with negative consequences for riparian systems (Postel and Carpenter, 1997, quoted in Matson et al., 1997)
	Changes water flows and water infiltration patterns (review in Dale and Polasky, 2008)
Use of fertilizers	Contamination of aquifers and increase in nitrates in drinking water (Bouwman et al. 2009, quoted in Power, 2010)
Use of pesticides and herbicides	Lixiviation of agrochemicals in water bodies (Wauchope, 1978, Haynes et al. 2000)
Practices that maintain or enhance ES	
Organic management of the soil	Increases soil organic matter increasing soil humidity and water retention capacity thereby reducing the need of irrigation (Reganold et al., 1987; Mäder et al. 2002, quoted in Kremen and Miles, 2012). Soil humidity represent 80% of water used by crops (Molden 2007, quoted in Power, 2010)
Diversification of nutrient inputs, use of leguminous crops and crop rotation	Reduces the need of chemical fertilizers which have a higher potential to leach into water bodies (Drinkwater and Snapp 2007, quoted in Power, 2010)
Use of cover crops and intercropping	Increases the uptake of nitrogen and the reduction of the presence of nitrates in water (see review in Power, 2010)
Conservation tillage and mulching	Reduce the evaporation of soil humidity by 35-50% reducing the need of irrigation (review in Power, 2010)
Native vegetation strips (*i.e.* woods)	Stabilizes water flux between humid and dry seasons (Guo et al., 2000)
Management of riparian vegetation	The potential to remove nutrients and sediments before they leach into superficial water bodies (Swinton et al., 2007)

2.4.5. Weather regulation

Agriculture is estimated to be responsible for 20% of greenhouse effect gas emissions, including 21 to 25% of carbon dioxide (CO_2) (from fossil fuel use and deforestation), 55 to 60% of methane (CH_4) (from cattle production, biomass burning and rice cultivation) and 65 to 80% of nitrous oxide (N_2O) (from biomass burning, croplands and animal waste) (IPCC, 2001). Intensive systems are significant emitters of greenhouse gas, as the intensive use of fertilizers, irrigation and machinery releases great quantities of such gases since these are all related to the use of fossil fuel. Extensive systems, in contrast, particularly those that depend on burning, emit greenhouse gases through the combustion of biomass during the process (Tab. 2.14). Management practices that may reduce harmful effects on this service are those focused on soil management, decreased agricultural inputs and the reduction or suppression of shifting (slash and burn) systems (Tab. 2.14).

Table 2.14 Management practices that reduce, conserve, or enhance the climate regulation service

Regulation services: climate	
Practices that reduce ES	
Use of fertilizers	Greenhouse gas emissions: carbon dioxide, nitrogen oxide, and methane production (review in Matson et al., 1997).
Conventional tillage	Carbon emission: Moldboard plow (15kg C/ha), chisel plow (11kg C/ha), and subsoil tillage (11kg C/ha), rotary hoe (2kg C/ha) (review in Lal, 2004)
Vegetation burning	Emission of methane, nitric oxide, and carbon monoxide and dioxide (Davidson et al., 2008)
Land use change	Release of the carbon stored in soil and vegetation. Conversion of natural ecosystems to agricultural soils reduces soil carbon of temperate regions in 30 to 50% (in 50 to 100 years), and 50 to 75% in the tropics (20-50 years) (Lal, 2008, quoted in Power, 2010).
Use of fossil fuels for mechanized agriculture and for the extraction of water, its distribution and irrigation of agricultural fields.	Increase in greenhouse gas emissions
Practices that maintain or enhance ES	
Use of slash and mulch	Reduction of greenhouse gas emissions in comparison with slash and burn agriculture (Davidson et al., 2008)
Organic agriculture	Decrease in the use of energy and increase in greenhouse gas emissions per hectare (attributed to the absence of chemical fertilizers and pesticides (review in Lynch et al., 2011, quoted in Kremen and Miles, 2012).
Conservation tillage and no-till	Increased capture of organic carbon in soil (only in the first 10 cm, depending on geographic area: Blanco-Canqui and Lal, 2007)
Conservation tillage, cover crops, use of green manure, agroforestry and crop diversification	Increase of carbon storage in soil (review in Lal, 2004)
Restauration of degraded soils to avoid hydric and eolic erosion	Reduction in carbon release from soils (review in Lal, 2004)

2.4.6. Biodiversity

Biodiversity is a core element that underlies all ecosystem services (MEA, 2005; review in Loreau et al., 2001). Notwithstanding its relevance, species extinction rates are 1,000 times higher at present than they were in the period prior to the appearance of the human species. It is estimated that these rates will be 10,000 times higher in the future (De Vos et al., 2015). The greatest threats to biodiversity are a consequence of the transformation of natural ecosystems for agriculture, overexploitation of species, introduction of invasive species, climate change and pollution due to waste and a surfeit of nutrients (MEA, 2005). Even when all types of agriculture affect biodiversity, the impact varies considerably according to the particular management practices involved (Tab. 2.15).

Table 2.15 Management practices with highly negative effects, and those that reduce negative effects on biodiversity

Biodiversity	
Practices that reduce ES	
Monocultures	Associated with the use of modern varieties thereby reducing the genetic variability of crops. Monocultures are also associated with the use of agrochemicals which have a direct impact on biodiversity (see below)
Intensification of shifting systems (e.g. shortened fallows and reduced agrobiodiversity)	Impaired ability of the vegetation to return to the previous state (*i.e*. species composition) (Scales and Marsden, 2008, quoted in Kremen and Miles, 2012)
Tillage	Alters the community of microorganisms and micro/macro invertebrates in soil, reduces the population of nematodes and mycorrhizae (review in Hendrix et al., 1986)
Use of fertilizers	Increases the frequency and severity of algal blooms, generating “dead zones” in coastal marine ecosystems (review in Power, 2010).
Use of insecticides and seed coatings	Long term alterations in communities of aquatic invertebrates (Beketov et al. 2008, quoted in Van Dijk et al., 2013). Use of neonicotinoids causally related to negative effects over olfactory learning, memory, feeding behavior and the locomotion of bee (Decourtye and Devillers, 2009, quoted in Sánchez-Bayo, 2014; Yang et al., 2008; Maini et al., 2010, quoted in Boily et al., 2013)
Use of herbicides	Reduction in species richness of larval amphibians by the use of glyphosate (Relyea, 2005)
Simplification of landscapes	Reduction in the diversity and abundance of species (review in Kremen and Miles, 2012)
Practices that maintain or enhance ES	
Polycultures (annual and perennial species)	Represent potential habitats for resident and migratory birds (Robbins et al., 1992)
	Use of a combination of early, mid and late successional perennial species is especially beneficial (review in Jose, 2009)
Home gardens	Associated with the presence of a great diversity of species (review in Jose, 2009)
Diversified landscapes and agroforestry systems	Provide habitat for species, preserve the germplasm of sensitive species, prevents complete land use change, and serve as biological corridors (review in Jose, 2009)
Organic agriculture	Associated to a greater abundance and richness of species (review in Kremen and Miles, 2012). Beneficial for birds, predatory insects, and species present in the soil (Bengtsson et al., 2005)
Maintenance of surrounding native vegetation	Serve as a refuge and wildlife corridors for a great diversity of terrestrial organisms (Batary et al., 2011)

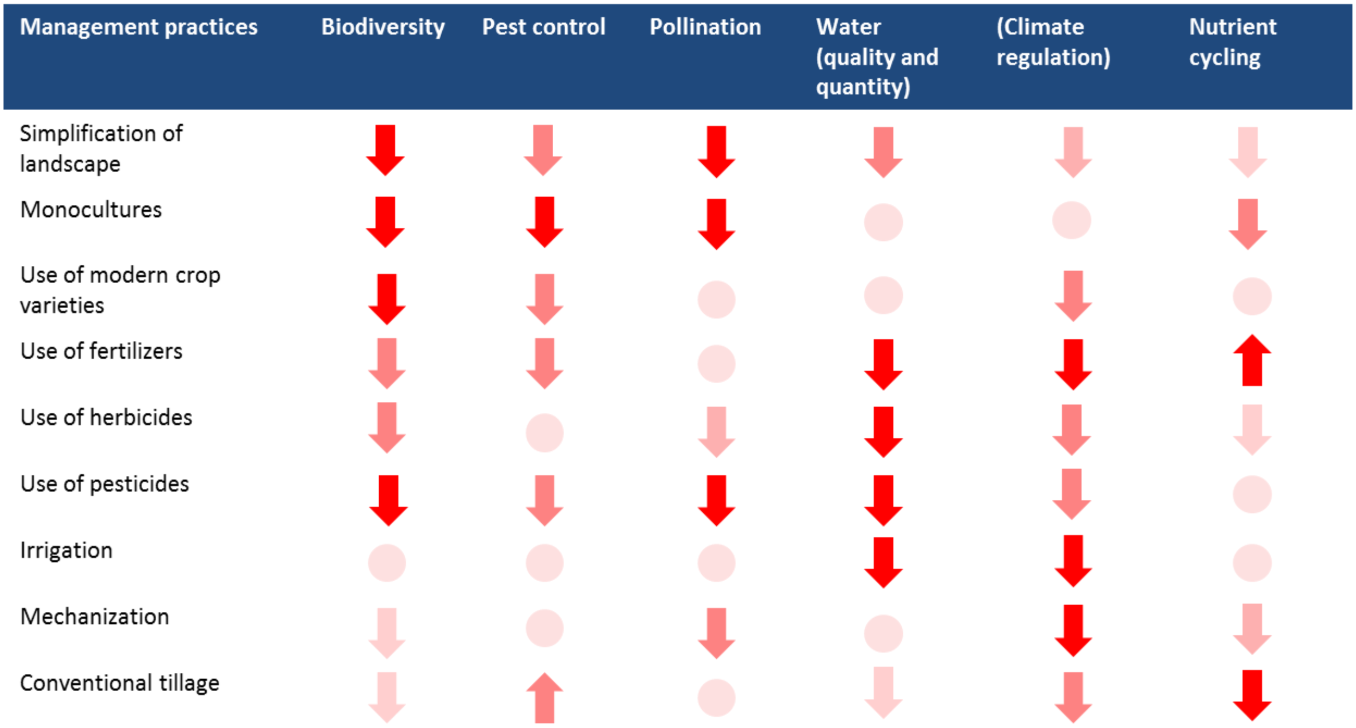
As shown in table 2.15, the management practices of intensive agricultural systems have detrimental effects for biodiversity that impact upon soil and air biodiversity at a local level, as well as the biodiversity of aquatic ecosystems thousands of kilometres away. In recent times, intensification of productive ecosystems has been proposed as one of the main causes of biodiversity loss (Tilman et al., 2001; Matson et al., 1997).

According to Tscharntke et al. (2005), farming intensification can occur at both local and landscape levels: Local intensification is characterized by a reduction in crop variety, an increase in the use of mineral fertilizers and pesticides, modern or genetically modified seeds, deep ploughing, farming machinery and drainage, as well as an increase in the size of farming units (*ibid*.). Landscape intensification is characterized by agricultural specialization reflected in large areas of monoculture, conversion of remaining habitats (coastal vegetation, strips of natural habitats in the surroundings and between cultivation fields), spatial and temporary simplification of the farming landscape, use of fallow lands and natural habitat fragmentation, among others (*ibid*.).

Biodiversity is affected both directly and indirectly by the use of agrochemicals. When pesticides are used, these effects are direct. As described previously, neonicotinoids (imidacloprid and clotianidin) and fipronil have harmful effects on a large variety of vertebrates (review in Gibbons et al. 2014). While imidacloprid and fipronil are toxic for some birds and most of the fish species that have been studied. All of the pesticides reviewed in Gibbons et al. (2014) had sub-lethal effects at genetic and cellular levels, affecting growth, reproduction and immunosuppression in a large variety of organisms. Clothianidin may directly affect diverse organisms, as is the case of birds that feed on seeds treated with this substance, or different organisms, due to their accumulation in the soil and vegetation surrounding maize fields (Krupke et al., 2012). In the case of fertilizers, there is an indirect impact, since their effects are mediated by a series of processes (*i.e*. eutrophication), as described previously.

In addition to reduced wild species biodiversity because of habitat loss and the use of pesticides and fertilizers, intensification processes can erode both planned and non-planned (or associated) farming units. Erosion of both intra- and inter-specific genetic diversity is a result of the specialization that accompanies intensification processes, the main goal of which is to enhance yields.

In summary, biodiversity loss reverberates not only in wildlife conservation, but also affects the production of the ecosystem services upon which farming activities depend, such as soil fertility and nutrient cycling, pest control and pollination (Fig. 2.26). Management practices usually affect more than one ecosystem service, thus increasing both the cost and difficulty of restoring these complex biological systems on which the provisions of humankind rely.



Management practices	Biodiversity	Pest control	Pollination	Water (quality and quantity)	(Climate regulation)	Nutrient cycling
Simplification of landscape	↓	↓	↓	↓	↓	↓
Monocultures	↓	↓	↓	●	●	↓
Use of modern crop varieties	↓	↓	●	●	↓	●
Use of fertilizers	↓	↓	●	↓	↓	↑
Use of herbicides	↓	●	↓	↓	↓	↓
Use of pesticides	↓	↓	↓	↓	↓	●
Irrigation	●	●	●	↓	↓	●
Mechanization	↓	●	↓	●	↓	↓
Conventional tillage	↓	↑	●	↓	↓	↓

Figure 2.26 Management practices associated with agricultural intensification and their impact on ecosystem services. Note: Circles represent absence of impact or negletive impact of management practices on ecosystem services; the arrows depict the direction of the impact (i.e. increase or decrease ecosystem service). Source: Own elaboration.

Key message 12: Genetically modified (GM) maize has continuously and controversially gained ground over its conventional (non-GM) counterpart over the last two decades. *It has been cultivated in 27 countries and currently accounts for 35% of global maize production. Five of the major maize producing countries account for 97% of GM maize production worldwide, which is concentrated in intensive large-scale systems directed mainly towards the livestock and ethanol industries. Production and commerce of GM maize has been controversial given the potential negative effects on the environment of GM varieties and their associated technological packages, but also due to the nature of the products and their ultimate use. Moreover, the patent system of all GM crops has been associated with a potential dependency of farmers on purchased seeds and inputs, while weakening the traditional seed exchange system and, consequently, affecting the crop genetic diversity generation process. This debate is particularly relevant in the centres of origin and/or centres of genetic diversity of maize.*

The extent of genetically modified (GM) crop cultivation has increased every year since commercial cultivation began. A single tobacco farm in China launched a virus-resistant commercial crop in 1988, only to be followed by a farm in California, in 1994, growing rotting-delayed tomato (Stone, 2010). In 1996, 1.7 million hectares (ha) were approved for GM cultivation, mainly in the United States. By 2014 (only 19 years later), this number had soared to 181.5 million ha. There has been a steady increase in area of around 10 million ha per year. During this 19-year period, GM crops have been cultivated in 36 countries from all around the globe. Since 1994, a total of 63 countries have granted regulatory approvals for the import and consumption of GM crops, their use in the manufacture of feed and their release into the environment (James, 2013). In 2014, cultivation of GM crops was approved by the governments of 28 countries, 6 of which made up for more than 90% of the total area under cultivation: the United States (40.3%), Brazil (23.3%), Argentina (13.4%), India (6.4%), Canada (6.4%) and China (2.2%). Other important GM growers are Paraguay (2.2%), South Africa (1.5%), Pakistan (1.4%), Uruguay (0.9%) and Bolivia (0.6%) (James, 2014).

Agricultural plants have been genetically modified to tolerate herbicides and to resist insects and viruses. More recent (second generation) GM varieties are designed to present other enhanced traits, such as drought resistance or nutritional content (BCH, 2016). The most common GM crop by far is herbicide tolerant (HT) soybean, followed by HT and insect resistant maize (Fig. 2.27). Genetically modified soybean, maize, cotton and canola account for almost the entire area of GM crops cultivated worldwide, and have been designed to present one or both (stacked) of the herbicide tolerant and insect resistant traits. Each one of these crops has gained ground over its conventional (non-genetically modified) counterpart over the last decade. Around 81% of the world´s cultivated soybean is now GM; the same percentage is true for cotton, while GM maize and canola now represent 35% and 30% of the total of their respective crops (James, 2012).

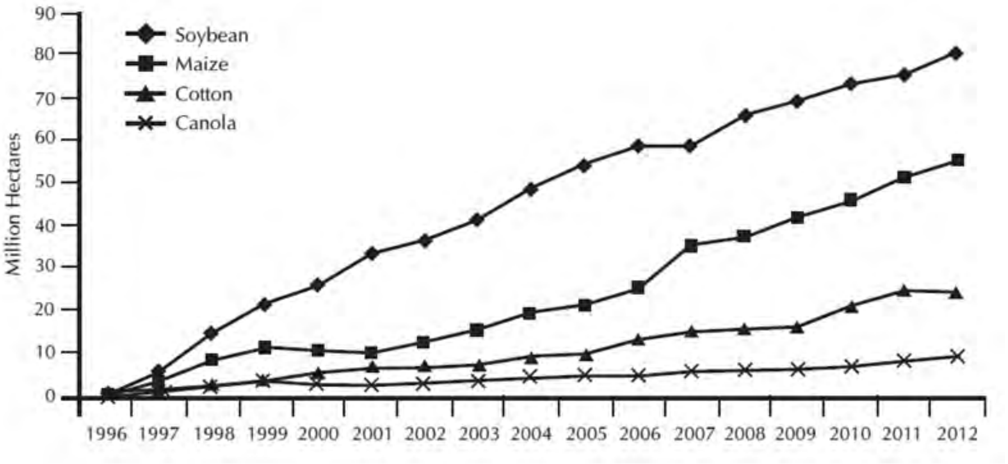


Figure 2.27 Historical area covered by the four main GM crops. Source: Taken from James, 2012.

In the case of herbicide tolerance, for example, Glyphosate inactivates an essential enzyme of the aromatic amino acid pathway of the plant[17]. Glyphosate tolerance is achieved by inserting a gene for an alternative version of this enzyme into the plant genome. This version is not inactivated by glyphosate and thus allows the plant to survive in the presence of the herbicide. This broad-spectrum herbicide, effective against any kind of plant and used to kill weeds that compete with crops (Duke and Powles, 2008), was discovered in 1970 in the laboratories of the Monsanto Company and introduced to the market one year later under the name of Roundup. It is absorbed through the foliage and transported to the growing parts of the plant (Nandula et al., 2005).

Insect resistance, on the other hand, has been achieved by genetically manipulating and introducing genes isolated from a soil bacterium called *Bacillus thuringiensis* (Bt) –hence the name Bt crops– into diverse species. These genes produce proteins (Cry and Cyt protein families) that, when expressed in the Bt-transformed-plant cells, kill insect larvae that feed on the plant (English, 2004; Bravo et al., 2007). There are different kinds of Bt transformation events, depending on the particular Bt gene used for the transformation of the plant. Most maize GM Bt events have been transformed with Bt genes directed to control insects of the Lepidoptera order (butterflies and moths), such as the European corn borer (*Ostrinia nubilalis*); however, genes directed towards the control of pests from the Coleoptera order (beetles such as the root worm (*Diabrotica* spp)) have also been used. Other transformation events have stacked traits aimed at both of these orders (BCH, 2016).

In total, 27 GM crops and 336 GM events have been approved in the world for commercial cultivation (James, 2013). Around 59% of the regulatory approvals have been for food use (direct consumption or processing) while 41% are for feed manufacture. “Maize has the most number of approved events (130 events in 27 countries), followed by cotton (49 events in 22 countries), potato (31 events in 10 countries), canola (30 events in 12 countries) and soybean (27 events in 26 countries)” (James, 2013: p. 10).

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[17] The 5-enolpyruvylshikimate-3-phosphate synthase or EPSPS enzyme of the shikimate pathway.

In the year 2013, GM maize covered around 55 million ha in 17 countries: the United States, Brazil, Argentina, South Africa, Canada, Philippines, Paraguay, Uruguay, Spain, Colombia, Chile, Honduras, Portugal, Cuba, Czech Republic, Romania and Slovakia (Tab. 2.17). In the European Union, five countries planted around 148 thousand ha of Bt maize, of which 94% were found in Spain (James, 2013). Table 2.16 shows the main GM events that have been approved in the world, seven of which are maize varieties that are either insect resistant, herbicide tolerant or are stacks with both traits. A drought tolerant GM maize variety has also been designed (by Monsanto) and was commercially launched in the United States in 2013. This event –which is called DroughtGard (MON87460) and contains a cold shock protein B gene from a soil microbe (*Bacillus subtilis*) (OECD and FAO, 2012) covered 275 thousand ha in the year 2014 –a fivefold increase from the previous year (James, 2014).

Table 2.16 Main GM crops, number of approvals for each one, and number of countries in which these approvals have been given (this is not equivalent to the number of approved events being cultivated in a given country, it could be inferior)

Rank	**GM - EVENT**		**Number of approvals**	**Number of countries**
1	Herbicide tolerant soybean	GTS-40-3-2	51	24
2	Insect resistant maize	MON810	49	23 + EU (28)
3	Herbicide tolerant maize	NK603	49	22 + EU (28)
4	Insect resistant maize	Bt11	45	21 + EU (28)
5	Insect resistant maize	TC1507	45	20 + EU (28)
6	Herbicide tolerant maize	GA21	41	19 + EU (28)
7	Herbicide tolerant soybean	A2704-12	37	19 + EU (28)
8	Insect resistant maize	MON89034	36	19 + EU (28)
9	Insect resistant cotton	MON531	36	17 + EU (28)
10	Herbicide tolerant and insect resistant maize	MON88017	35	19 + EU (28)
11	Insect resistant cotton	MON1445	34	15 + EU (28)

Source: Own elaboration with data from James, 2013.

Table 2.17 shows that 97% of all GM maize is grown in five countries: the United States, Brazil, Argentina, South Africa and Canada. It also shows that all five grow by far more GM than non-GM maize within their boundaries.

Table 2.17 World GM maize commercially cultivated area, by country

Rank	Country	GM maize area (million ha)	% of maize area cultivated with GM in each country	% of total world GM maize area
1	United States	34.1	96%	62%
2	Brazil	12.1	85%	22%
3	Argentina	3.3	88%	6%
4	South Africa	2.4	76%	4%
5	Canada	1.6	99%	3%
6	Philippines	0.8	31%	1%
7	Paraguay	0.44	44%	1%
8	Uruguay	0.145	99%	<1%
9	Spain	0.1	26%	<1%
10	Colombia	0.075	12%	<1%
11	Chile	0.045	32%	<1%
12	Honduras	0.027	8%	<1%
13	Portugal	0.008	8%	<1%
14	Cuba	0.003	2%	<1%
15	Czech Republic	0.003	3%	<1%
16	Romania	0.0002	<1%	<1%
17	Slovakia	0.0002	<1%	<1%
	WORLD	55.1	35%	100%

Source: Own elaboration with data from James, 2012 (GM maize area); and FAOSTAT, 2015 (total maize area).

GM maize production is mainly directed towards the livestock and ethanol industries. The USA cultivates 62% of GM maize in the world and, at 96% of the cultivated area; almost all maize that is produced within its territory is GM (Tab. 2.17).

In Canada (the world´s fifth largest GM maize producer), almost 100% of maize production is GM and is used for feed manufacture and processed food. Brazil and Argentina (the world´s second and third largest GM maize producers, respectively), together with the USA and Canada, account for 93% of the total cultivated area of GM maize and produce almost exclusively yellow maize, which is mainly directed towards feed manufacture and exportation. On the other hand, the production of GM white maize is important in South Africa. This African country is the fourth largest GM maize producer, the second largest producer of white maize (after Mexico) and the leading exporter of white maize worldwide. Around 57% of the South African maize produced in the year 2013 was white and 84% of this white maize was GM (James, 2014). This means that GM white maize production in South Africa accounts for almost half of the total maize production of this country (6 million tons)

(FAOSTAT, 2015), which is destined mainly for direct consumption and is placed in the white maize export market. However, this production only represents 2.8% of the world GM maize production.

The production of GM maize has been controversial partly because of the possible negative effects on the environment of the two most widely used GM traits: Glyphosate tolerance and Bt insect resistance. The use of glyphosate based herbicides (GBH) has been associated with biodiversity loss, affecting vertebrates and invertebrates in agricultural landscapes and test-animals (Haughton et al., 2003; Hawes et al., 2003; Paganelli et al., 2010). Experiments have shown that GBH are highly toxic to larval amphibians (Relyea, 2005, 2011, 2012; Relyea and Jones, 2009) and negatively affect the growth, reproductive maturity and number of offspring of water fleas (*Daphnia magna*) and of rats that have been fed with soybean containing glyphosate residues (Dallegrave et al., 2007; Borggaard and Gimsing, 2008; Romano et al., 2010; Cuhra et al., 2015). The impact of GBH on water quality and non-target aquatic organisms –through leaching and proximity to water bodies– has also been studied and debated (Jiraungkoorskul et al., 2003; Frontera et al., 2011; Lajmanovich et al., 2011; Salazar-López et al., 2011).

The image of glyphosate as an environmentally friendly herbicide has been brought into question by such research results, as well as by the debate on whether the use of herbicide resistance GM technology reduces or increases herbicide use overall. According to a model analysis of the use of herbicides in the USA through the years 1996-2011, there has been an upward trend in herbicide use per hectare in crops using GBH, compared to crops using other type of herbicides (Benbrook, 2012). Drawing upon USDA data, this analysis estimates that the GBH technology has led to a 239 million kilogram increase in herbicide application over this sixteen-year period. The main cause of such increased herbicide use in GBH crops is, according to this report, the evolutionary development and rapid spread of glyphosate-resistant weeds, usually associated with inappropriate use of the herbicide. Glyphosate herbicide tolerant crops in the USA (including maize, soybean, and cotton) seem to have only achieved reduced herbicide use for the first six years of the commercial use of this technology; i.e., from 1996 to 2001. From 2002, the spread of glyphosate-resistant weeds has increased the use of GBH and other (non-GBH) complementary herbicides (Mueller et al., 2003; Duke, 2005; Owen and Zelaya, 2005; Benbrook, 2012).

Bt crops, on the other hand, have reduced insecticide applications in the US over the same sixteen-year period, although the emergence of maize rootworm populations that have become resistant to Bt toxins has been reported, for example. The emergence of these Bt resistant pests is provoking a return to the use of former maize soil insecticides (Benbrook, 2012).

In addition to the possible deleterious environmental effects described here, driven by the large-scale use of GM crops and their agronomic packages (associated herbicides), the introduction of these crops has caused concern in several areas, including coexistence, monitoring capacity (along the production and supply chain), and the possible consequences of intellectual property aspects related to the patent system on maize diversity in the centres of origin and diversity of this crop (Acevedo et al., 2009; Acevedo, et al., 2011; Burgeff et al., 2014). Agribusiness corporations that have invested in the research, design and production of agricultural GM technology have the exclusive legal right to provide GM seed and decide the limits of use of its offspring obtained through the harvest, in every growing season. This impinges upon the historic practice of selection, saving and exchange of seeds carried out by the farmer. In this sense, intellectual property rights tied to agricultural GM organisms are potentially and indirectly detrimental to the traditional seed exchange systems managed by smallholders, which have been a keystone of agrobiodiversity evolution and conservation; i.e., central to the millenary adaptation of food production systems to environmental and cultural diversity and change.

Key message 13: Maize has been a central crop in the climate change debate. *The expansion of the harvested area of maize has been regarded as a driver of deforestation and forest degradation. However, the use of maize for the production of agro-fuel has been positioned as an important mitigation measure. Climate change forecasts show negative effects on maize production worldwide, which could be particularly detrimental to those communities that depend on this grain for food and those producing it in rainfed systems. Caloric availability from cereals is likely to be reduced. Price increases in maize, caused by increasing demand, will be notably aggravated by the effects of climate change.*

Climate change represents a worldwide threat to agriculture. Unhindered growth of greenhouse gas emissions is raising the Earth's temperature and this will bring about different effects at a global, regional and local level, affecting various ecosystem processes. Agriculture will be affected through impacts on crops, soils, livestock, insects, weeds and diseases (Reilly et al., 1996). These impacts and responses include acidification and eutrophication of water bodies, spread of diseases, weed proliferation, soil erosion, variation of micro-climatic patterns and changes in water availability (Elbehri et al., 2011).

World agricultural activities take place over a wide range of environmental and climatic conditions that will imply different local and regional impacts. While agriculture has historically been able to adapt to changing climatic conditions, there is much uncertainty regarding its potential adaptation under current climate change scenarios (Reilly et al., 1996). Some regions may experience gains in production due to favourable local climatic conditions, but the overall scenario indicates that higher temperatures and changes in precipitation will eventually reduce crop yields, encourage weed proliferation, increase short-run crop failure and contribute to a long-term decline in production that will prevent many regions from achieving sufficient yields to meet the needs of a growing population (Nelson et al., 2009).

The world's population is expected to reach 9 billion people by 2050, increasing the demand for food and ecosystem services (Shiferaw et al., 2011). The accelerated pace of climate change, combined with the growing population, represents a risk to food security and livelihoods around the world but especially in poor countries. Maize is a vital crop for ensuring food security. Together with wheat and rice, it provides at least 30% of the food calories of 4.5 billion people in developing countries (Shiferaw et al., 2011). Maize demand is expected to double by 2050 in the developing world and to continue presenting the highest production globally (Cairns et al., 2013). Maize is vulnerable to the effects of climate change. Extreme environmental conditions expected under climate change scenarios will affect the incidence of pests as well as the geographical distribution of landraces and annual yields. The impacts of climate change on maize production include bio-physical effects on production, changes in prices, and changes in per capita caloric consumption.

1. Bio-physical effects on production: Climate change is likely to lead to increased water scarcity and the changes in precipitation patterns and an increased requirement for water by crops will lead to long-term production decline. Changes in precipitation patterns will lead to some regions experiencing excessive soil moisture or waterlogging in maize production areas.

Increased temperatures affect physiological, biochemical and molecular processes that will impact maize yields. Crops under heat stress can experience increased sterility, a shortened life cycle, reduced light interception and perturbation of the carbon assimilation process. In Sub-Saharan Africa, maximum temperatures are predicted to increase by 2.6 °C across the maize environments. Increasing temperatures by a few degrees may increase yields in temperate areas but in tropical regions this will be detrimental. Changes in temperature and water availability will increase disease and pest outbreaks in agricultural regions. Temperature influences the reproduction and distribution of insects and the development of maize diseases (Hellin et al., 2012).

2. Changes in prices: Even without climate change, prices for the most important agricultural crops (rice, wheat and maize) will increase between 2000 and 2050 due to the increasing demand of a growing population: the price for maize would increase by 63%, but climate change will cause an additional price increase of 52-55% for maize for the same period. Table 2.18 shows the expected effects of climate change on maize production obtained by the International Food Policy Research Institute, adapted from Nelson et al. (2009).

Table 2.18 Climate change effects on maize production.

	South Asia	East Asia and Pacific	Europe and Central Asia	LA and Caribbean	Middle East and North Africa	Sub Saharan Africa	Developed countries	Developing countries	World
2000 (mmt)	16.2	141.9	38	80.1	8.2	37.1	297.9	321.3	619.2
2050 No CC (mmt)	18.7	264.7	62.7	143.1	13.1	53.9	505.1	556.2	1061.3
2050 No CC (% change)	15.4	86.5	65	78.7	59.8	45.3	69.6	73.1	71.4
CSIRO (% change)	-18.50	-12.70	-19.00	-0.30	-6.80	-9.60	11.50	-10.00	0.20
NCAR (% change)	-8.90	8.90	-38.30	-4.00	-9.80	-7.10	1.80	-2.30	-0.4

Source: Adapted from Nelson et al., 2009.

The table considers two climate scenarios: those of The National Center for Atmospheric Research, USA (NCAR) and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO). The results indicate that climate change will have negative effects on maize production worldwide. These effects will be more pronounced in developing countries, where a fall of between 2.3 and 10% production is projected. Maize production in every region is expected to be negatively affected under the climate change scenarios; South Asia, central Asia and Europe are projected to present the greatest drops in production. However, Europe will not be as severely affected by these drops, due to the particular economic circumstances of this continent.

3. Changes in per capita caloric consumption: The decline in grain production will translate into a decline in caloric availability in certain areas of the world and this will mainly affect those countries were maize is a staple crop. Without climate change, caloric availability would increase from 2000 to 2050 in both developing and developed countries. Table 2.19 shows the differences in caloric consumption in 2050 under climate change and non-climate change scenarios (adapted from Nelson et al., 2009). Under both climate change scenarios (NCAR and CSIRO), the results show a drop in daily per capita caloric consumption to levels below those of 2000 worldwide.

Table 2.19 Daily per capita calorie availability with and without climate change.

Cereals	**2000**		**2050**	
		No CC	NCAR	CSIRO
Developing countries	3,450	3,645	3,190	3,215
Developed countries	2,696	2,886	2,410	2,432

Source: Adapted from Nelson et al., 2009.

The above results show that there is some uncertainty regarding the extent to which climate change will affect the production of grains, and maize in particular. However, it is clear that there will be an overall negative effect on agricultural production worldwide that will impact both food security and sovereignty, especially in rural and poor regions.

Projections for regions. Africa and Latin America are regions where maize is particularly vulnerable to climatic variability and change. In many areas within these regions, maize is grown under rain-fed conditions by smallholders (Cairns at el., 2012). Approximately 40 million people in Latin America and 130 million in Sub-Saharan Africa depend to a large extent on maize for food security and income generation (Jones and Thornton, 2003).

An analysis for Latin America and Africa, presented by Jones and Thornton in 2003, forecasts an overall reduction in yield by the year 2055 in smallholder rain-fed maize production. In some areas, a 10% decrease in maize yields can be compensated by technological inputs and agricultural intensification; however, inhabitants of areas where a one ton reduction in yield is expected will experience drastic disruptions to their life styles.
The following table presents projections in yields for Latin America and Africa broken down by the maize mega-environments (Hartkampt et al., 2001). In both regions, average yield decreases in the tropical and subtropical environments. The only environments that experience increased yield are those of the temperate cold and the mesic subtropical cold winter (Tab. 2.20).

Table 2.20 Average maize yields (kg/ha) for 2055.

Maize mega-environment	Mexico, Central and South America		Africa	
YEAR	**2000**	**2055**	**2000**	**2055**
Dry lowland tropical	1046	765	487	368
Mesic lowland tropical	716	678	800	715
Wet lowland tropical	1166	974	1055	928
Pluvial lowland tropical	1358	1293	0	0
Dry mid altitude tropical	1164	1092	1029	907
Mesic mid altitude tropical	1361	1069	1586	1370
Wet mid altitude tropical	1522	1369	1400	1168
Dry highland tropical	880	796	1195	1165
Mesic highland tropical	1469	1347	1472	1882
Wet highland tropical	1771	1985	2083	2160
Dry lowland subtropical	0	0	763	656
Mesic lowland subtropical	1083	1019	989	814
Wet lowland subtropical	1230	1020	1251	1036
Pluvial lowland subtropical	1412	1252	1142	1117
Dry mid altitude subtropical	568	470	346	572
Mesic mid altitude subtropical	1256	1331	1208	984
Wet mid altitude subtropical	1657	1347	1518	1256
Dry highland subtropical	892	877	449	417
Mesic highland subtropical	1306	1488	1649	1708
Wet highland subtropical	1886	2192	2074	2208
Mesic subtropical cold winter	331	930	187	646
Mesic temperate lowland	937	1012	801	586
Wet temperate lowland	1120	988	1019	849
Mesic Temperate warm	1043	1040	1354	1008
Wet temperate warm	1764	1571	1634	1401
Mesic temperate cold	1265	1406	1458	1183
Wet temperate cold	1803	2300	1455	1498

Source: Adapted from Jones and Thornton, 2003.

2.5 Public policies on maize

Key message 14: Subsidies have played and still play an important role in maize production policy. *Even though subsidies may be applied in order to address legitimate concerns, they can be socially and environmentally detrimental. While subsidies for maize inputs, such as fertilizers, can increase productivity in certain cases, they have not improved the economic conditions of the most vulnerable farmers. The main beneficiaries of such policies are relatively wealthier farmers. Moreover, subsidies in the form of price-setting programs have promoted the development of large-scale farms rather than protecting family farmers. Input subsidies encourage the abandonment of traditional polyculture "safety-net" systems and stimulate local intensive-input management practices.*

The current state of the global maize market, in which agricultural and commercial policies develop, is characterized by two consecutive record harvests in the USA, the highest recorded levels of reserves and the lowest market prices in the last five years (OECD-FAO, 2016). The perspective for the coming decade indicates that international commerce in cereals will grow faster than production; developed countries will supply the demand of coarse grains, including maize, to developing countries[18] and prices will continue to decrease (ibid). Agro-fuel (particularly maize ethanol) production will grow slowly over the coming years. Considering the projected low prices of oil, levels of maize production for agro-fuels will depend on the incentives and support policies implemented by governments in the producer countries (*ibid*.).

In spite of the different socio-economic and political landscapes of the maize producing countries, some of their agricultural policies share common objectives: they aim to increase maize yields and productivity, protect smaller farmers (or the most vulnerable), ensure food security, improve the economic conditions of rural and urban populations, allow countries to compete in international agricultural markets and, most recently, transfer to sustainable agricultural practices. As will be discussed later on, these agricultural policies have often had mixed (if not unexpected) effects.

Governments attempt to accomplish the objectives described above through three main types of agricultural policies: 1) public expenditure (for example, building infrastructure, providing credit, funding research, providing extensionism, seed production and financing deficit and direct payment programs); 2) price and commercial controls; and 3) production and market management policies. From the producers´ perspective, agricultural policies can be classified into three categories: 1) policies that affect relative prices, determined by macroeconomic policy; 2) policies of resources, including human resources, land tenure and natural resource management; and 3) policies that promote access to agricultural inputs, markets and technology (FAO, 2004).

Subsidies may be applied in order to address legitimate concerns such as encouraging domestic production to ensure food security, rather than complete reliance on trade; to mitigate excessive price fluctuations and to promote sustainable management practices by compensating for environmental externalities (Moon, 2011). When used transitorily, these may facilitate a transition towards an economic system that is less dependent on

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[18] Coarse grain generally refers to cereal grains other than wheat and rice — in the OECD countries, those used primarily for animal feed or brewing.

subsidies; they are useful in cases of natural disaster and can compensate for situations of imperfect information and market failure (FAO, 2004b).

However, subsidies favour less-competitive activities, are hard to eliminate once implemented, impose high fiscal costs, negatively impact the environment, can have counter-productive effects among the beneficiaries, incentivize profit-seeking behaviours among large organizations of producers (FAO, 2004b; Moon, 2011) and distort trade (Ostria, 2013) in detriment to the original legitimate concerns and legislation and policy objectives.

The Single Commodity Transfer (SCT) is an indicator developed by the OECD to measure the annual value of transfers made to producers of a specific commodity. Figure 2.28 shows the average percentage of transfers made to farmers with respect to their gross income for maize during the period 1995-2014. The figure shows that subsidies have played a major role in agricultural policy. All main maize producing countries, except Russia and Ukraine, have supported their maize producers over the last two decades. The countries that provided the largest share to their producers were China, Indonesia and the European Union, followed by Brazil, Mexico, Canada, USA and South Africa. However, during the most recent years (2011-2014), transfers to maize producers in Brazil, Canada, USA, Mexico, South Africa and the European Union decreased considerably with respect to those of the period 2000-2010. In contrast, China and Indonesia have recently increased their support to maize farmers (OECD, 2015).

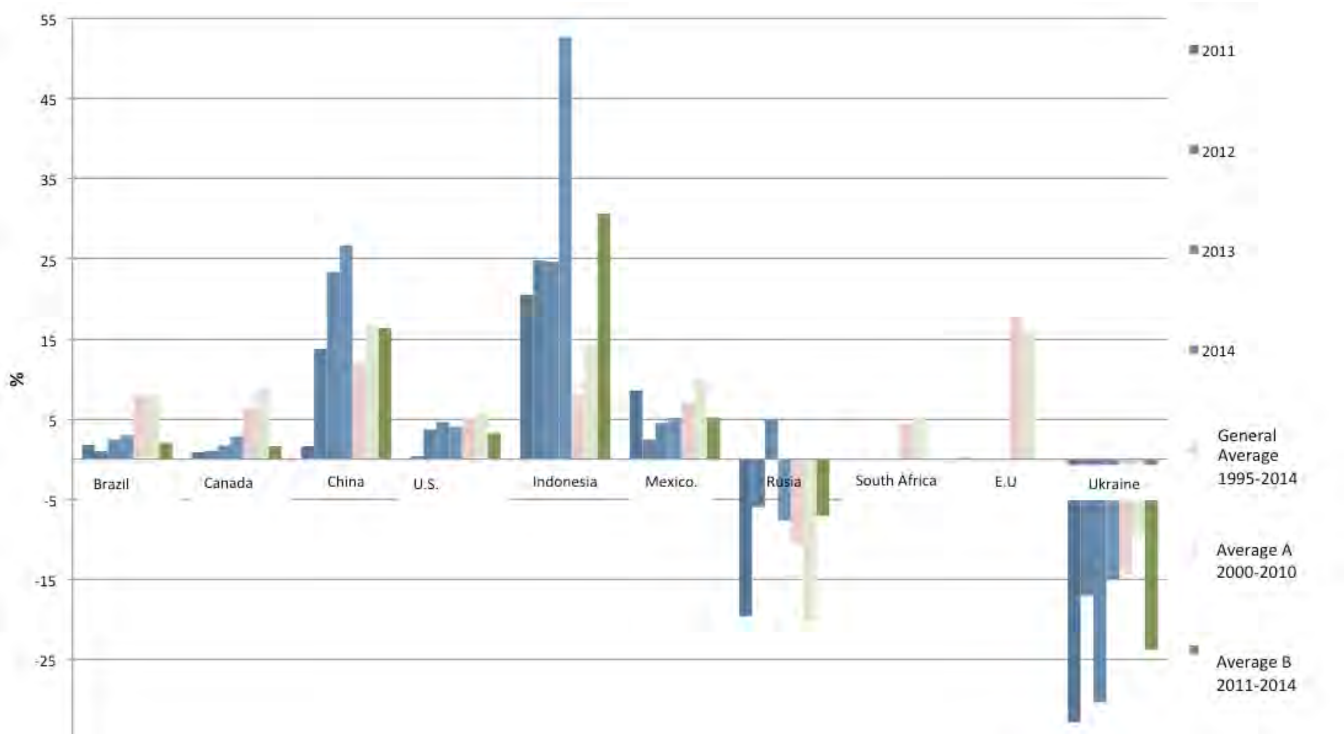

Figure 2.28 Single commodity transfers for the period 1995-2014 in 10 main maize producing countries. Source: Own elaboration with data from OECD (2015) Agriculture Statistics.

In agriculture, subsidies that promote production have led to environmental damage (Steenblik, 1990; Ostria, 2003). Such impacts are the result of overproduction and promotion of input-intensive farming systems, which have led to, for example, overuse of fertilizers and water (Steenblik, 1990). Moreover, in order to benefit from subsidies, farmers tend to cultivate marginal farmland, where it is impossible to replace depleted soil nutrients (Ostria, 2013). The environmental effects of subsidies depend heavily on policy context. Adequate subsidies could create the enabling conditions for best agricultural practices (La Vina et al., 2007).

The following paragraphs present some evidence of the socio-economic impacts of maize subsidies, as well as their role in promoting certain types of agricultural systems and practices in contrasting countries, including Rwanda, Zambia and Tanzania in Sub-Saharan Africa, and the USA.

In Sub-Saharan Africa, the current main objective of agricultural policy is to increase and modernize agricultural production yields while reducing poverty and eradicating hunger. The evidence shows that policies that make improved seeds and subsidized chemical fertilizers available in countries like Rwanda and Zambia have led to increased yields, increased farmers´ income and decreased poverty rates -as conventionally measured (Hanjra and Culas, 2011; Dawson et al. 2016). However, on closer examination, it is mainly the relatively wealthy minority who benefitted from this modernization process. For the poorest producers, these policies actually resulted in dispossession of land, inequality and increased poverty. Most households were negatively impacted by the loss of subsistence practices.

Subsidized fertilizers have also encouraged small producers in Rwanda to abandon traditional polyculture systems for subsistence and local trade and to adapt to production systems involving the use of improved seed varieties, more intensive inputs and credit (Dawson et al., 2016). In Zambia, subsidizing maize to maintain low prices and using subsidized fertilizers have also encouraged the promotion of monocultures and the expansion of maize production into areas with unsuitable biophysical conditions, causing soil acidification and degradation (Hanjra and Culas, 2011). Mainstream alternative agricultural policies may also cause environmental degradation. The agricultural reform of 1991 in Zambia eliminated price distortions in the form of subsidies for maize and fertilizers. This reform resulted in efficient use of fertilizers; however, it caused an increase in shifting farming systems. The reduced access to fertilizers led to a decline in maize production, producer profit and household-level food security. Shifting cultivation in Zambia involves a cropping period of 2-6 years, which is then followed by fallow periods of one or two decades. While this farming system is regarded as a low-input technology, it is a major driver of deforestation because the land must be set-aside for long fallow periods (*ibid*).

Similar trade-offs were found in Tanzania, when modelling the effects of subsidized fertilizer vs. free trade. Tanzania has shifted from heavy state regulation to private sector decision-making. The use of fertilizers and additional land generated a sustained positive increase in production, even higher than that seen with maize trade liberalization. Fertilizer subsidies induced more intensive systems. Maize liberalization stimulated food crops and the expansion of the agricultural frontier. At least in the case of Tanzania, subsidies for fertilizers have relative advantages compared to maize trade liberalization, since the latter might cause deforestation and greater environmental impact (Grepperud et al., 1999).

Historically, agricultural legislation and policy in the USA have been framed by three main concerns: 1) protect family farms; 2) protect farmers and the food supply from economic instability and weather shocks; and 3) increase productivity and output. During the 1930s, when extreme droughts and the economic recession represented a threat to food supply, rural employment and price stability, the US Congress approved The Farm Bill, which established the first large-scale direct maize subsidies. At the time, these subsidies took the form of a fund to increase lending to farmers and to purchase maize and other crop surpluses in order to stabilize prices. The objective was to stop overproduction. However, this measure was unable to prevent deflation of maize prices. As prices continued to decrease, farmers increased production, which further decreased prices due to the continued surplus (Kammer, 2012). The US Congress reacted with more subsidies in the form of mandatory price supports in order to align the levels of maize supply and demand. Major increases in productivity as a result of technological innovation and commercialization took place at this time. The Farm Bill then promoted the creation of large-scale industrial farms and the actual decline of family farms (Kammer, 2012). In the early 1930s, the approximate average size of a farm in the USA was 59 hectares (ha). By 2007, the average farm size was 169 (ha), and only 6% of all farms produced 75% of the value of agricultural production in the USA (Lyon, 2012).

Key message 15: The agricultural policy of the United States of America plays a critical role in global maize production, trade and supply. Subsidies that cause or encourage overproduction have been a central component of USA agricultural policy for almost four decades. Subsidies in the USA push prices down and negatively affect producers from other countries in the context of free trade agreements since they do not receive similar subsidies and cannot compete with the subsidized agriculture. The USA has become the largest exporter of maize. Given its extensive commercial network, any supply disruption (for example, due to a price increase or deviation of production from food and livestock feed to maize ethanol) can be critical for maize availability and consumption in other countries. Maize subsidies have affected almost every component of the national and global food systems; they have mostly benefited the livestock and sweetener industries. Finally, they encourage input-intensive large-scale maize production systems than can have negative effects on water availability and quality, soil fertility, biodiversity, air pollution and GHG emissions.

After World War II, agricultural policy in the USA continued to try to impede overproduction through direct assistance programs, subsidies to remove agricultural land from production and more credit (Kammer, 2012). During the late 1970s, supply management policies and food reserves were dismantled. Policies such as acreage requirements and crop selection by farmers became more flexible, but subsidies continued. In response to the food crises of the 1970s, the system of target prices and deficiency payments[19] was established in order to address global decline in production (*ibid*.). Since then, subsidies to discourage overproduction were replaced by subsidies that encourage it, such as deficiency payments, and these remain a central component of current agricultural policy. Between 1995 and 2010, US tax expenditure on maize subsidies reached an average of 5 billion dollars per year, totalling 77.1 billion dollars (*ibid.*).

The most recent agricultural legislation (known as the 2014 US Farm Bill) eliminated direct payment subsidies, which paid farmers regardless of whether or not they incurred losses. Producers can choose between Price Loss Coverage (PLC)[20] - a type of deficiency payment where producers and owners receive individual payments if the maize market year price falls below its reference price and Agricultural Risk Coverage (ARC) - in which farmers can choose between county coverage and individual farm coverage. In the ARC-County option, crop revenues are estimated using average-county yields[21]. A payment is made if the ARC-County actual crop revenue is less than the ARC-County revenue guarantee. Under the ARC-Individual coverage, a payment is made if the actual crop revenue for all crops covered on the farm per planted acre falls below the ARC-IC guarantee.[22] (USDA, 2014a). The argument in favour of the new programs is that they are not tied to yearly planting decisions but instead payments are made on the basis of a percentage of a fixed area that is defined at the time of implementation of the law and once producers have selected the coverage programs of their preference. The

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[19] Payments that producers would receive whenever the market price fell below a target (reference) price specified by Congress.

[20] The PLC is the difference between the national marketing year average (MYA) price and the effective price multiplied by the payment yield and 85% of the base acres. The effective price is the maximum of the MYA and the loan rate.

[21] The ARC-County actual crop revenue is the actual county yield multiplied by the maximum of the national marketing year price or the loan rate specified in the farm bill.

[22] The ARC-Individual coverage is determined by the farm yield multiplied by the maximum of the national marketing year price and the crop loan rate, summed over all covered commodities and divided by the planted acreage of the farm that year (University of Minnesota, 2016)

new Farm Bill promised to cut subsidies and save taxpayers a total of $23.3 billion dollars over the 10-year period following the Bill´s approval (USA Senate Committee on Agriculture, Nutrition, and Forestry, 2014). However, new estimates by the Congressional Budget Office indicate that the combined cost for the PLC and the ARC for 2016-2018 would be $19.7 billion, which is 70% higher than the original estimates (Weir, 2016). Given that prices have been low, farmers have largely benefited from these deficiency payment-type programs.

Price variation hedges have been controversial in the World Trade Organization.[23] Subsidies push prices downwards, affecting free trade agreements. The imports of other countries become artificially cheaper, negatively affecting local producers who do not benefit from similar subsidies and therefore cannot compete (Meyer et al., 2014; USDA, 2014a). Given its competitiveness, as well as the governmental support provided to the maize production industry, the USA is the largest exporter of maize in the world, exporting over 400% more maize than Argentina, the second largest exporter. The USA is critical for world food security given its commercial connections with over 180 nations, which, in most cases, are not connected directly to each other. Thus, if for any reason the USA is unable to produce and export large quantities of maize, the food supply in North and Latin America could be at risk (Wu and Guclu, 2013).

Highly subsidized maize became a cheap input for the production of ethanol, despite the fact that it only produces half the amount of ethanol per acre of other sources (Eubank, 2009). Starting in 2005, there has been an increasing deviation of maize produced in the USA from food and feed manufacture to fuel ethanol. It has been claimed that the soaring demand for agro-fuel from the USA poses a serious threat to the world´s poorest people (Boddiger, 2007) and has a substantial effect on nutrition (ibid). This, in addition to higher energy prices, higher food production costs and adverse climatic conditions has resulted in an increased demand for food and feed and increased food prices worldwide (ibid). It is estimated that increased demand for biofuel from 2000 to 2007 accounted for 39% of the increase in real maize prices (Rosegrant, 2008). “The number of food-insecure people would rise by over 16 million for every percentage increase in the real prices of staple foods” (Runge et al., 2002, quoted in Boddiger, 2007).

After Japan and Korea, and as a result of the North American Free Trade Agreement, Mexico has become the largest importer of maize, almost entirely from the USA. As a result of the decrease in the proportion of the total global maize export from the USA since 2005, Mexico suffered “one of the worst food security problems” (Boddiger, 2007, Buntrock, 2007, quoted in Wu and Guclu, 2013). The increase in yellow maize prices increased the price of Mexican tortillas (the most important staple food in the Mexican diet), which are made with white maize, since white maize is a substitute for yellow maize for the livestock and other industries (Weis, 2007). Maize represents approximately 60% of the final cost of tortillas. An increase of 20% in the price of maize as a result of ethanol production, transmitted to the Mexican white maize market, raises the cost of tortillas by 14%, affecting food insecure Mexicans (*ibid*.). Higher maize prices also increase dairy and meat prices (*ibid*.). During this crisis, the added maize importation costs for Mexico totalled $1.5-$3.2 billion, which is a significant amount.

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[23] In 2007, the European Union and other maize producing countries such as Brazil, Argentina and Canada filed a complaint with the WTO requesting the elimination of USA agricultural subsidies arguing their distortive effects on international markets.

A price increase in maize imports has negative impacts on consumers, particularly food insecure consumers who are not producers (*ibid*.).

The maize supplies of other nations that import large amounts of maize from the USA, such as Japan and Saudi Arabia, could also be jeopardized as a result of US supply disruptions. Even regions that do not import large amounts of maize from the USA -or where the maize trade network is more diverse (e.g. Europe)- would be impacted by higher prices resulting from a decrease in supply (Wu and Guclu, 2013).

Maize subsidies in the USA affect not only the prices of almost every component of the US food system, but also the global food system. Maize subsidies reduce the production costs of processed foods containing maize, such as corn syrup, starch and oil, making them accessible to all world markets (Schoonover and Muller, 2006; Eubank, 2009).

High fructose corn syrup (HFCS) has become a cheaper sweetener than sugar cane (Eubank, 2009); however, the USA and other nations, including its commercial partners, are currently facing a public health crisis due to overweightness and obesity. Over the last half century, the average annual consumption per-capita of high-calorie sweeteners increased by approximately 18 kilos and HCFS accounts for over 80% of the additional calories consumed every day in the form of sweeteners (Harvie and Wise, 2009). Producers of HCFS have benefited from an implicit subsidy of approximately USD $243 million per year, and over USD $4 billion since 1986 (ibid). Thus, producers of soft drinks, the main users of HFCS, have saved nearly USD $100 million annually and about USD $1.7 billion since the mid 1980s when this industry began to use HFCS in their products (*ibid*.). Between 1985 and 2000, “the real cost of (unsubsidized) fresh fruits and vegetables increased nearly 40% while the price of fats and sugars declined” (Schoonover and Muller, 2006).

Some estimates show that, if maize were not subsidized, its price would increase by between 5 and 7%. This would not seriously affect HCFS prices because its production costs respond more to the manufacturing process than to the cost of raw materials. An increase of 5% in the price of maize would lead to an estimated increase of 0.53% in the price of pork (Babcock, 2015). However, other estimates show that the declining prices of unhealthy food account for as much as half of the increase in the obesity rate (Fields, 2004). While it is difficult to estimate the degree to which the translation of low maize prices into cheaper high-calorie-dense foods, soft drinks and other highly processed foods have promoted the increasing consumption of these foods, there is no doubt that US agricultural policies have benefited industries that produce goods that are detrimental to public health (Harvie and Wise, 2009).

Overproduction of maize has also benefited the industry of concentrated animal feeding operations (CAFOs), where animals are fed with subsidized maize instead of grass. CAFOs have thousands of animals in small areas, creating large concentrations of excrement and antibiotics, which often then spill into local rivers and are responsible for large methane emissions, contributing to climate change (Eubank, 2009). Moreover, the widespread use of antibiotics in CAFOs has increased the risk for more virulent and resistant microorganisms, reducing the effectiveness of antibiotics to treat infections in both livestock and humans (Gilchrist et al., 2007).

Subsidies that effectively eliminate risks and ensure revenue to producers impede the action of market forces: no matter the market price, the incentive is always to produce more. One of the Aichi targets of the Convention on Biological Diversity for 2020 is that "...incentives, including subsidies, harmful to biodiversity are eliminated, phased out or reformed in order to minimize or avoid negative impacts…" (CBD Decision X/2 in Merckx and Pereira, 2015). In spite of attempts to include environmental protection measures as part of agricultural policy, maize subsidies in the USA –and in other countries- have potentially negative environmental consequences, both on-farm and off-farm, including reduced water quantity and quality and increased soil erosion, biodiversity loss, air pollution and GHG emissions (Eubank, 2009). Maize subsidies encourage input-intensive large-scale maize production systems of hybridized varieties of maize on irrigated lands far from water bodies that require enormous amounts of water and the application of fertilizers and pesticides on suboptimal agricultural lands, thereby negatively impacting ecosystem services and biodiversity (*ibid.*).

The maximization of maize production promoted by agricultural policies in the USA prevents adoption of good practices, such as no-till farming, cover cropping and residue mulching. These methods can sequester between four and six times as much soil carbon as intensive conventional systems and can prevent soil erosion, e.g., with adoption of crop rotation and a fallow season to rest the fields (FAO, 2008). Instead, the industrial farms that maximize productivity depend on fossil fuels. They require chemical fertilizers, the tractors used are powered with fossil fuels and electricity is intensively used for irrigation and other equipment (*ibid.*).

Subsidies that maximize maize production must shift to subsidies for sustainable agriculture that include a wide variety of farming techniques. In those lands suitable for agriculture, agricultural subsidies should support measures that protect soil and water quality and usage while allowing and encouraging high yields. Depending on the socioeconomic context, in less productive areas, subsidies may promote rewilding and natural succession management (Merckx and Pereira, 2015); in subsistence farms, there should be promotion of subsidies for agro-ecological practices that imply lower input intensity, a greater variety of crops and higher productivity (*ibid.*). Farmers would be willing to move towards sustainable agricultural practices and food systems if it makes financial sense to them (Eubank, 2009). Subsidies in the context of agricultural policy must be aligned with food security goals, as well as public health and environmental policy.

Key message 16: Agricultural goods in free-trade agreements should be treated differently from any other type of goods since they provide food and cultural diversity, i.e., they provide ecosystem services that constitute basic human rights. Countries have different and complex agri-environmental needs and challenges, which cannot therefore be solved by relying exclusively on free trade. Governmental regulations, sustainable incentives, and collective action must also be considered. Agricultural trade can address food shortages and surpluses across countries; it can provide welfare in the form of lower input costs and final prices of goods that benefit producers and consumers alike. However, unlimited incentives to increase production may cause irreversible loss of agricultural ecosystem services and rural development. Trade liberalization of maize has had mixed and unexpected results. The case of the North American Free Trade Agreement (NAFTA) offers some insights into these matters. Large-scale production systems have been mostly favoured, while market-oriented smallholders have been negatively impacted and (semi) subsistence farmers increased their production thanks to their links to local markets and because they are responding not only to market signals but also to their need for maize in order to ensure food security. The NAFTA has neither stemmed the flow of immigrants nor reduced the price of *tortillas*, the main staple food in Mexico, as had been expected. Finally, the impact on the genetic diversity of maize is still unclear but threats to its conservation have been identified.

The economic principle of comparative advantage postulates, in general, that trade has great power to increase the total world output and consumption, thereby improving living standards. In other words, if there are two countries and two goods, both countries will benefit from specializing in what they are relatively best at producing and then trade all the other goods, even if one of the countries has an absolute advantage in producing both goods. The idea that comparative advantage is the only source of trade has been contested, since evidence shows that government interventions can increase national welfare at another country´s expense when industries are characterized by economies of scale, external economies and imperfect competition (Krugman, 1987, quoted in Moon, 2011).

Moreover, free trade has had mixed results. For example, on the one hand, there is evidence of a causal link between trade with developing countries and wage inequalities and job loss in the USA (Autor et al, 2013; Pierce and Schott, 2012). On the other hand -disregarding the effects of trade on wages- it has been found that international trade improves the welfare of the poorest consumers via their expenditure channel. On average, the benefits of free trade are estimated at 63% for the 10th percentile of income distribution (those whose income is larger than the income of 10%) and 28% for the 90th percentile (those whose income is larger than the income of the 90%) (Fajgelbaum and Khandelwal, 2016).

According to Moon (2011), free trade agriculture has specific features that mean it cannot be treated as other manufacturing sectors for the following reasons: 1) In addition to commodities, agriculture produces positive externalities and public goods such as ecosystem services, which are critically affected by management practices at the same time (see message #11); 2) agriculture is very closely related to important global public goods, such as food security in the least developed countries (LDC) and climate change mitigation and adaptation; 3) agriculture plays different roles among countries. For LDC that are dependent on food imports, the priority is to invest in agricultural infrastructure and to increase productivity in order to promote food security; developing countries that are agricultural exporters aim to balance agricultural development with conservation; developed food-importing countries aim to secure a minimum level of domestic production in order to protect smallholders and to find ways to meet their own food demand in the event of international crises; finally, the challenges for developed food-exporting countries are to move to sustainable agricultural practices and to eliminate trade distortions. According to the author, these agricultural issues and challenges are too complex to believe that free trade alone will provide the solution and the public goods nature of agriculture make governmental intervention, collective action and transnational cooperation inevitable.

The recognition of such differences by the World Trade Organization is reflected in two mechanisms: 1) the 145 special and differential treatment provisions integrated into multilateral trade agreements that encourage developed countries to give developing countries access to their markets and provide them with technical assistance and, to a certain degree, exempt developing countries from commitments to restrict their policies of domestic support and export subsidies, and 2) the box system that categorizes policies and subsidies depending on whether they distort the market or address legitimate societal concerns[24](*ibid.*).

Following the principle of comparative advantages, economic growth through free trade brings specialization of agricultural production. Such specialization usually promotes the concentration of farms, which leads to increased productivity and competitiveness (FAO, 1999a) but also brings unequal social gains (or losses): it benefits producers in large agricultural exporting countries but, in the absence of safety-nets, damages the small producers that cannot compete in the market (Panagariya, 2002, Fabiosa et al., 2005, quoted in Moon, 2011), and increases unemployment and poverty (FAO, 1999a). Moreover, the incentive to produce more in exporting countries increases farmers´ incomes but also acts to promote land use change and deforestation (Moon, 2011).

The impact of free trade on ecosystems is also unequal: it has been argued that environmental and natural resources are normally undervalued under free trade schemes and that “economic growth may have resulted in unequal exchange of ecological footprints and irreversible loss of biodiversity” in the developing world (Daly and Goodland, 1994; Ropke, 1994, Andersson and Lindroth, 2001, Muradian and Martinez-Alier, 2001, quoted in Moon, 2011: p. 17). Since the market system fails to internalize negative externalities, soil and water are most likely to be undervalued in the production process (Weis, 2007, quoted in Moon, 2011). Moreover, environmental sustainability in agriculture is associated with a long-term perspective, while free trade often stresses short-term benefits in terms of production costs that can decrease through large-scale intensive standardized and uniform production. Unless producers internalize negative externalities related to soil erosion, and sustainably produced agricultural products are labelled, free trade is unlikely to promote environmentally sustainable practices (López, 1994, Mahe, 1997, Blanford and Fulponi, 1999, quoted in Moon, 2011). Free trade generates competitive pressure on farmers thus preventing them from making efforts to reduce their GHG emissions. The lack of incentives for farmers to implement environmentally sustainable practices on soil and water is similar to the case of emissions. In terms of adaptation, free trade could help to cope with the risk of food shortages due to shifting patterns of agricultural production (*e.g.*, Reilly et al., 1994, Nelson, 2009, Huang

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[24] agricultural protectionism may have legitimate concerns, such as maintaining an adequate level of domestic production as a method by which to promote food security instead of relying entirely on trade, to preserve the cultural value of agriculture, to mitigate excessive market fluctuations inherent to agriculture and to correct market failures such as the inability to internalize positive and negative externalities. Protectionist regulations that protect the interests of rent-seekers such as large organizations of producers in developed countries are detrimental and must be eliminated (Moon, 2011).

et al., 2011, quoted in Moon, 2011). However, trade itself should not be seen as a substitute for national adaptation strategies (Moon, 2011).

In summary, the unique and diverse challenges of agriculture cannot be addressed by relying exclusively on free trade; a broader vision is required that includes market mechanisms as well as governmental regulation, sustainable economic incentives and collective action (Hodge, 2007, quoted in Moon, 2011).

Trade liberalization of maize has had mixed and unexpected results. The case of the North American Free Trade Agreement (NAFTA) offers some interesting insights: In spite of its non-competitivity, maize production in Mexico actually increased (Yúnez-Naude and Serrano-Cote, 2009). As in other developing countries, Mexican small subsistence producers coexist with large-scale commercial producers. The former engage in different activities in order to diversify their income and are price inelastic, while the latter respond directly to price changes by increasing productivity and yields (*ibid.*).

Medium and large-scale commercial farmers have been the main beneficiaries of governmental subsidies. This has allowed them to increase their productivity, protecting them from US competition (Yúnez-Naude and Taylor, 2004). Market-oriented small farmers were negatively impacted, but rain-fed production by small farms and households has remained stable in spite of decreased prices thanks to local market linkages between producing and consuming households (*ibid*) and because they may not only be responding to market signals but also to their need for maize in order to ensure food security[25] (*ibid.*).

Since NAFTA, the amount of cultivated rain-fed land has increased while yields have remained similar. Irrigated lands have decreased but yields on these lands have increased (Yúnez-Naude and Taylor, 2006). Maize production in Mexico has increased, partly due to the considerable support of the Mexican Government, most of which has gone to commercial producers. Such support has been funded by public taxes or oil revenue. The NAFTA has not improved specialization and, given the heavy governmental support, has not encouraged the efficient use of resources or development of agriculture (Yúnez-Naude and Taylor, 2006). It has been argued that less profitable farmers have had to migrate either to urban areas or to the USA (Nadal, 2000; Gonzalez, 2006). Medium producers have been forced to reduce their costs through a reduction in labour, leading to fewer employment opportunities and a stronger pressure to migrate among the employed farmers (Nadal, 2000). Even if migration from Mexico to the USA can also be explained by other factors, including historical patterns, the currency devaluation and the pull of employment opportunities in the USA, NAFTA has not stemmed the flow of immigrants, as was expected (Audley et al. 2003). Remittance income has stimulated consumption, increasing the shadow price of maize and encouraging subsistence households to increase their maize production, given the devaluation of the Mexican peso (Yúnez-Naude and Taylor, 2006). Finally, lower consumer prices for maize products have also failed to materialize and tortilla prices have actually risen (Nadal, 2000).

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[25] Governmental support programs, the devaluation of the Mexican currency and income transfers also contributed to the increase of maize production by subsistence farmers (ibid).

In the case of competitive producers, NAFTA has caused an increased use of fertilizers and promotion of monocultures, contributing to soil erosion. Small holders have also contributed to soil erosion through extension of the agricultural frontier into marginal lands (*ibid*.).

The impact of NAFTA on local maize diversity is unclear. On the one hand, it has been argued that migration has resulted in a loss of traditional knowledge about maize seeds, contributing to genetic erosion (Nadal, 2000). On the other hand, it has also been claimed that NAFTA may have contributed to the protection of local maize diversity given that decreasing prices encouraged conversion from commercial maize into subsistence production, thus increasing maize diversity (Dyer and Yúnez, 2003). However, given that there is no direct relationship between subsistence production and the type of seeds used, it is uncertain whether the transition from commercial to subsistence production will result in the use of traditional varieties (Perales, pers. comm.). Depending on the interpretation of farmers´ responses to price changes, it could be claimed whether maize conservation is under threat or not (Dyer and Yúnez, 2003). This and other potential threats to Mexican maize diversity (see message #12) prompt the implementation of conservation programs, including *in situ* or dynamic conservation (Nadal, 2000), or actions that address specific threats to conservation individually (Dyer and Yúnez, 2003).

Key message 17: Research and Development (RandD) is key for ensuring regional and global food security. It has contributed to improved yields and production and to reductions in real prices. Most agricultural research over recent decades, including that of maize, has moved from public organizations to private companies; however, increased funding for public RandD in both developing and developed countries makes sense given its high rates of return and the positive effect it has in terms of ensuring food security, especially in the poorest sectors of society. Public RandD serves the needs of users with limited market access or purchasing power, such as smallholders in developing countries; these users are normally ill served by private research. Public and private RandD investments have different roles that can be complementary but are not replaceable.

It has been claimed that changes in the demand and supply of agricultural goods will challenge the agricultural system worldwide (Nelson et al., 2010; Alexandratos and Bruinsma, 2012; FAO, 2012; OECD-FAO, 2012; Searchinger et al., 2013; Fischer et al., 2014). Even without considering hunger alleviation, demand for agricultural goods is expected to increase as a response to increased population growth, agro-fuels and Gross Domestic Product per capita. This could translate into an increase of 1.1% in the annual demand for agricultural products by 2050, relative to the period 2000-2007 (Alexandratos and Bruinsma, 2012, quoted in Fisher et al., 2014). More specifically, by 2050, the demand of maize is expected to increase by 60% compared to this same period (Fisher et al., 2014).

In order to influence agricultural productivity, investment in Research and Development (RandD) and extensionism are key (Fuglie et al., 1996; Fuglie and Heisey, 2007; Evenson and Fuglie, 2009; Alston et al., 2010; Bientema et al, 2012; FAO, 2012; Fuglie, 2012; Fuglie et al, 2012). In the long term, RandD -translated into technological change- has significantly contributed to improved yields and production and to a reduction in real prices. Moreover, it reduces the importance of food price variability for food security (Alston and Pardey, 2014). However, investment in public goods such as RandD is generally low and incomparable to the total resources earmarked for agriculture. The General Services Support Estimate (GSSE) is an indicator developed by the Organisation for Economic Co-operation and Development (OECD) that measures levels of spending in agricultural RandD, capacity building, extensionism, phytosanitary inspection and storage, as well as the marketing and promotion of products and services by some of the leading maize producers worldwide (OECD, 2014). According to this indicator, the aggregate expenditure of the OECD countries for the period 2011-2013 dropped in comparison to the 1990s. In real terms, only Australia, Canada, China, Indonesia and the European Union presented a real increase in the GSSE. The largest increases were made by Australia and China (*ibid*.). The expenditure of Brazil, China and India in RandD together represented 25% of the global total in 2008 and also contributed to almost half of the total global increase in RandD for the period 2000-2008. The important improvements in crop yield and productivity presented by China and Brazil can be partly explained by these investments in agricultural RandD (Shome, 2015).

It should be noted that, over recent decades, privately funded RandD has played the major role in the overall picture of agricultural RandD and is currently growing faster than public agricultural RandD. Private RandD is rising in both developed and developing countries (Pray and Fugile, 2015) and is already offsetting public spending in the European Union (OECD, 2014). Governments of developing countries have taken measures to promote private RandD, including elimination of trade barriers and an increased stimulus for private involvement (Stads and Sène, 2011). Such policies and new commercial opportunities offered by scientific advances, as well as the liberalization of agricultural input markets are driving this shift (Pray and Fugile, 2015).

Private and public agencies have different incentives for their research (Spielman and von Grebmer, 2004). Private agencies are funded by firms with the objective to maximize profits. They invest in research where marginal benefits exceed marginal costs, which should ideally result in products attractive to consumers. Public agencies usually carry out research in the public interest. Their products and knowledge possess characteristics of public goods (non-excludability and non-rivalry); their results become evident in the long term and serve the needs of users with limited market access or purchasing power, such as the small holders of developing countries (ibid). Greater funding for public RandD both in developed and developing countries makes sense given the continuing high rates of return and positive effects it has in terms of ensuring food security for the poorest (Alston and Pardey, 2014. The growing importance of private RandD should therefore not be reflected in decreased public investment, since the two have different roles. These roles can be complementary (King et al., 2012; Pray and Fugile, 2015), but not replaceable.

3. MAIZE PRODUCTION SYSTEMS: A GENERAL TYPOLOGY

Efraín Hernández Xolocotzi/CONABIO

3. Maize Production Systems: A General Typology

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A typology is "the study and interpretation of types" (Jary and Jary, 1995, quoted in Emtage et al., 2006). Typologies have been used to study, program, plan and evaluate agricultural systems, rural and regional development, natural resource management, public policies and technical innovations. The variables used to define a typology usually respond to the aim of the study and to assumptions of the factors that affect the phenomena of interest (Emtage et al., 2006). Following the conceptual framework of agricultural typologies developed by Kostrowicki (1977), a maize farming system may be understood as a generally recognized form of growing maize that is characterized by a set of attributes. Definition of type is based on similarities between various individual agricultural holdings that produce maize[26]. Agricultural holdings characterized by similar sets of attributes can be repeatedly found dispersed across space. Nevertheless, while typologies somehow group agricultural holdings according to some shared properties, it is also acknowledged that differences exist among them. Here, we have developed a typology that aims to characterize the attributes of maize farming systems that have the most influence on impacts on ecosystem services. This is a necessary step towards fulfilling one of the objectives of this study, namely to improve our understanding of economic dependencies and interactions between the maize sector and ecosystem services (Sukhdev et al., 2014).

The global farming typologies that have been developed to date are based on farming practices and/or biophysical determinants. For example, Dixon et al. (2001) describe 72 farming systems across what they refer to as "the six developing regions of the world", which are defined by production practices and farm characteristics (*i.e.* water resource availability, production intensity, farm size, dominant crop and dual crops), as well as by biophysical characteristics (i.e., climate, altitude and location). Cassman et al. (2005), however, design a global cultivated system framework based on the combination of agroecological (*i.e.* tropical and temperate, humid and arid, and low and highland) and enterprise/management (*i.e.* irrigation, input intensity, shifting cultivation, livestock, and freshwater aquaculture) contexts.

Maize farming systems vary not only in terms of productivity level, but also of mechanization, management practices, crop uses and characteristics of the producers and their production units, as well as in the socioeconomic, cultural, and biophysical environment in which they develop, in addition to the purpose of the output. Depending on the management practices adopted, production systems can provide ecosystem services or generate negative impacts on the environment (also known as ecosystem disservices) (Zhang et al., 2007; Power, 2010; Tewari et al., 2010).

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[26] A holding, or agricultural holding, is "an economic unit of agricultural production under single management comprising all livestock maintained and all land used wholly or partly for agricultural production purposes, without regard to title, legal form, or size. Single management may be exercised by an individual or household, jointly by two or more individuals or households, by a clan or tribe or by a juridical person such as a corporation, cooperative or government agency. The holding's land may consist of one or more parcels, located in one or more separate areas or in one or more territorial or administrative divisions, providing the parcels share the same production means utilized by the holding, including labour, farm buildings, machinery or draught animals, inputs and other management practices. The requirement of sharing the same production means utilized by the holding, such as labour, farm buildings, machinery or draught animals should be fulfilled to a degree to justify the consideration of various parcels as components of one economic unit" (FAOSTAT http://faostat.fao.org/site/375/default.aspx)

The typology of the main production systems in this study is the result of a review and analysis of the existing literature. With this typology, we intend to capture the broad diversity of maize farming systems and management practices at a global scale. The challenge when trying to define a set of unique management practices in order to differentiate production systems is that these practices tend to overlap among producers. For example, intensive use of agricultural inputs can be pervasive in both intensive and smallholder systems, while full mechanization, irrigation and tillage are prevalent in both organic and intensive systems. Despite the substantial overlap of management practices that exists, at least three main systems, each with two subtypes, can be distinguished from the literature review: 1) smallholder systems (shifting and stable), 2) intensive systems (irrigated and rainfed), and 3) organic (small-scale and large-scale).

In order to map the potential distribution of maize production systems, we used yield as a proxy variable of the intensity of agricultural practices, which to a certain extent define the described systems. Agricultural intensity has been measured using indicators of both agricultural input and output (Erb et al., 2013). Some of the input intensity indicators used include cropping frequency, and inputs of labour and capital per unit of land area, while output indicators include yield and stocking density of livestock (*ibid*.). We defined three different yield groups as proxies of agricultural systems. Areas with maize yield of less than 2 ton/ha were considered to represent smallholders, areas with yields from 2 to 6 ton/ha were considered as intermediate producers and those with maize yields over 6 tons/ha were considered as intensive systems. The 2 ton/ha level used to geographically map potential smallholder systems was established based on existing literature (Kenya: Tittonel et al. 2008; Uganda: Otunge et al., 2010; Mexico: Turrent et al., 2012) and historical maize yields in the US, which ranged from 20 to 30 bushels per acre (1.35 to 2.02 ton/ha) before the advent of seed improvement and hybridization and intensive use of nitrogen fertilizers (approx. 1870-1935) (Troyer, 2006). The resulting map is presented below (Fig. 3.1); the distribution of each system is described in the corresponding section.

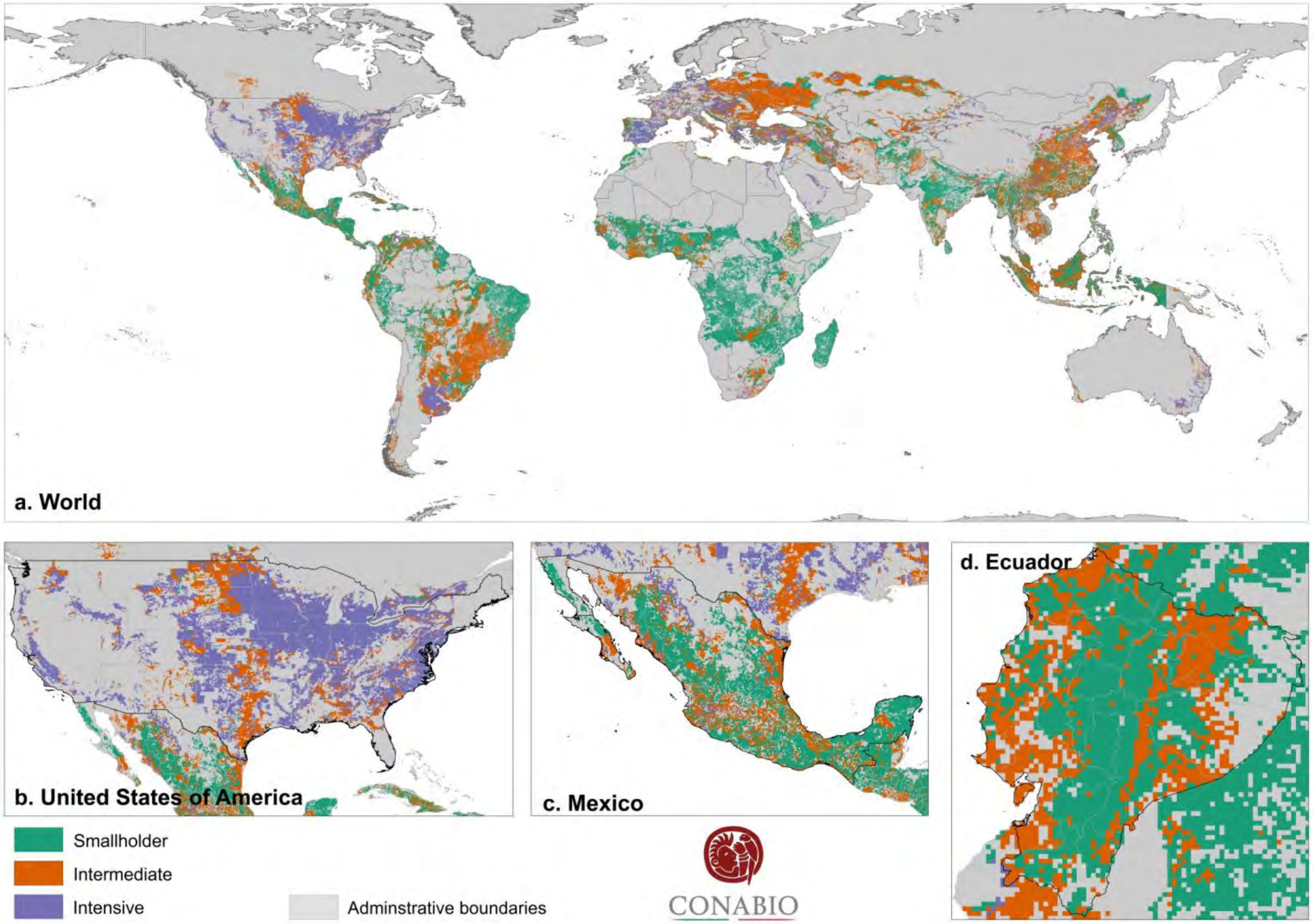

Figure 3.1 Distribution[27] of smallholder (< 2 ton/ha), intermediate (2-6 ton/ha) and intensive maize systems (> 6 ton/ha). Source: Own elaboration with data from You et al., 2014.

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[27] It is important to note that colored cells do not represent the area of land where maize is produced, but only the presence or absence of maize production in that particular area, as modelled by You et al. (2014).

BOX 3.1 Limitations of using yield as a proxy for intensity of maize production systems

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The use of yield as a proxy for agricultural systems entails many caveats. Yield is evidently not the sole result of input intensity but rather determined by a multiplicity of factors of which environmental context is a critical one. Therefore, if some basic environmental conditions like rainfall, sunlight radiation, type of soil and temperature are not optimal for plant growth high yields will not be achieved even under a high intensity management. In this case the use of yield gaps could prove more adequate to reflect the interaction between inputs and environmental conditions (Licker et al., 2010). Another very important caveat of using yield level as a proxy of agricultural system is to equate input intensity with yields. High inputs can be used in a very inefficient way leading to low or intermediate yields, and conversely, intermediate yields can potentially be achieved without a significant increase in inputs by improving management practices that promote ecosystem services underlying agricultural production (Ponisio et al., 2015). Last but not least, the link between yield and agricultural systems may also be questioned, for example, there is evidence that smallholders are not necessarily low-yielding systems and also not low-input systems (Perales, 2016). Given these caveats, the results and interpretations of the following exercise should be taken with care considering the former limitations.

In addition to mapping production intensity as a proxy of maize systems, we also aimed to identify and map exclusively rainfed and irrigated maize areas. For this, we used available maps of rainfed and irrigated maize production areas around the world (MAPSPAM: You et al., 2014). We used a map of the physical area of irrigated maize available in a raster format with a resolution of 5x5 ARC minutes (approx. 10 km^2) (*ibid*.). Each cell of the mentioned map was reclassified as irrigated, mixed or rainfed, according to the percentage of type of irrigated area within each cell. A cell was considered as irrigated when more than 75% of its maize area was irrigated, rainfed when less than 25% of the cell was irrigated and mixed when the irrigated area ranged between 25 and 75%. The resulting map is presented below (Fig. 3.2).

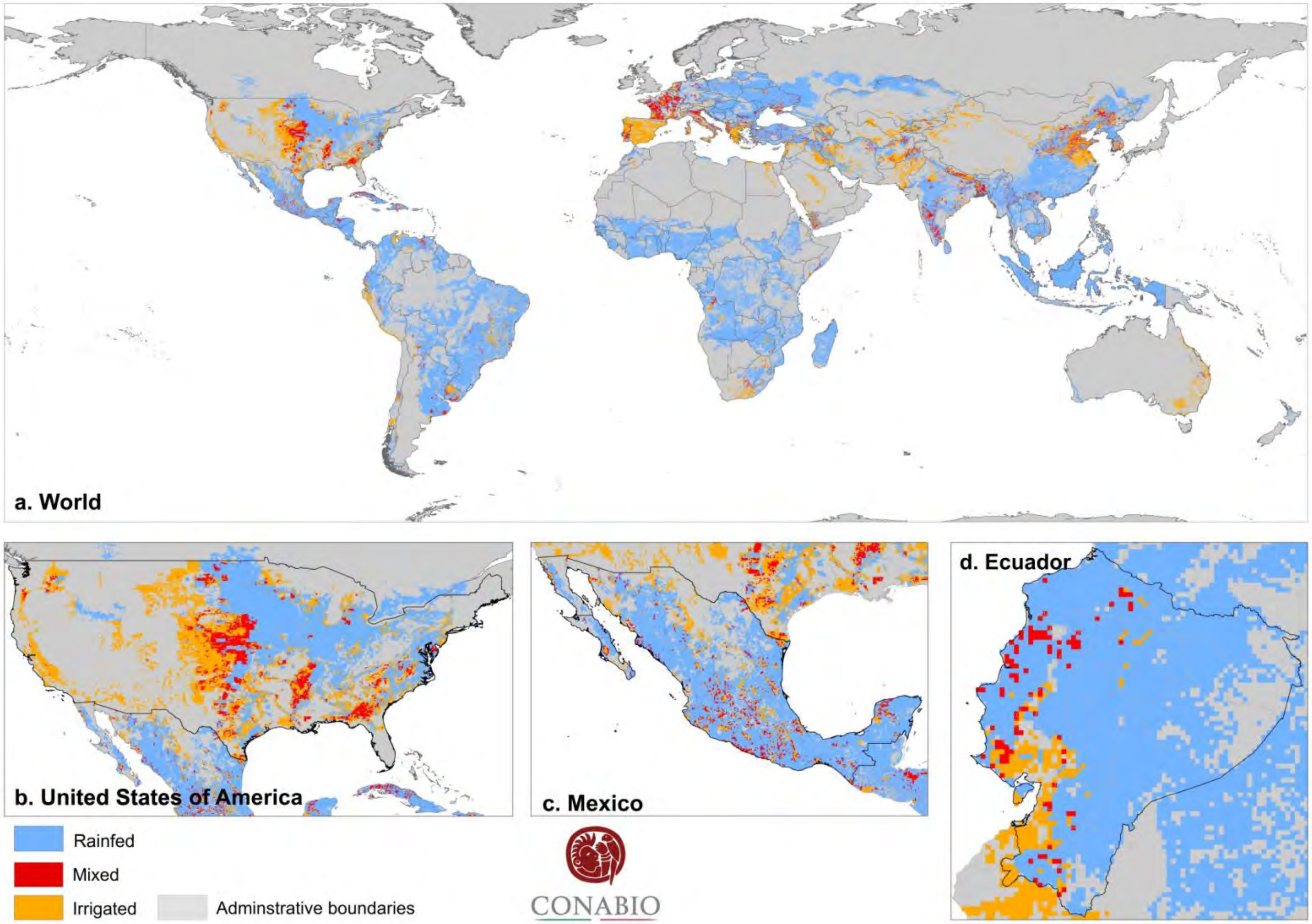

Figure 3.2 Distribution[28] of irrigated (>75% of total maize area irrigated), mixed (between 25 and 75% irrigated) and rainfed (< 25% irrigated) maize. Source: Own elaboration with data from You et al., 2014.

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[28] Colored cells do not represent the area of land where maize is produced, but only the presence or absence of rainfed and irrigated maize production in that particular area, as modelled by You et al., 2014.

3.1 Smallholder maize systems

The first system is represented by two types of smallholders –shifting and stable. Both are subsistence[29] or semi-subsistence[30] oriented production units in which either part or all of the agricultural production is consumed directly by the household, as food or in other uses (*e.g.* feed, construction).

An important distinction for classifying smallholder farmers is whether their agricultural production decisions and their consumption decisions are coupled or not. The conventional agricultural household decision model postulates that household production and consumption decisions are uncoupled (Singh et al, 1986). Production decisions and crop choices are therefore determined only by crop profitability, while consumption decisions are based only on the income generated in the households from agriculture and other sources and the prices of the crops they wish to consume. However, this model assumes the existence of perfect markets, which is not normally the case, particularly for smallholder goods. In fact, landraces are not often found in markets. As has been shown for smallholder farmers in Mexico and in the Andes (Zimmerer, 1996; Dyer, 2006; van Dusen and Taylor, 2005; Arslan and Taylor, 2009; Skarbo, 2014; Zimmerer, 2014; Bellon et al., 2015), consumption and production decisions are coupled. So consumption preferences directly influence production decisions in terms of which crops or varieties to produce. Thus, cultural identity, preferences and other personal characteristics directly contribute to crop choices.

Smallholder maize production systems represent not only the most extended maize system around the world (Fig. 3.3) but also the most diverse in terms of agricultural inputs, levels of mechanization, production aims, and inter and intraspecific agrobiodiversity. Smallholders are mainly represented by traditional farmers whose food security partially depends on the range of agricultural products grown in the field (Baiphethi and Jacobs, 2009).

For smallholders, agrobiodiversity is a key aspect for managing fertility (Postma and Lynch, 2012), pest and diseases (Xiahong et al., 2010), as well as meeting the nutritional needs of their households (Kahane et al., 2013). Smallholders largely rely on family labor and on culturally acquired knowledge to manage ecosystem services underlying farm productivity (Denevan, 1995; quoted in Altieri, 1999). These systems are also characterized by the production of low yields of the staple crop, which might be attributed, among others, to the distribution of subsistence or semi-subsistence farmers on more marginal lands, the use of polycultures (*i.e.*, a higher number of crops per ha) and deficiencies of nutrients and water.

Shifting and stable smallholdings differ mainly in the landscape structure that results from the cropping-fallow cycle and crop diversification in the former, and the relative ease of transition towards more intensive practices in the latter.

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[29] Subsistence farming has been defined according to both production and consumption criteria. From a production point of view, it has been considered as a production unit that sells less than 50% of its produce (Mosher, 1970; quoted in Kostov and Lingard, 2004) and from the consumption perspective as an agricultural production unit that produces for its own consumption (Todaro, 1995; quoted in Kostov and Lingard, 2004).

[30] Semi-subsistence farming: "*the farm producing mainly for self-consumption, but also selling a certain part of the production, in which the surplus part that is sold has a degree of regularity and consistency*" (Giurca, 2008)

Shifting smallholders. Shifting cultivation is described as an agricultural system in which "…an area of forest is cleared, usually rather incompletely, the debris is burnt, and the land is cultivated for a few years - usually less than five - then allowed to revert to forest or other secondary vegetation before being cleared and used again" (Upadhyay, 1985). Shifting cultivation systems around the world share some common characteristics: 1) rotation of fields, 2) use of fire for clearing (although there are some exceptions), 3) land left in fallow for regeneration, 4) mainly dependent on human labour for land clearing, plot preparation, seed sowing, weeding and harvesting and 5) intercropping of different crops (including in some cases perennial crops) (Thrupp et al., 1997).

This system used to be the main form of agriculture both in Northern latitudes (review in Thrupp et al., 1997) and in tropical and subtropical regions around the world for the last three thousand years (Moya-García et al., 2003, quoted in Ochoa-Gaona et al., 2007). Recent estimates suggest that 35 to 1,000 million people, mainly semi-subsistence and small-scale farmers belonging to approximately 3,000 ethnic groups (Mertz et al., 2009) distributed across approximately 64 countries in the tropical and sub-tropical regions of Africa, Asia and Latin America, still depend on this type of cultivation system (Thrupp et al., 1997; Li et al., 2014). Shifting agriculture is known under a variety of local names: *swidden* (Old English), *rai* (Sweden), *milpa, conuco, roza* (Latin America), *shamba, chitemene* (Africa), *jhum* (India), *kaingin* (Philippines), *ladang* (Indonesia and Malaysia), *khoriya* or *bhasme* (Nepal), *conuco* (Venezuela), *chiteme* (Central Africa), *ijran, upraon, talaon* (Himalayas), taungya (Burma) and *khoriya* or *bhasme* in Nepal (Conklin 1957, Terra 1958, Spencer 1966, quoted in Christanty, 1986; Sánchez et al., 2005, Kerkhoff and Sharma 2006, quoted in Aryal et al., 2010). Shifting cultivation is also known under the name of swidden and slash-and-burn agriculture (Thrupp et al., 1997).

As mentioned previously, shifting cultivation is characterized by different stages in addition to those pertaining to the annual cultivation cycle that is common to all systems. These include site selection, clearing, burning, planting, weeding, harvesting and succession (Thurpp et al., 1997). Site selection represents a crucial aspect of the system and consists of the identification of fallow land suitable for clearance to accommodate a new cultivation cycle. The fallow period required to replenish soil fertility is highly variable and depends on ecological, biogeographical and climatic factors (Chazdon, 2003). For example, fallow periods of more than 5 years are required in the humid and sub-humid tropics for the recovery of crop performance in low base status soils (Szott et al., 1999). Farmers use different indicators to select fallow land, including length of fallow period, vegetation composition and the presence of indicator plants and earthworm casts (review in Norgrove and Hauser, 2016).

Once a plot is chosen, clearing the field involves cutting down of the vegetation present in the field selected for the current cropping cycle. As the volume of woody vegetation increases over the course of the fallow period, the longer the fallow period the greater the effort required to clear the field. The land can be cleared by the individual householder or with the help of others. Clearing usually takes place at the beginning of the dry season in order to ensure that the cut and slashed woody vegetation is dry prior to burning (Christanty, 1986). Some trees are left on the field and protected from burning because of their usefulness or to speed regeneration during the fallow period (Conklin, 1957, Watters, 1960, quoted in Christanty, 1986).

Burning of the plot occurs after the clearance and/or protection of selected trees, after which the remaining debris are burnt to allow the incorporation of carbon and carbonated matter in the humus (Ribeiro et al., 2015).

Burning allows not only the efficient clearing of the slashed and cut vegetation from the field and the elimination of a great proportion of weeds and weed seeds, but also increases the short-term availability of nitrogen and phosphorus in the soil (Kauffman et al., 1993, Giardina et al., 2000, Wan et al., 2001, quoted in Ochoa-Gaona et al., 2007). Additional benefits include the elimination of unwanted insects, plant diseases and microbial pathogens and the alteration of soil structure and reduced soil acidity (Rambo, 1981, Peters and Neuenschwander, 1988, quoted in Thrupp et al. 1997; review in Ribeiro et al. 2015).

Planting of the crops usually coincides with the appearance of the first rains of the rainy season, ensuring adequate moisture supply for the growth of the plants. Manual planting is carried out using a digging stick or hoe (Christanty, 1986). The staple crops that are produced in shifting cultivation systems depend on the region and include maize, rice, millet and sorghum. In some cases, more than one staple crop is produced simultaneously in the same field (Atran et al., 1993). Since shifting agriculture is mainly aimed for self-consumption and sale of surplus in local markets, intercropping of diverse cultivars represents a central aspect of the productive and ecological rationality of this system. From a production perspective, intercropping increases yield through the cultivation of nitrogen-fixing species such as bean (Li et al., 2003; Zhang and Li, 2003; Latati et al., 2013), reduces soil-borne diseases through intercropping (Hiddink et al., 2010, quoted in Kremen and Miles, 2012), maintains soil moisture and reduces the growth of weeds through cover crops such as squash (Price and Norsworthy, 2012) and also improves the diet of peasants by increasing the diversity of nutrients available to them. Conklin (1957, quoted in Christanty, 1986) divided the cropping or planting phase into two events: grain cropping and non-grain cropping. Grain cropping represents the phase in which cereal is cultivated alongside legumes and vegetables just after burning the field, while non-grain cropping (root and tree crops) takes place following the harvest of the former crops (*ibid*.).

The yield of the staple crop (*e.g.* maize) in these systems is usually low to very low, not only because of the relatively marginal conditions in which shifting cultivation in practiced relative to other maize systems, but also because it is intercropped with other cultivars. Moreover, yields in shifting cultivation depend on the length of the fallow period, but also on the number of years of continuous use. Usually, yields are highest in the first year, and decrease every year thereafter. That is when farmers abandon a field and move to another (*milpa-roza*, *milpa-caña*, etc.) The investment of labour also changes. In the first year, labour input is high in order to fell the vegetation, but low in terms of controlling weeds. In the second year, there is a reduced need to clear, but the pressure of weeds increases (Bellon, pers. comm.).

The classic Milpa system that prevails today throughout Mesoamerica (*i.e.,* Central America and the Southern region of Mexico) is characterized by intercropping maize with bean and squash and sometimes also a root crop (Hernández-Xolocotzi et al., 1994; Lara-Ponce et al., 2012). More species-rich milpas can also include chayote, watermelon, cantaloupe, bottle gourd, chilli pepper, tomato and cotton. These may not necessarily be planted intercropped in the milpa but can also be grown in domestic gardens (Atran et al., 1993). One or several landraces of the main staple and associated crops are normally planted in these systems (Lara-Ponce et al., 2012). This same study reported the presence of nine landraces of maize and nine of beans in the *milpas* of *Mayans* in San Jose and San Andrés (Peten, Guatemala). In Yaxcabá, Yucatán, Interián (2005) reported 10 varieties of maize, four of bean and three of squash. Creolized maize, which are landraces with introgression from open pollinated varieties and modern varieties, can also be found (Camacho-Villa and Chávez-Servia, 2004; Lara-Ponce et al., 2012).

Along with field clearing, weeding is one of the most labour-intensive phases of the shifting cultivation cycle. The management of weeds is crucial because they represent the principal competition for maize (Cancian, 1972). Traditionally, weeding is carried out by manually pulling the weeds from the soil with different tools such as machetes or hoes (Lara-Ponce et al., 2012). Use of herbicides to control weeds can also be found in these systems, but it is a recent development. For example, in Yaxcabá, Yucatán, the use of herbicides increased from 0% in 1968 to 90% in 1982 (Ku Naal, 1992; quoted in Parsons et al., 2009). The presence of fallow periods and the use of burning are also management practices that act to reduce weed competition (de Rouw, 1995; Akobundu et al., 1999). Intercropping also controls weeds (Liebman and Dyck, 1993, quoted in Kremen and Miles, 2012). In addition, weeds may be tolerated by farmers in some places, given their value as forage, food, medicine or as ornamental plants (Blanckaert et al., 2007). Crop damage from pests is also highly tolerated as the loss in production is calculated by farmers in this traditional agricultural system (Brown and Marten, 1986).

In contrast to intensive systems, harvesting is an activity that takes place at different moments of the cultivation cycle, since the different planted variants and species show different periods of maturation. As mentioned previously, there are also cases in which cropping, and therefore harvesting, occurs at different moments (Conklin, 1957, quoted in Christanty, 1986). Cereals are harvested after several months, while root crops and perennial crops are harvested later (*ibid.*). Although the period of time during which cultivation takes place is highly variable, it usually takes two or three years for the soil nutrients to be depleted by leaching, erosion and nutrient uptake and this, coupled with increased weed pressure, dictates when the field is left in fallow (Beets, 1990, quoted in Aweto, 2012).

Fallow land is defined as a previously cultivated plot left unsown for a period in order to restore its fertility as part of a crop rotation or to avoid surplus production and allow the reposition of soil organic matter (Christanty, 1986). The length of the fallow period is highly variable and depends, in addition to biogeographic and climatic conditions, on many different factors including demographic pressure, government restrictions on forest use, changes in land tenure systems, policies that promote cash crops and family land holding size, among others (Nair and Fernandes, 1983, quoted in Thrupp et al. 1997). Fallow land can be classified according to fallow period length (Forest fallow: 20-25 years; Bush fallow: 6-10 years; Short fallow: 1 or 2 years), the dominant vegetation in the fallow (woody and grassy), tree growth and size (Low forest fallow: herbaceous, shrubs, vines, and low tree growth; High forest fallow: reduction of herbaceous cover and predominance of woody vegetation) (Webster and Wilson, 1966, quoted in Christanty, 1986). During the vegetative fallow period, weeds are suppressed (de Rouw, 1995), soil physical properties improved and carbon and nutrient stocks restored in the biomass (Szott and Palm 1986, Nye and Greenland 1960, quoted in Sánchez et al. 2005). Fallow periods of between 25 and 30 years have been reported in the Yucatán Peninsula (Rico-Gray and Garcia-Franco, 1992), although much shorter fallow periods are found in recent literature (Weisbach et al., 2002; 6 to 12 years: Caamal-Maldonado et al., 2001). This trend toward shorter fallow periods has been confirmed by the meta-analysis of van Vliet et al. (2012), in which a total of 49 out of 59 case studies reported a decrease in this crucial stage of the shifting cultivation cycle. Fallows are also actively used by the *campesino* farmers to plant root and tree crops, to collect edible and commercial products, or to hunt (Thurpp et al., 1997). Fallow fields of shifting cultivation show the fastest rates of forest recovery compared to intensive or extensive agricultural systems (Guariguata and Ostertag, 2001). As a result of this basic feature of the system, shifting cultivation leads to a mosaic of secondary forests in different stages of succession (Conklin, 1961; Harris, 1972; Hiraoka and Yamamoto, 1980; McGrath, 1987).

According to the meta-analysis of van Vliet et al. (2012) shifting systems are in decline around the world, 55% of the studies reviewed report a decrease in area of this practice, while 32% report an increase and 13% report no change. In most countries, both increases and decreases in shifting areas can be found. The principal land use of converted shifting fields have been monoculture tree crops, annual crops and wet paddy rice in Asia; grass pasture in Latin America and annual crops in Africa (*ibid*.). Changes of shifting cultivation systems to more intensive land uses show both positive and negative impacts on local livelihoods. The positive associations include increased household income, health; education and social networking, while the negative associations include out-migration and the loss of cultural identity (review in van Vliet et al., 2012). The environmental consequences are mainly negative: a permanent decrease in forest cover at the landscape scale with a concomitant loss of agrobiodiversity and wildlife, increased weed pressure, reduced soil fertility and increased soil erosion, as well as decreases in water quality due to the use of chemical pesticides and fertilizers (review in van Vliet et al. 2012).

Stable smallholders. Stable smallholders remain spatially constant and are therefore, in some cases, more prone to intensifying maize production and shifting towards semi-commercial production. This change implies a reduced agrobiodiversity harvested in the fields, as well as increased agricultural inputs and, depending on the market, the use of improved seeds. However, substantial differences seem to exist between regions in this shift. For example, Mexican landraces are extensively cultivated in smallholder systems, even in semi-commercially-oriented fields (Perales et al., 2003), while in Malawi, hybrid seeds are grown for subsistence purposes and are provided in part by an extensive subsidies program implemented by the government to boost maize production in order to alleviate hunger (Denning et al., 2009). As mentioned previously, smallholders are in some cases inserted into the local markets, and produce maize both for self-consumption and sale. The double purpose of production among these smallholders is expressed in the use of both landraces and hybrids in the same field (Bellon and Hellin, 2011; Olson et al., 2012). In other cases, infrequent landraces can become common if driven by local market demand (Perales et al., 2003). Smallholder systems are a rich mosaic of traditional agricultural forms and management practices and, while the use of synthetic fertilizers and herbicides has become common among these systems (Bellon, 1991), full transformation to commercially-oriented intensive systems is less likely given their low capitalization and poor market integration, as well as fluctuating international prices (Aguilar, 2004).

Smallholders once were (and still are in some places) the main promoters and guardians of agrobiodiversity, but cultural changes as well as the aggressive strategies of commercial seed enterprises and governmental programs are changing the agro-biodiverse smallholder landscape. Intensification of smallholder maize systems can be attributed to the diminishing availability of an adequate labour force to assist in labour-intensive activities such as weeding, guarding the fields against animals that prey on the crops and harvesting a diversity of crops that mature at different times (Van Dusen, 2000). Market integration (van Dusen and Taylor, 2005), agricultural development triggered by governmental programs and subsidies (Denning et al., 2009) and rupture of the intergenerational transmission of traditional agricultural knowledge because of a shift in economic activities, among others. The implications of smallholder intensification are observed at both the ecosystem and cultural levels. As farmers increase intensification, they rely more and more on external knowledge and inputs, which occurs at the same time as the loss of traditional ecological knowledge related to such agricultural management as well as the loss of the culinary culture associated with the rich agrobiodiversity of traditional smallholder fields.

As can be seen in the following map[31] (Fig. 3.3), smallholders constitute the most widely distributed maize system across the world and are predominant among some of the main maize consuming countries, including Mexico, Central America, Ecuador, Peru, Guyana, Western Brazil, Sub-Saharan Africa, Madagascar, India, Malaysia, and Borneo. Smallholders are practically absent in the USA but are prominent throughout Mexico and Ecuador. In Mexico, they occur throughout the southern portion of the country, as well as in the mountainous and arid regions of the north. In Ecuador they are mainly distributed across the entire Andean region, as well as some parts of the coastal and Amazonian regions of the country.

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[31] Smallholder systems are mainly considered to be rainfed and, even in cases where supplemental water is supplied, this is not supported by irrigation infrastructure and therefore these are not considered as irrigated systems.

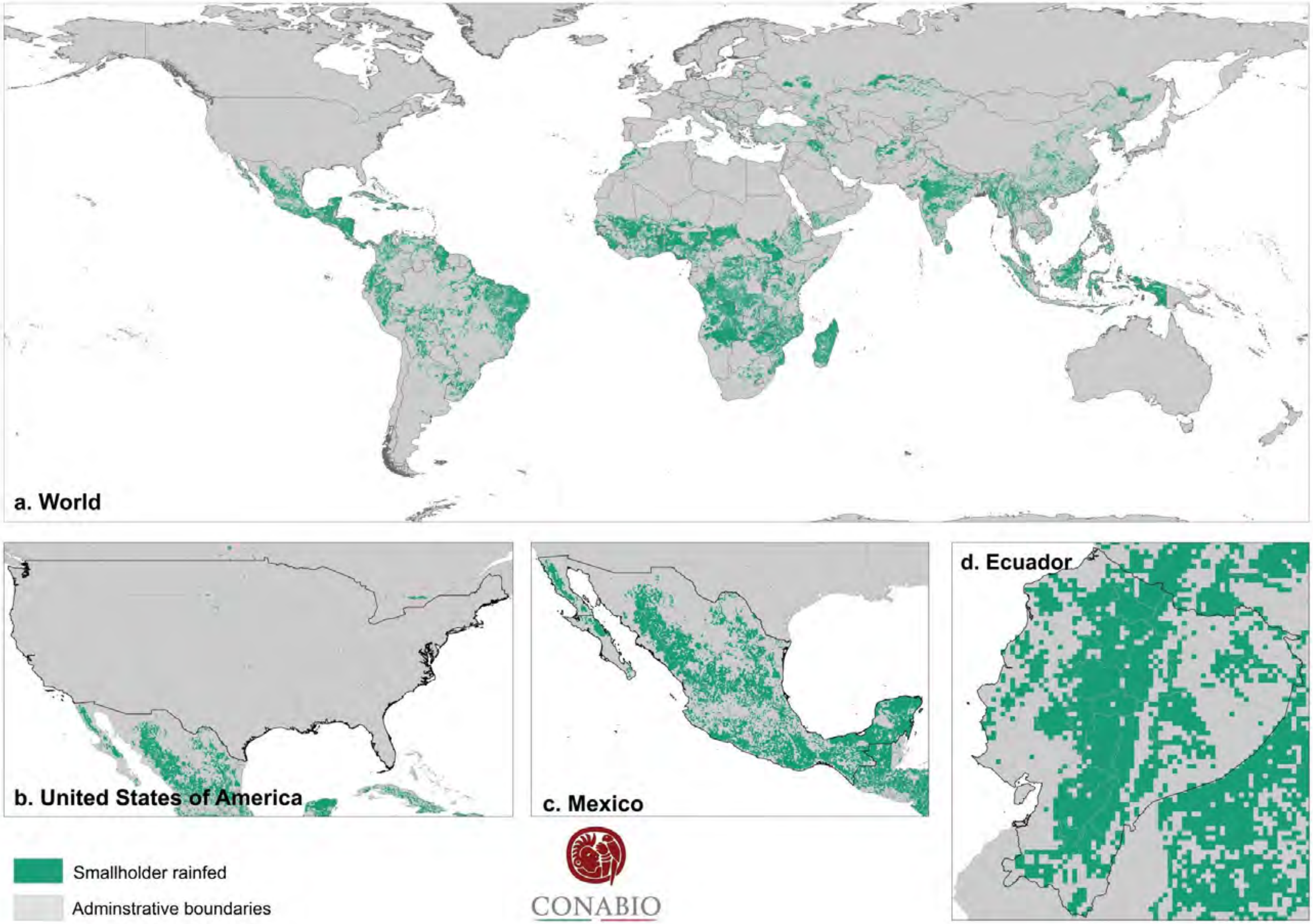

Figure 3.3 Worldwide distribution of maize smallholder systems (< 2 ton/ha). Source: Own elaboration with data from You et al., 2014.

When compared to other maize systems, smallholders are distributed across geographical regions with the highest mean annual temperature (21.9 °C), highest annual precipitation (1319 mm/year) and highest reference evapotranspiration rates (1337 mm). Regarding the topographical conditions, smallholders are distributed across the widest range of altitudes from 191 to 916 meters above sea level (1st and 3rd quartile) and have the highest mean altitude (615 m) among all of the systems (see graphics in Annex 1 objective 2). A logical consequence of this topographical allocation is that the distribution of slope classes is more homogeneously spread among smallholders than any other maize production system (Fig. 3.4).

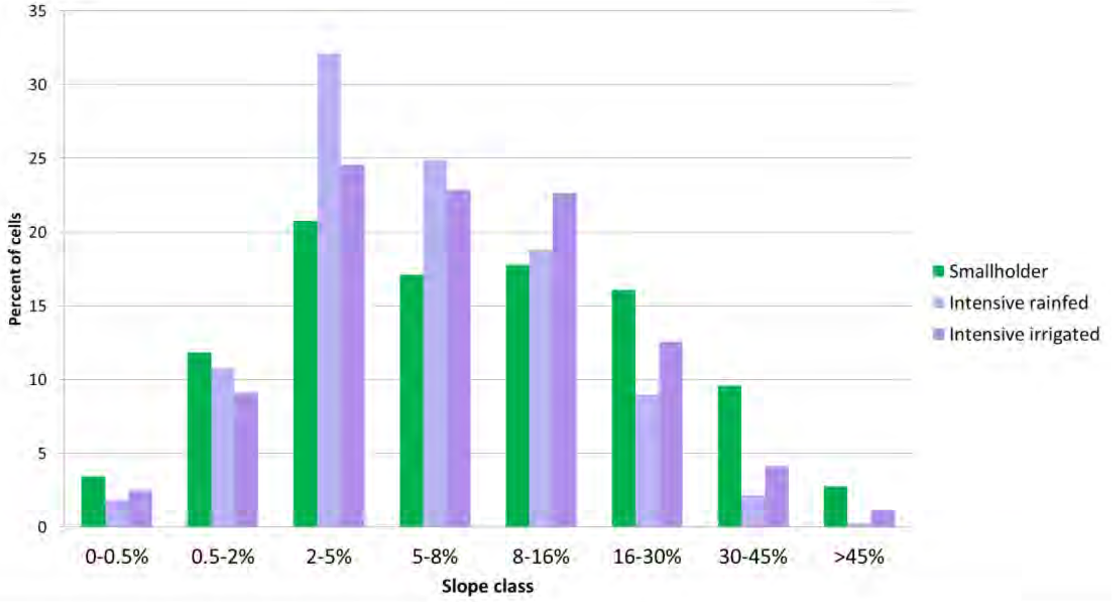

Figure 3.4 Distribution of slope classes among maize production systems. Source: own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

The dominant soils that characterize smallholder distribution correspond to ferrosols (13.86%), acrisols (11.6%), leptosols (11.14%), cambisols (9.86%) and arenosols (9.24%) (Fig. 3.5). Ferrosols occur in tropical and subtropical regions with rainforest vegetation and are high in metal oxides with low fertility for agricultural purposes (IUSS Working Group WRB, 2006). These soils are still used for shifting cultivation (*ibid.*). Acrisols are strongly weathered acid soils found in regions with a subtropical, wet tropical or warm temperate climate; they are not very productive and are generally used for subsistence farming, commonly under a shifting cultivation regime. Leptosols are shallow soils found at medium or high altitudes with a strongly dissected topography. Cambisols are the second most extensive soil group and are present in the temperate and boreal regions of the world. Finally, arenosols are sandy soils that occur in both arid and humid regions with extremely cold and hot temperatures (IUSS Working Group WRB, 2006).

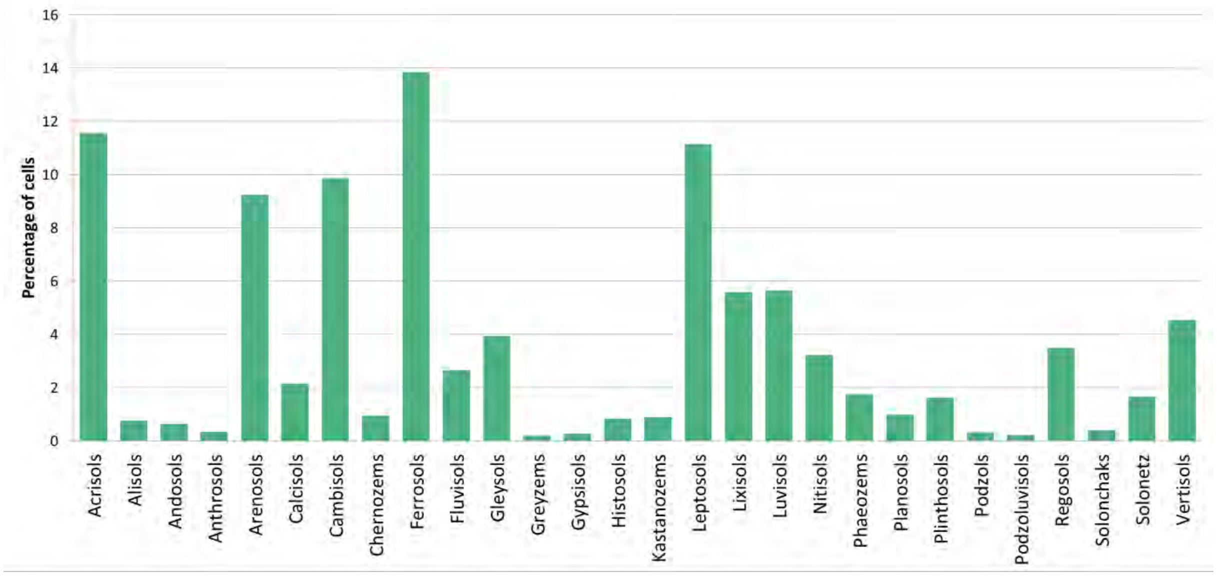

Figure 3.5 Distribution of dominant soils across smallholder maize systems. Source: Own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

When compared to intensive systems, smallholders are distributed over relatively nutrient-limited soils. While a little over 60% of the smallholder area is situated on soils with no or slight constraints in nutrient availability, almost 40% are found on soils with moderate or severe nutrient constraints (Fig. 3.11).

3.2 Intensive maize systems

Intensive maize systems are fully commercially-oriented; their main focus lies in maximizing profit. In these systems, profit results from producing the highest marginal yield possible per cost incurred and is the result of controlling almost every factor affecting the growth of a plant, including the genetic makeup of seeds, nutrient input, control of weeds, pests and diseases and water provision (Matson et al., 1997), as well as maximizing plant density. The rise of intensive systems was marked by the development of chemical fertilizers, pesticides and herbicides, agricultural mechanization and hybrid seeds (Pingali, 2012). The impact of these developments can be clearly seen in the impressive yield increases in practically all annual crops (Grassini et al., 2013). The case of maize is paradigmatic in this sense. In fact, maize was the first crop to undergo a rapid technological transformation (Griliches, 1957; quoted in Byerlee and López-Pereira, 1994). The rise of intensive maize systems was also marked by the exponential diversification of the use of maize and maize by-products in the food industry, as described in messages #4 and #5. Byerlee and López-Pereira (1994) identify a set of stages of technical change in commercial maize production systems. The first phase (1930-1950) was characterized by the development and adoption of hybrid seeds, the second (1950-1980) by the widespread adoption of chemical fertilizers, herbicides and pesticides and the third phase, which started in 1980, was characterized by an increasing concern about the stagnation of yields in response to increasing inputs, as well as the environmental consequences of agricultural production. This shifted the focus from input intensification to input efficiency, encouraging case-based approaches of agricultural inputs (*ibid*.).

In intensive maize systems production and consumption decisions are uncoupled and the ratio of capital to labor is very high (lots of expensive machines, few workers). In the less intensive smallholder systems, however, there is a low ratio of capital to labor (few machines, more direct human and animal labor involved) (Bellon, pers. comm.). In these systems, all phases of the production process are fully mechanized, including soil preparation, sowing, weeding, fertilizing and harvesting. The farms of intensive maize producers also tend to be much larger than the production units of smallholders. According to the FAO (2014b), only 3% to 7% of farms in Sub-Saharan Africa, the Middle East and North Africa are over 10 ha in area. In contrast, farms of this size account for 17% in Asia, 27% in Europe and 46% in America. To achieve economies of scale in order to pay for higher capital investment fixed costs (expensive machines), a certain level of scale is required; *i.e.* farms must exceed a certain size in order to make the system economically viable.

The use of synthetic fertilizers has a wide prevalence in practically all of the intensive maize systems around the world. Clearly, intensive systems are not the only ones to make use of these, since an increasing number of smallholder system now rely on them. Smil (2002) estimated that the use of nitrogen fertilization has contributed to 40% of the increase in per-capita food production over the past 50 years. The average use of fertilizers spiked during the second phase of input intensification alluded to by Byerlee and López-Pereira (1994). The average application of fertilizers in 1950 was 10 kg/ha, but in 1980 it spiked to 150 kg/ha (ibid.). In the USA, nitrogen fertilizers are used in 97% of all maize fields, phosphorus is used in 80%, potash in 65%, and sulphur in 29% (USDA, 2014b). At the global level, maize is among the cereals with the highest fertilizer application rates (135 kg/ha), followed by wheat (116) and rice (112) (FAO, 2006a).

Like inorganic fertilizers, chemical herbicides are a basic input in intensive systems. According to the Chemical Use Survey of the USDA of 2014, chemical herbicides are used in 97% of the area planted with maize in the fifteen US states included in the survey. In fact, it has been found that the largest US maize enterprises applied more fertilizer per hectare, and treated a higher percentage of their maize area with herbicides and insecticides, than was the case with the smaller producers (Foreman, 2014).

Disease and pest control in intensive systems is achieved through different practices that the USDA classifies as avoidance, prevention, monitoring and suppression. The 2014 Chemical Use Survey of the USDA collected data pertaining to fertilizer and pesticide use and pest management practices on maize farms of fifteen states, including those in the Corn Belt. Avoidance strategies included actions such as choosing a crop variety for specific pest resistance (reported for 57% of maize planted area), planting in locations planned to avoid cross infestations of pests (24%), planting of harvesting dates adjusted (21%), crop rotation (84%), row spacing, decreasing plant density, or adjusting the directions of rows (19%). Prevention methods included maintaining habitat for beneficial insects or vertebrates (14%), burning or removing of crop residues (9%), cleaning of equipment and implements after field work to reduce spread of pests (35%), burning, chopping, spraying, mowing, and ploughing of field edges, ditches or fence lines (56%), leaving the field fallow to manage insects (1%), killing weeds with a flamer (1%), use of minimum or no-tillage (67%), ploughing residue using conventional tillage (32%), using seed treated for insect or disease control (23%) and using water management practices (8%). Monitoring methods encompass diagnostic laboratory services used for pest detection via soil or plant tissue analysis (13%), field mapping (18%), scouting for pests during routine tasks (26%) and scouting for diseases

(80%), insects and mites (81%) and weeds (92%). Suppression actions included releasing beneficial organisms (1%), applying biological pesticides (10%), maintaining buffer strips or borders rows (8%), use of floral lures, attractants, repellents, pheromone traps or biological pest control (1%), maintaining ground covers, mulches or other physical barriers (47%), use of pesticides (32%) and growing trap maize to manage insects (2%) (USDA, 2014b). Chemical fungicides and insecticides are used in 12 and 13%, respectively, of the area planted with maize (*ibid*.).

Intensification is accompanied by a loss of non-crop habitats and simplification of plant and animal diversity at plot, landscape and regional scales (Stoate et al., 2001). Some features of the agroecosystems that harbour biodiversity, such as grasslands, field boundaries, water-courses and trees, are lost when systems are intensified (Stoate et al., 2001). Degradation of biodiversity is not only evident at the landscape or species level, but also at the genetic level. Intensive agriculture depends on the use of high yield seed varieties to achieve homogenous plant production. These varieties are specifically selected for their adaptation to certain soil properties, water requirements and pest or weed resistance. Approximately 50 to 60% of the increases in maize yield have been attributed to the development and use of hybrid varieties (Duvick, 1992, 2005). Hybrid inputs to yield were not as evident in the first phase of the Green Revolution compared to the second phase (Byerlee and López-Pereira, 1994). Leading seed companies from the USA report that the commercial life of a hybrid is approximately 7 years, after which they are replaced by new hybrids with higher yields (Duvick, 1984 ; quoted in Duvick and Cassman, 1999). Even though improvements in hybrid maize seeds have primarily focused on increased yields, other improvements such as improved tolerance to maize borer, improved yield at higher plant densities or higher tolerance to region-specific diseases such as maize dwarf mosaic virus have also occurred (Duvick and Cassman, 1999). Increases in rainfed yield gains can be attributed to the improved tolerance to a set of abiotic and biotic stresses (*ibid*.). Measured changes of hybrid maize characteristics between 1967 and 1991 include: ears per plant (+8%), tassel dry weight (-36), grain protein (-10%), grain starch content (+2%), stalk lodging (-75%), root lodging (-57%), leaf “stay green” (+29%), leaf angle (+122%), anthesis-silk interval (-74%) and tolerance to maize borer (+41%) (Duvick and Cassman, 1999). By 1990, practically all of the intensive maize systems around the world used hybrid seeds (Morris, 2002). By that time, a new technological seed development was taking place. The cultivation of genetically modified (GM) crops began in the early 1990s, mainly with two genetically modified traits: insect and herbicide resistance (as described in message #12). In 2013, 27 countries planted biotech crops in approximately 175.2 million of ha in 16 countries (James, 2013). In the USA, GM maize has increased slowly but by 2015 circa 89% of the area of this crop was planted with GM varieties (USDA, 2016e).

Intensive farming practices tend to favour monocultures. However, a scant interspecific diversity can be found in the form of crop rotation or double cropping in these systems. Crop rotation and double cropping, where two different crops are sown in the same field at different times of the year or intercropping, where two crops are sown in the same field at the same time, are also practiced in intensive production systems for several reasons. In the USA, double cropping was practiced in about 890,308 ha in 2012 (Borchers et al., 2014). On average, in the period 1999-2012, the largest areas with double cropping in the USA were in the Southeast (7.47% of cropland), Southwest (5.32%), Northeast (9.58%), and Midwest (5.32%) (*ibid*.). About half the area dedicated to double cropping was double cropped with soybeans between 1999 and 2012 (*ibid*.). In 2010, the double cropped maize fields in the North and South of the USA were preceded by winter wheat (26% and 63%, respectively), rye

(53% and 24.4%, respectively), alfalfa and other hay sources (4.4% and 1.4%, respectively), oats (5.5% and 3%, respectively), clover and other grasses (1.8% and 0.8%, respectively), and other crops (9.3% and 6.7%, respectively) (*ibid*.).

Intensive systems can be rainfed, mixed and irrigated. Intensive irrigated systems differ from rainfed intensive systems in that they are able to “escape” the geographical and seasonal limitation imposed by rainfall regimes. It is possible to grow two cycles of maize or to grow maize in places in which it would be impossible under non-controlled conditions. Furthermore, irrigation can significantly boost crop yields by providing plants with the moisture they require at critical times during the growing period (Mueller et al., 2012).

Intensive rainfed and irrigated systems are present in the main maize producer countries (Fig. 3.6 and 3.7). Intensive rainfed systems are predominant in the US Corn belt, northeast China, Turkey, Hungary, eastern Germany, France and Italy, while irrigated systems are present in the central, southeast and west coastal USA, Portugal, Spain, Greece, certain parts of Saudi Arabia, western Iran, northeastern and northwestern China and the east coast of Australia. In Mexico, intensive rainfed and irrigated systems are present in the state of Jalisco, and in some parts of Sinaloa and Chihuahua. In Ecuador, intensive rainfed and irrigated systems with yields of over 6 ton/ha are practically absent, but rainfed maize systems that produce 2 to 6 ton/ha appear throughout the Ecuadorian coastal and Amazonian region, while intermediate irrigated systems are found on the south coast of the country. In Mexico, intensive irrigated systems are few and scattered throughout the northern part of the country.

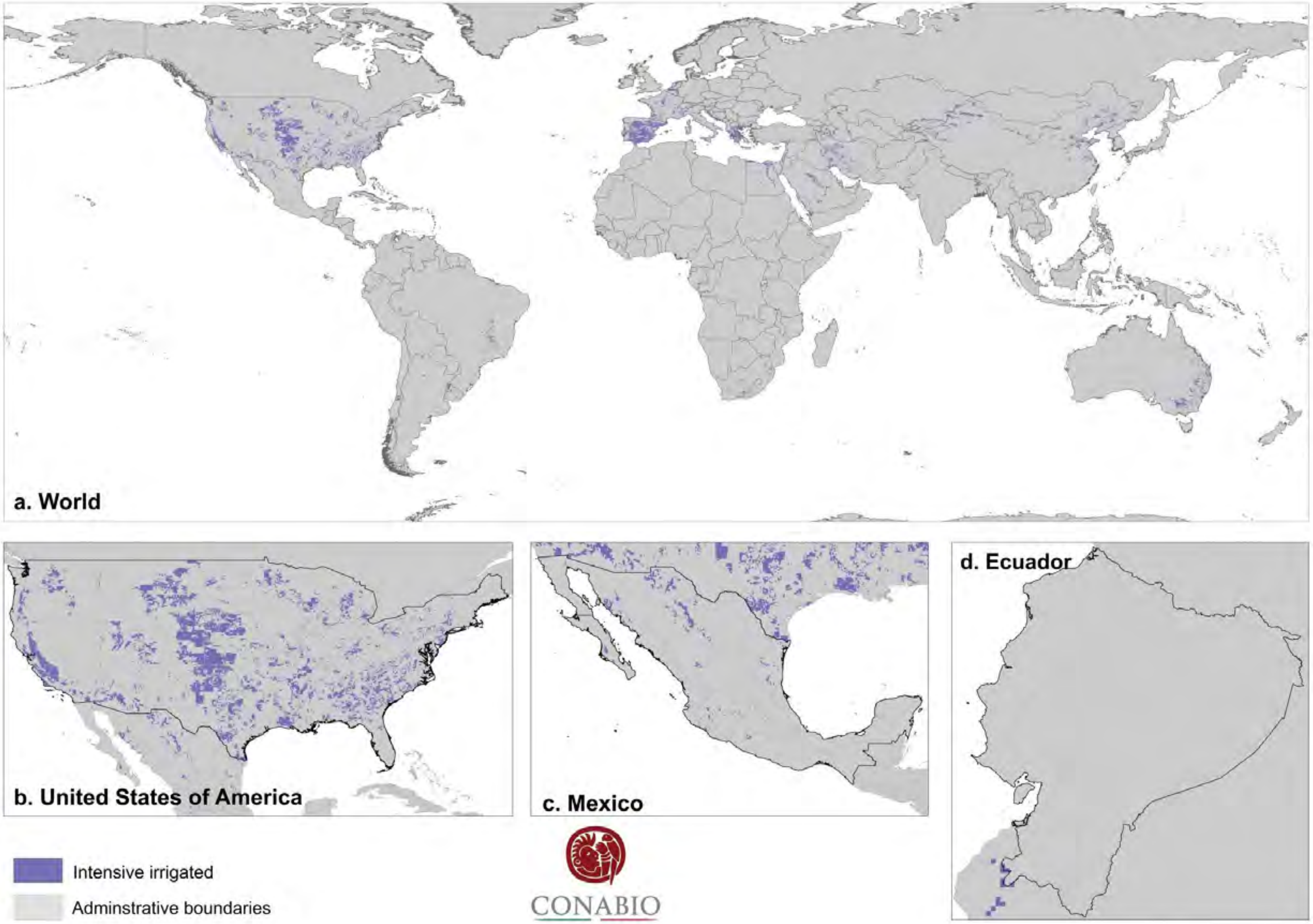

Figure 3.6 Worldwide distribution of **intensive irrigated** maize production systems. Source: Own elaboration with data from You et al., 2014.

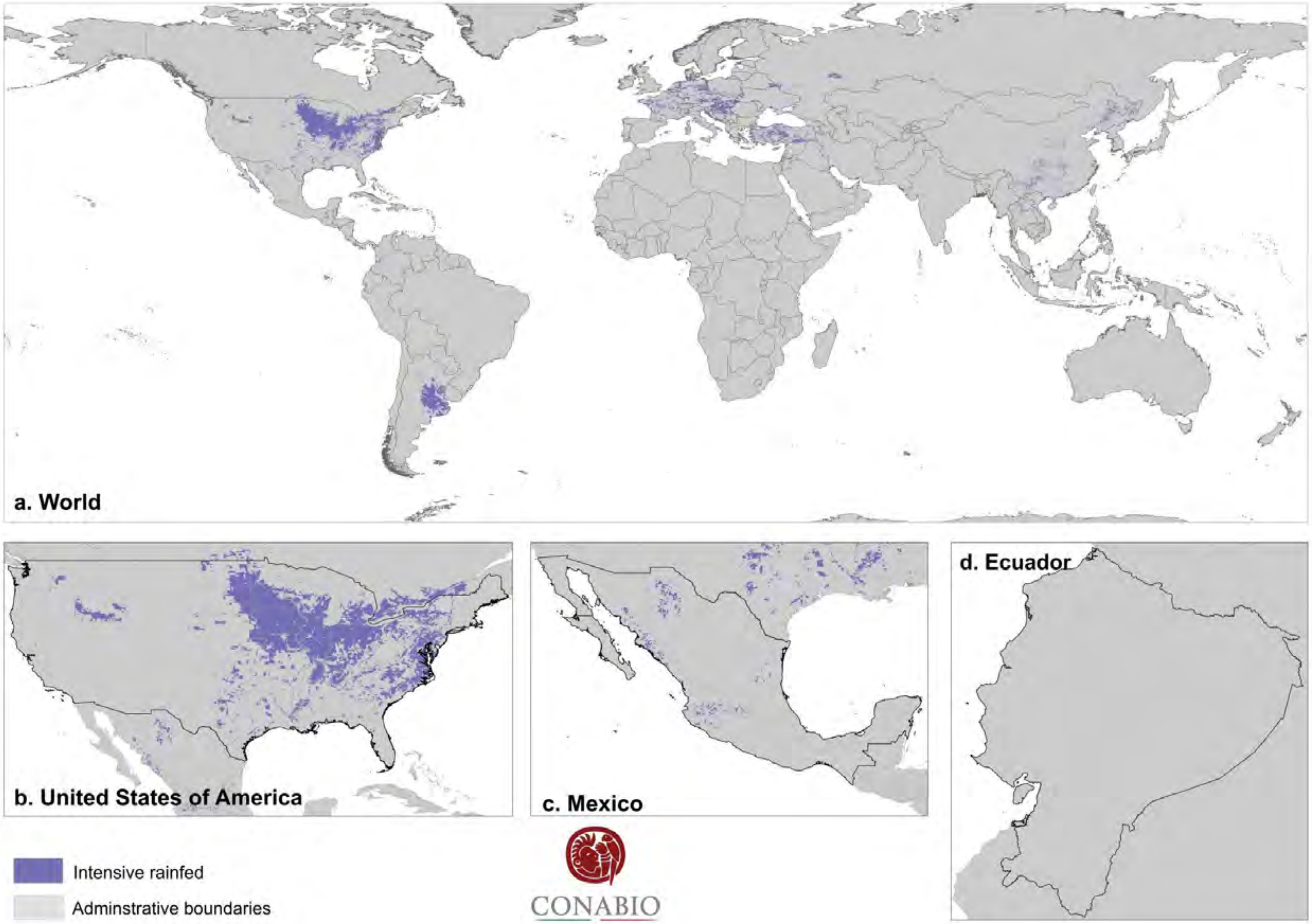

Figure 3.7 Worldwide distribution of **intensive rainfed** systems. Source: Own elaboration with data from You et al., 2014.

The altitudinal distribution of intensive rainfed systems is between 100 and 370 m (2nd and 3rd quartile), while intensive irrigated systems are distributed at higher altitudes (121 to 926 m). Intensive rainfed systems have a higher percentage of their area on more even terrain (44.7 % of cells in slope classes of less than 5%) compared to intensive irrigated systems (36% of cells in the same slope classes). As expected, intensive irrigated and rainfed areas differ significantly in their maximal annual temperature (31.4 and 29 °C respectively), annual precipitation (626 and 883 mm) and reference evapotranspiration (1205 and 941 mm). In summary, irrigated systems are distributed in significantly warmer places with lower rainfall and higher evapotranspiration rates.

Almost 50% of the intensive rainfed area is situated in phaeozem and luvisol soils (Fig. 3.8). Phaeozems are dark soils rich in organic matter that are present in warm to cool regions (IUSS Working Group WRB, 2006) and luvisols are soils that are common in cool temperate and warm regions with a discernable dry and wet season (IUSS Working Group WRB, 2006). Both are considered highly fertile soils (FAO, 1986). Slightly more than 40% of intensive irrigated systems are distributed in luvisols (13.6%), cambisols (12.1%), calcisols (9.8%), and kastanozems (11.6%) (Fig.3.9). Calcisols and Kastanozems are soils found in dry and warm environments (IUSS Working Group WRB, 2006).

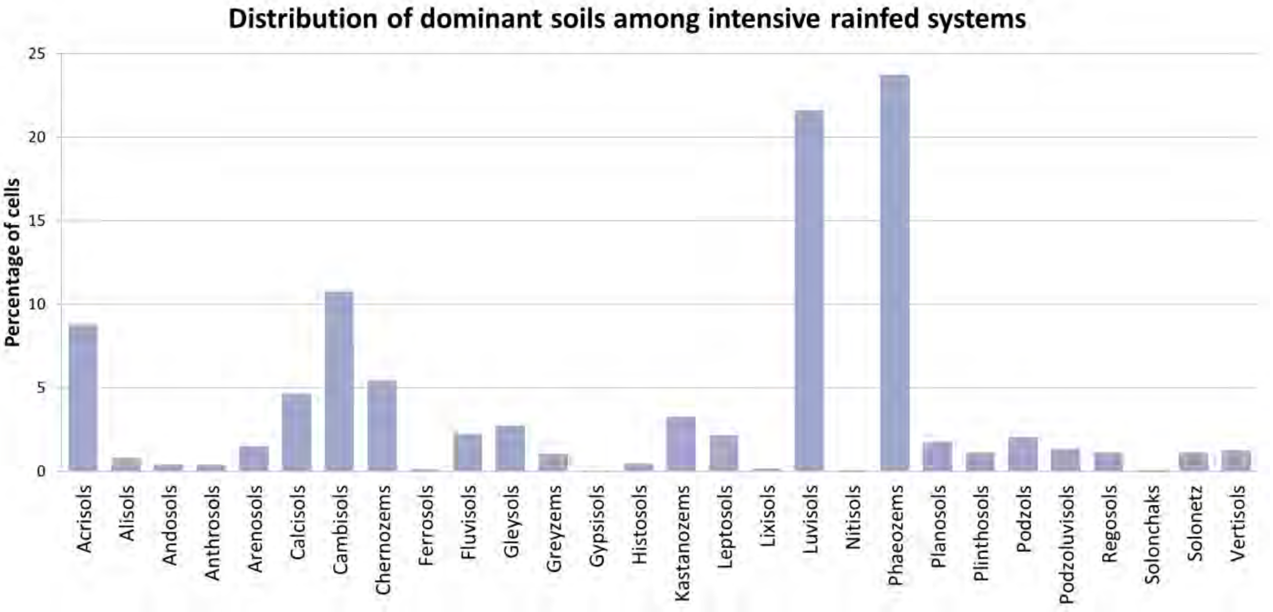

Figure 3.8 Distribution of dominant soils across the distribution of intensive rainfed maize systems. Source: own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

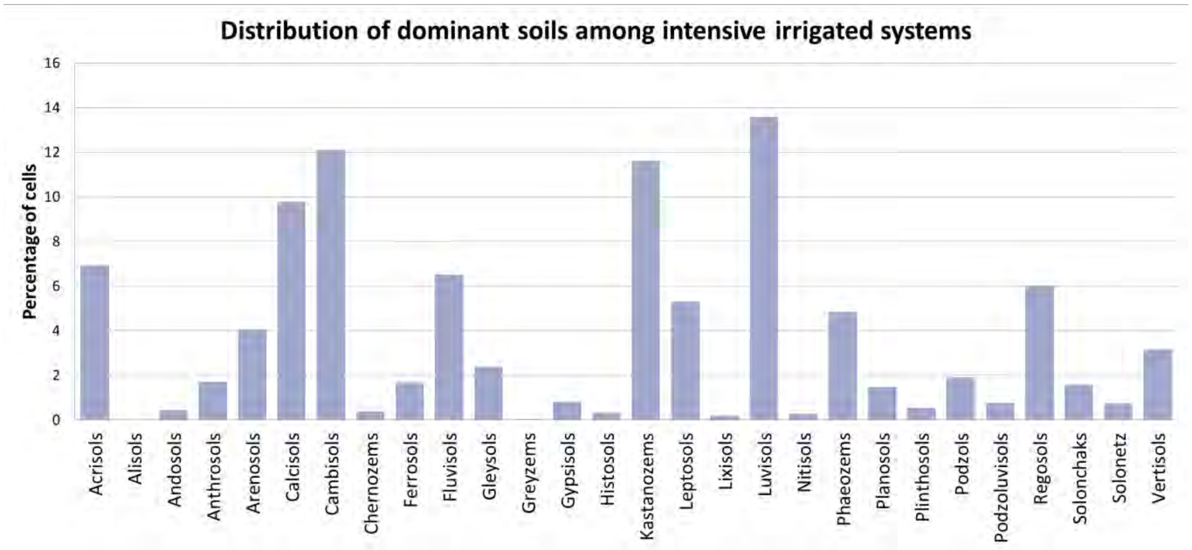

Figure 3.9 Distribution of dominant soils across intensive irrigated maize systems. Source: own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

As a result of the former distribution, a high proportion (approximately 70%) of both intensive rainfed and irrigated maize systems are found on soils with no or only slight constraints in nutrient availability, which partly explains the historical development of intensive systems in these areas.

3.3 Intermediate maize producers

As shown in figure 3.1, intermediate yield level production accounts for a high proportion of the distribution of maize areas around the world. Intermediate producers cannot be classified as smallholders, given their relatively high yields (2 to 6 ton/ha) which indicate the possible use of monocultures, herbicides and some fertilizer inputs at the lower yield range (2 to 4 ton/ha) and the use of improved seeds in addition to these inputs at the higher yield range (>5 to 6 ton/ha).

We hypothesize that the intermediate producers are a heterogeneous mixture of intensified smallholders that still do not possess the capital and level of technification of intensive systems, or are intensive systems operating in suboptimal environmental conditions.

Intermediate systems are distributed in central and southern Brazil, Mexico, Ecuador, Venezuela, Argentina, Canada, USA, central Europe, small parts of Africa, southern and northeastern China, throughout the Caucasus, southern Russia, central and southern India, Indonesia and Malaysia. These systems are thus present in both the main producer and consumer countries. In the USA, they are distributed in the north and southeast of the Corn Belt. In Mexico, they are found throughout the central plateau, the Gulf of Mexico, southern Baja California Peninsula, the state of Campeche and in some parts of the state of Chiapas. In Ecuador, they are prominent along the coast and in the Amazonian region.

The extended distribution of intermediate producers is reflected in the large interquartile ranges of mean annual temperature; slope index and annual precipitation found in these areas (see graphics Annex 1, objective2).

The predominant soils among intermediate producers are acrisols (12.6%), ferrasols (11.6%), cambisols (10%) and chernozems (9.9%), accounting for almost half of the area over which these producers are distributed (Fig. 3.10). As stated above, acrisols, ferrosols and cambisols are also predominant among smallholders. The first two are low fertility soils prevalent in tropical and sub-tropical regions, while the cambisols, along with luvisols (7.5%) and phaeozems (5.6%), are soils present in cool/temperate regions of the world where intensive systems prevail.

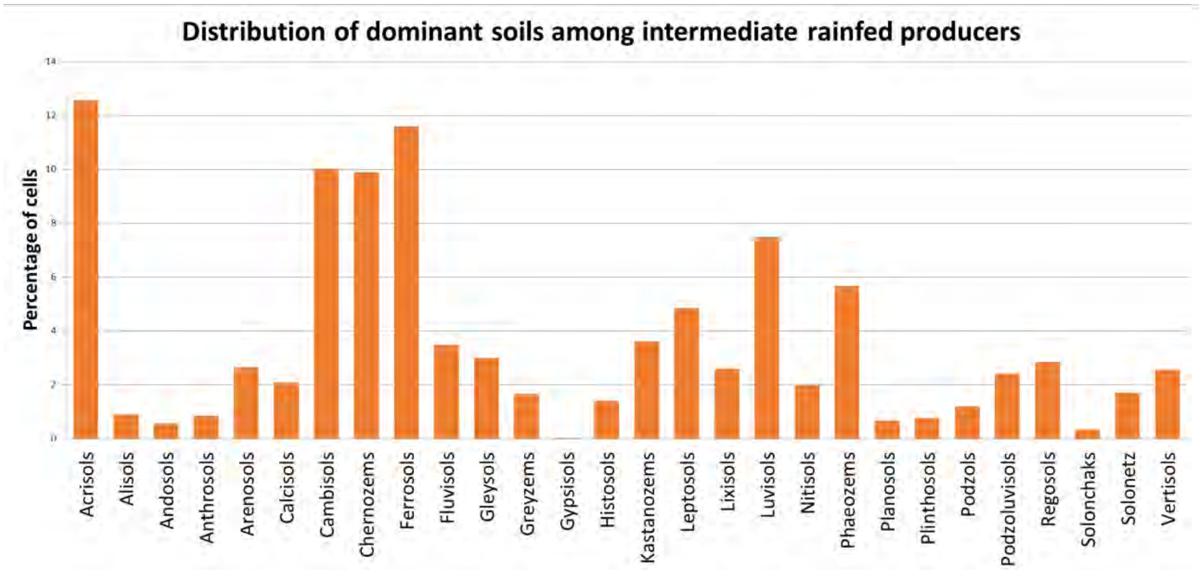

Figure 3.10 Distribution of dominant soil among intermediate maize producers. Source: own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

When compared to intensive systems, the allocation of intermediate producers over less fertile type of soils is confirmed when analyzing constraints in nutrient availability (Fig. 3.11).

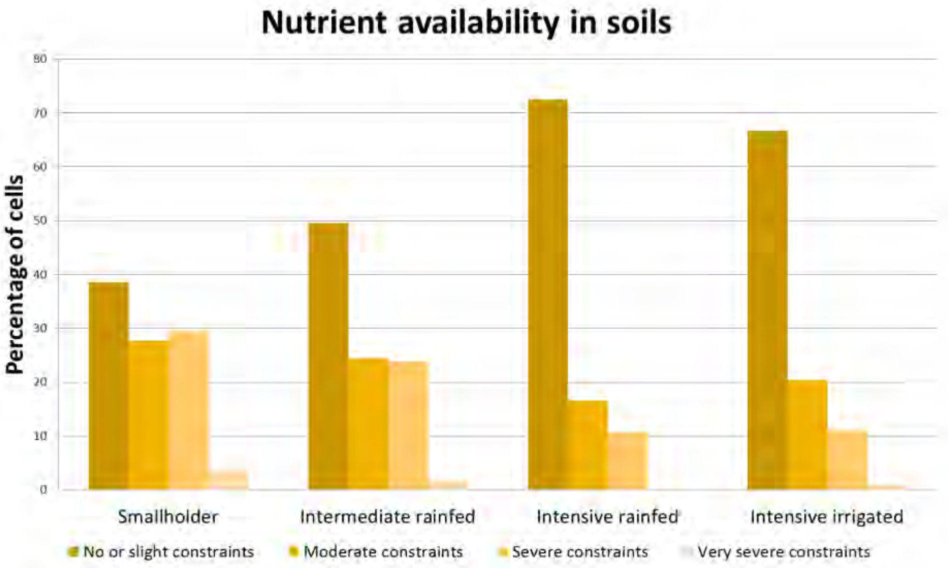

Figure 3.11 Distribution of nutrient availability constraints in soils among maize systems. Source: own elaboration with data from You et al., 2014 and IIASA-FAO, 2012.

The distribution of intermediate producers over both intensive and smallholder producing regions points to a very heterogeneous group of maize producers. Intermediate producers present in regions where maize is not regularly consumed as a staple crop are evidently not producing maize for self-consumption, which makes them commercial producers. This might be the case in the central-southern and central-northern portions of the USA, southern Russia, southeastern China and southern Brazil. On the other hand, intermediate producers in countries such as Mexico and Ecuador may comprise a mix of commercial producers, such as those of the coastal areas of Ecuador that are known to produce maize for the poultry industry, and intensified semi-commercial maize producers in the plateau of Mexico who still plant native varieties under intensified conditions (using herbicides and fertilizers). For example, there are reports of smallholders in Mexico reaching yields of 6 ton/ha under suitable circumstances and using seeds from locally adapted landraces (Perales et al., 2003; Aragon, 2016). Situations where such circumstances are present are difficult to map at a global scale, therefore making it challenging to clearly distinguish intermediate producers from smallholders.

3.4 Organic maize systems

The origin of organic agriculture is closely tied to the advent of industrial or intensive agriculture, which began in 1840 when the first inorganic fertilizers were developed, although these were not fully adopted until after World War II (Kristiansen, 2006). During the 1960s, the ideological basis of organic agriculture gained momentum with the zeitgeist of that time (Kristiansen, 2006), but the formal beginning of the modern movement of organic agriculture was marked by the founding of the International Federation of Organic Agriculture in 1972 (IFOAM, 2014). Organic maize systems can be defined as agricultural schemes that prohibit the use of genetically modified seeds, chemical fertilizers, pesticides and insecticides (Woodward and Vogtmann, 2004, quoted in Kristiansen, 2006). Based on these criteria, many smallholder producers around the world could be considered organic systems; however, the main difference between organic farming and other similar types of agriculture is the reliance of organic systems on a well-defined set of recommended management practices recognized through a certification process (Rigby and Cáceres, 2001). Organic systems can be seen as a fusion between intensive and traditional systems since they are basically commercially-orientated systems that depend on management practices developed by traditional agriculture, such as intercropping, crop rotation and the use of organic fertilizers, among others.

Organic schemes use two means to regulate the production and processing of food products: 1) control of inputs and 2) the requirement for certain practices or environmental results (Stolze et al., 2000). Both fertility and pest and disease management are a challenge for organic production given the ban on synthetic pesticides and fertilizers.

Management of soil fertility is regulated through the use of crop rotation with forage legumes, cover crops and green manures, intercrops and organic fertilizers such as livestock manures, composts and other organic components such as cottonseed, feather, blood and fish meal (Kuepper, 2002).

Von Fragstein et al. (2006) divide crop protection mechanisms for the management of pests and diseases used in organic farming into: 1) colonization prevention, 2) population regulation and 3) curative practices. Colonization prevention includes sanitation measures (flaming, steaming, debris elimination), temporal asynchrony (deliberate timing of planting in order to avoid pest arrivals), establishment of unconducive conditions (crop rotation, use of repellent cultivars), spatial isolation (use of barrier crops or natural strips) and disruption of colonizers (*ibid*.). Population regulation includes the selection of resistant cultivars, intercropping, competition and insectary vegetation/predator resources (flowering plants in field margins, hedgerows, cover crops). Curative measures are achieved through the use of organic pesticides such as soaps, oils and compost teas, and inorganic pesticides such as sulfur dust, iron phosphate, CO_2, and N_2, the use of plant extracts, inundative biological control (introduction of predators, parasitoids, bacteria and viruses, and physical removal − trapping, handpicking) (*ibid*.).

The management of weeds is one of the most challenging aspects of organic farming, but many of the former practices that are used for both fertility enhancement and pest/disease control, such as crop rotation, the use of cover crops and flaming, are also used for the control of weeds along with mechanical weeding methods (Finney and Creamer, 2008).

Large-scale certified organic units are similar to intensive units in their capitalization and level of mechanization (Foreman, 2014). Nevertheless, conventional maize farms in the USA tend to be significantly larger than certified organic farms (290 *vs.* 73 acres) (*ibid*.). Large-scale certified organic maize producers dedicate a high proportion (77%) of their production to the production of feed for the livestock and poultry market (77%), while only 15% is grown for direct use as food (*ibid*.). Small-scale certified organic maize systems, on the other hand, are mainly represented by small farmers that merchandize their products on roadside stands, farmers markets and community-supported agricultural farms, and present limited mechanization.

In 2013, 43.1 million ha of agricultural land worldwide were either under certified organic management or in the process of conversion to this system (Willer and Lernoud, 2015). About 7% of the land under organic agriculture was being used to produce perennial crops such as coffee, olives, nuts, diverse fruits, grapes and cocoa (*ibid*.). The rest were used to produce annual crops including cereals and vegetables. The area destined for the production of cereals was 3,309,788 ha, with maize accounting for 10% of this area, after wheat (36%), oats (14%) and barley (11%) (*ibid*.). Currently, the main producers of organic maize are China and the U.S., which together account for 54.7% of the entire area of organic maize production.

The extent of certified organic maize production around the world is shown in the map in figure 3.12. While the number of countries producing organic maize is relatively large (53), the area dedicated to this product is relatively small, as described above. Nevertheless, with increasing demand for organic dairy and organic meat (OMSCO, 2016), the area dedicated to the production of organic feed also increases.

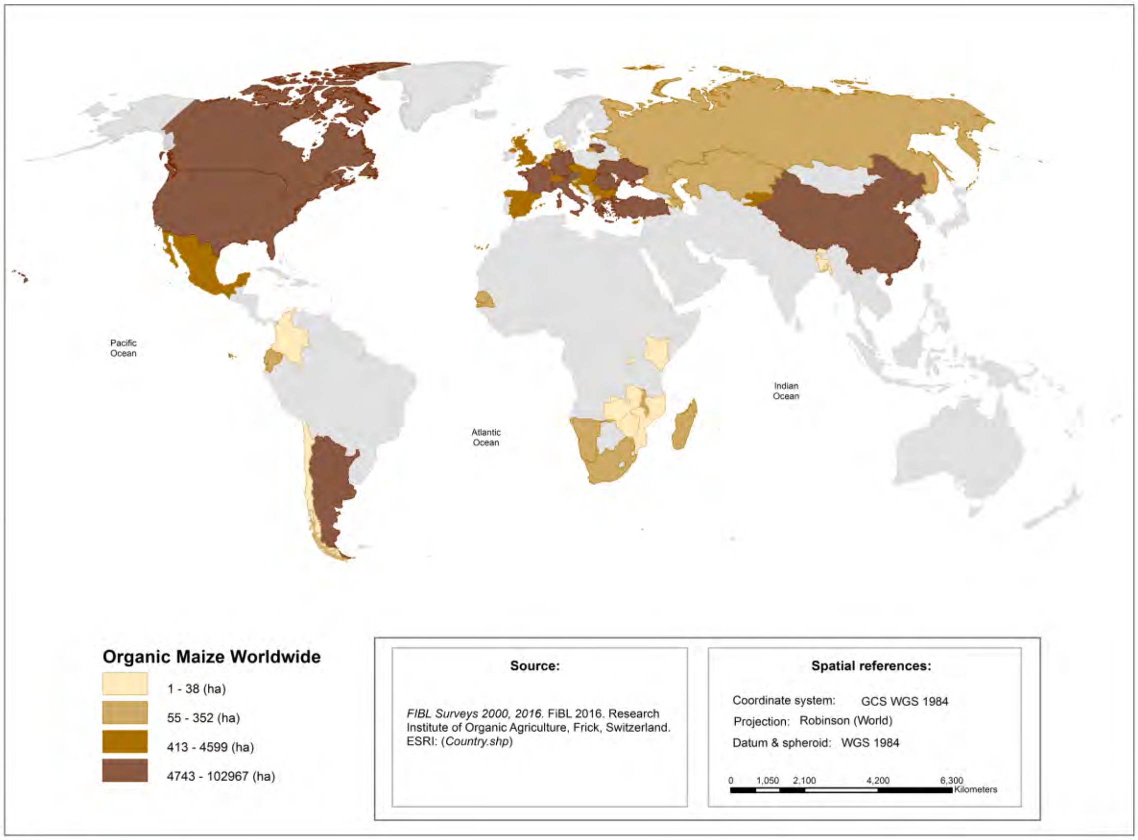

Figure 3.12 Certified organic maize production worldwide. Source: Own elaboration with data from http://www.organic-world.net

In conclusion, mapping of maize systems defined by yield shows a particular distribution around the globe, which may explain the development of these systems in these regions. Intensive rainfed systems have flourished in regions with fertile soils, sufficient rainfall, relatively low evapotranspiration and even topography. High investment in technology and inputs is less risky and more cost effective under these environmental conditions. Maize breeding for these areas is also simpler because there is less environmental variability or such variability can be reduced by the use of agrochemicals. Hence, the wide adaptation of a single variety can be promoted by breeding programs, instead of the local adaptation of several varieties (see box 5.1 and 5.2 in “The dependency of global systems on maize genetic diversity” for review of the genetic basis of breeding for intensive systems). On the other hand, smallholders have to continuously adapt to harsher conditions (*i.e.* soils with nutrient limitations, areas with higher or lower temperatures, higher altitudes, steeper slopes, etc.), where the use of a wider degree of agrobiodiversity represents the key to this adaptation (see message #8 in section 2 and “The dependency of global systems on maize genetic diversity” in section 5). The maize systems mapped here, which were defined solely on the basis of yield, differ significantly in terms of the main environmental conditions assessed (see Annex 1), suggesting the importance of these as limiting factors for agricultural production and for the maintenance of the agricultural knowledge systems that remain vital for a large part of maize production worldwide.

4. MAIZE PRODUCTION AND CONSUMPTION IN THE CASE STUDY

4. Maize Production and Consumption in the Case Study Countries

Author: Yatziri Zepeda

The goals, objectives, and challenges of maize production can be very different in the different regions of the world. Such differences are reflected in the diversity of existing maize production systems and in the contribution of these systems to food security[32]. This can be illustrated by our case studies: Ecuador, Mexico and the USA. These countries show marked differences not only between them but also within them in terms of their management practices, uses, market orientation, channels of commercialization, end users, and the type of diets they support. In these three countries maize substantially contributes to the local and national diets but in different ways. The following description of maize production and consumption in these countries and states seeks to provide an introduction to our study cases and to lay down a justification for their selection for our bottom-up approach to valuation.

Maize uses and levels of intensification: Ecuador, Mexico and the United States of America

The most recent data on the use of maize in Ecuador reported that, in 2009, 77% of the total maize production was consumed by the national poultry meat industry, 9% was for self-consumption and seeds, 1.6% was commercialized for human consumption and 9.1% was wasted during drying and cleaning (León-Vega, 2010). Most of this is hard maize (1.53 million tons in 2014), generally produced in either rain-fed or irrigated intermediate systems of the Coast Region (INECa, 2014). Hard maize is produced with improved seeds, fertilizers and pest-control products. In contrast, soft maize and maize landraces (0.11 million tons) are mostly produced in the Highlands Region (*ibid.*). It is the most important kind of maize for food either for self-consumption or for the internal market. Soft maize production in this region is characterized by rainfed low–input systems. The approximate average yield for 2012 is estimated at 1.05 ton/ha (0.21-3.75 ton/ha). The 14 indigenous groups that live in the Highlands Region depend on the cultivation of maize (Tapia, 2015). Both hard maize in the Coast Region and soft maize in the Highlands are produced mostly by small and medium size farms whose farmers largely commercialize their product through intermediaries and other enterprises (Banco Central del Ecuador, 2015). Often, soft maize in Ecuador is associated to other crops, particularly legumes that improve the soil quality and complete smallholders' diets.

In 2013 Mexico produced 22.6 million tons of maize, mostly white; imported 7.2 million of maize, mostly yellow, and exported 0.71 million tons. Almost 45% of the total production was used as food and around 40% was used for feed; five percent was for food manufacture, 1% for seeds, 0.1% for other purposes, including the production of ethanol, and 9% was wasted (FAOSTAT, 2016). The role of white and yellow maize in food security in Mexico is different: Over a quarter (27%) of the white maize produced locally in 2011 was for self-consumption, 59% was commercialized for food, only 12% was used as feed, and a small amount was used as seeds, other uses and waste (Servicio de Información Agroalimentaria y Pesquera, 2011). In contrast, about 70% of the yellow maize consumed that year was used as feed, a quarter was used by the starch industry (*ibid.*), and the rest was for

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[32] Food security is achieved "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (World Food Summit, 1996).

human consumption and others. Approximately 5% of the national production of maize is yellow maize, while all white maize was produced locally (*ibid.*). Over the last decade, Chiapas, Jalisco and Sinaloa have been among the top five producers of maize in Mexico. Sinaloa became the main maize producer in the 1990s. Currently, its maize yields are the highest in the country (over 10 ton/ha). Sinaloa produces maize mostly under irrigation for commercial purposes (Eakin et al., 2015). It is estimated that about 70% of the white maize in Sinaloa is used for food and the rest is used as feed and for industrial products (Bausch, 2011). Jalisco is the second main producer of white maize, just after Sinaloa, as well as the second largest producer of yellow maize after Chihuahua (Servicio de Información Agroalimentaria y Pesquera, 2013). Jalisco and Sinaloa together produce one third of the total national production of white maize (SAGARPA, 2014, quoted in Castañeda-Zavala et al., 2014). The weather in Jalisco is currently favorable for the production of rain-fed maize. There are small producers who devote their production to self-consumption and eventually commercialize their surplus, and medium producers, who produce mostly for commercial purposes and a minimum fraction is used for self-consumption: approximately 67% of the farmers produce for commercial purposes and for self-consumption. Seventeen percent exclusively commercialize their production and only 5% produce entirely for self-consumption (Castañeda-Zavala et al., 2014). Given the increasing demand for yellow maize, and its higher price, small and medium producers in Jalisco are moving towards the production of yellow maize, affecting the production of white maize for food (*ibid.*). Currently, most part of the maize produced in Jalisco is used as food, including the production of tortillas (12%) the production of other foods (23%) and food products like sweeteners, starches, emulsifiers, flours, gums, etc. (12%). The rest is used for feed (29%) and other industrial products (*ibid.*).

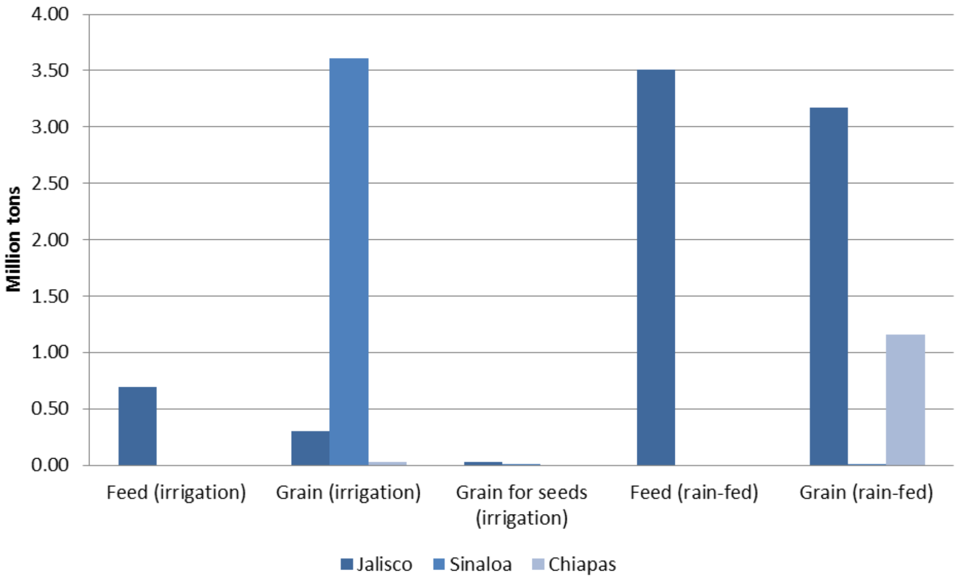

Figure 4.1 Maize production in Jalisco, Sinaloa and Chiapas, Mexico by use and water management practice. Source: own elaboration with data from SIAP, 2014.

Figure 4.1 shows that Jalisco produces an important part of rainfed and irrigated maize for food and feed. Sinaloa produces, mostly, irrigated maize for food, and Chiapas, rainfed maize for food, too. In Chiapas, maize is the main component of the population´s diet (Martínez-Jiménez et al., 2015). Approximately 50% of the total agricultural area in Chiapas is cultivated with maize (Hall, 2001). The principal agricultural system in the state is characterized by small-scale rain-fed self-consumption production of maize (Eakin et al., 2015). The most important agricultural system of the region is the milpa, a traditional polyculture where maize is associated to other crops of importance for the family economy, including for example, beans, squash, chilies, tomatoes and edible weeds (Benitez et al., 2014). While yields in milpa systems may be lower than those in intensive monocrops, milpa produces a relatively reliable harvest fundamental for household food security under uncertain environmental conditions (Tuxill et al., 2010). In the highlands, an area with high levels of poverty where the population is mostly indigenous, mechanization of agriculture is unsuitable due to the steep slopes. However, in the Central Valley and the Meseta Comiteca, where mechanization is possible, maize is grown for commercial purposes (Eakin et al., 2015). Maize production is the main source of income for 22.7% of the farmers in Chiapas (*ibid.*). Non-indigenous producers prefer commercial seeds and are more inclined to accept new varieties whereas indigenous producers prefer to maintain landraces with a mixture of colors and sizes for a number of reasons (Brush and Perales, 2007) (see sections 2, key messages 8, 9 and 10).

Worldwide, over the last ten years, the United States has been the main producer and exporter of maize (USDA/ERS, 2016b). In 2015, the USA produced an estimated 15.4 billion bushels of total supply (391 million tons, approximately[33]). Most of this maize (over 30%) was used as feed and residual[34]; 42.2% was used as food, seed and for industrial, including the production of ethanol, and 12.3% was exported (USDA, 2016a). Average yields in the U.S were estimated at 7.98 ton/ha in 2013 (Langermeier and Lunik, 2015). Over 80% of the cultivated maize is located in the Corn Belt states. For the last two decades, Iowa has been the main producer of maize with average yields of 12.91 ton/ha (USDA, 2016a). In 2015, Iowa produced 2.5 billion bushels of maize for grain (63.5 million ton approx.) and 8.16 million tons of maize for silage, for a total of 71.6 million tons approx., according to the USDA (2016a). During 2014/2015, 43% of maize production in Iowa was used for the production of ethanol; 15% for dried distillers grains with solubles from ethanol production [35]; 12% was used for other processing, including the production of starches, sweeteners, and over 4,000 industrial products; 9% to exports; 8% hogs; 6% residual use; 3% beef cattle; 3% poultry, and 1% diary industry. Only 1% of all the maize grown in Iowa is produced for human consumption as food USDA, 2016a). Iowa maize systems are intensive and have relied heavily on rainfall but as a response to more frequent and intense draughts, it is transitioning from relying on rainfall to the implementation of irrigation systems (*ibid.*).

Like Iowa, maize production in Nebraska is also mostly used to produce ethanol. Out of the 1.3 billion bushes produced in 2015, or approximately 33 million tons, 35% was used for ethanol, 18% was exported, 16% was used for feed, another 6% was corn displaced by distillers grains, 10% was carryout, (or the amount of maize left over after the demand was satisfied), 9% used in other processing, and 6% was residual (Nebraska Corn Board, 2016). Nebraska is one of the states that relies on irrigation (46% of its area), although most of the agricultural land in Nebraska is rainfed (54%) (University of Nebraska, 2012). In 2015, Minnesota produced 1.43 billion bushels of maize for grain (36 million tons approx.) and 9.68 million tons of maize for silage (USDA, 2016b), for a total of 46 million tons approx. The largest share of maize production in Minnesota is exported (42%). About

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[33] 1 bushel = .0254 ton http://www.grains.org/buyingselling/conversion-factors

[34] Residual or unaccounted disappearance is the usage that cannot be verified

[35] Distillers grains is a co-product of the ethanol production process, used as feed ingredient for livestock and poultry diets. Corn distillers dried grains/solubles (DDGS) are recovered in the distillery and contain the nutrients from the incoming corn minus the starch. DDGS typically contain 27% protein, 11% fat and 9% fiber.

40% is used for processing, including both ethanol and other corn processing; 17% is used for feed and 2% for other uses (Minnesota Department of Agriculture, 2012).

Maize production in these three states takes the form of industrial monocrops. They use hybrid and GM seeds that tend to uniformity, given the requirements of highly mechanized production systems. From 1996 to 2016, the adoption of genetically modified (GM) maize in the Unites States went from nothing to 89%, in the case of herbicide-tolerant crops and from 8% in 1997 to 79% in 2016 in the case of insect-resistant seeds (USDA, 2016a). In contrast, in 2008, Ecuador´s constitution declared the country as "free from transgenic crops and seeds". In Mexico, the cultivation of GM maize was halted in 2013. A collective action is in place against GM maize being released in the environment claiming possible damage to the genetic diversity in the center of origin and genetic diversity of maize, results of the action are still to be seen, the in depth legal analysis is underway. There are many concerns relating the future effects of using GM maize[36] where genetic diversity is present and under selection (human and natural). The consequences of their adoption on local maize diversity, on accompanying species diversity and on wild relatives when present have not been studied fully. A way forward would be to generate the necessary scientific, technical data both on the genetic diversity at stake as well as the social processes that relate to the use of this diversity prior to deciding if GM maize is the right decision for countries like Ecuador and Mexico in relation to maize production and use (Acevedo et al., 2011; Burgeff et al., 2014).
Moreover, Mexican and Ecuadorian landraces are a key provider of cultural ecosystem services for smallholders, particularly for the indigenous communities (see sections 5.4 and 6.4).

Maize production and food security among the case study countries

Food security is achieved "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO/WFS, 1996). Maize plays an important role in the diet of these maize-producing countries but in different ways. In Mexico maize is used primarily as a staple for the entire population and it is, and has been for millennia, mostly consumed in the form of tortillas. Self-consumption maize (23% of the total production) is a fundamental component to reach the food security of about two million Mexican smallholder families, who live in a context of fragile socioeconomic and biophysical environments, and who depend on the natural capital (INEGI, 2014). Box 4.1 shows the important contribution of smallholders (0 to 3 tons/ha) in fulfilling the needs of maize supply in Mexico, in spite of their relatively low yields. Self-consumption of maize is also important in Ecuador (9%), but in this country the largest share of maize is used by the poultry industry. In all three countries maize plays an important role in feeding animals. Approximately, 77%, 40%, and 36% of the total production in Ecuador, Mexico, and USA is used for feed, respectively. While there is a surplus of white maize in Mexico, there is a deficit in the production of yellow maize. Out of the 11 million tons of yellow maize consumed annually in Mexico, most of which are imported, about 70% are used as feed, 25% for the starch industry and the rest is for human consumption and other uses. Remarkably, the production of maize for ethanol in Iowa (41.5 million tons in 2014/2015) doubles the total amount of maize production in Mexico used for food, feed and self-consumption. Over 8.5 million tons of maize produced in Iowa is used for processed products, including

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[36] The current GM constructs commercially available in locally adapted genetic backgrounds through commercially available seeds.

processed foods. Exports in the state represent 9%. Last but not least, also about 9% of the total maize production in Mexico and Ecuador is wasted (no data for USA).

Tables 4.1 and 4.2 show the relative contribution of maize grain in achieving food security in the three case studies countries. In Mexico, the per capita daily caloric intake from maize grain, mainly in the shape of tortillas and other local maize-based foods and drinks, is over a thousand kilocalories, compared to 97 in the U.S and 36 in Ecuador[37]. Moreover, the contribution of maize to the daily necessary protein intake in Mexico is 26.86 gr while in USA is 1.76 gr and in Ecuador 0.95 gr[38] (http://maizeatlas.cimmyt.org/gis-web-viewer). Additionally in Mexico maize for human consumption is mostly based in the preparation of a dough through a process called *nixtamalización* (which consists in cooking maize grain with a lime solution and letting it rest for 14 to 18 h before washing it and preparing the dough) that increases the nutritional value of the proteins present in the maize grain (Paredes et al., 2009).

Table 4.1 Contribution of maize grain in the total food supply and daily caloric intake in Ecuador, Mexico, and USA.

	Food supply from maize (g/capita/day)	**Food energy from maize (kcal/capita/day)**	**Protein from maize (g/capita/day)**
Mexico	336.8	1042.59	26.86
USA	35.51	97.16	1.76
Ecuador	12.6	36.38	0.95

Source: own elaboration with data from http://maizeatlas.cimmyt.org/gis-web-viewer

Table 4.2 Contribution of maize grain in the daily necessary protein intake in Ecuador, Mexico, and USA.

	Protein from maize (g/capita/day)
Mexico	26.86
USA	1.76
Ecuador	0.95

Source: own elaboration with data from http://maizeatlas.cimmyt.org/gis-web-viewer

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[37] Estimated daily caloric intake needs range from 1,000 to 3,200, Kcal depending on age, gender and level of physical activity (http://www.cnpp.usda.gov/sites/default/files/usda_food_patterns/EstimatedCalorieNeedsPerDayTable.pdf).

[38] Daily safe levels of protein intake range from 9.4 gr to 47.4 gr in the case of infants, children and adolescent girls and boys, and from 33 to 66 gr in the case of adult women and men (WHO/FAO/UNU, 2002).

Box 4.1. Contribution of smallholder farmers to Mexico´s maize supply

Author: Mauricio Bellon

There is a common perception among urban elites in Mexico that smallholder maize farmers are unproductive and make a minimum contribution to the food security of the country. However, a review of the official data on maize production and the rural population that lives where this crop is produced challenges this view. According to official government statistics in 2010 -the same year of the last national census in Mexico- the bulk of maize production during the main rainy season under rainfed conditions took place in 1997 municipalities (out of 2270) with yields below 3 ton/ha and with an area planted of 4,686,955 ha (78.4% of the total area planted). Maize production in these municipalities was 5,936,955 ton (49.8% of the total rainfed production) with an average yield of 1.3 ton/ha (SIAP, 2010). These municipalities had a rural population of 21,396,614 people (INEGI, 2010). Assuming a daily per capita consumption of 267 grams of maize grain, equivalent to 97.5 kg (Ranum et al*.,* 2014), this level of production could feed about 61 million persons in one year. So in spite of the low yields observed there, maize supply needs of all rural population in these municipalities could be met, with surpluses to feed an additional 184.7% of the rural population. While there is no guarantee that in fact this production reaches all that population, these estimates provide a reasonable assessment of how local production contributes to fulfill maize needs of people in rural areas and shows that maize produced by smallholder farmers with low yields contributes substantially to the food maize supply of the country.

Source: Data from INEGI, 2010 and Ranum et al., 2014.

Maize also plays a fundamental role in the USA diet, but in the shape of feed, sweeteners, and other processed foods. During the last century, meat consumption in the USA increased in almost 200% (FAO, 2010). On average, Americans eat 300% more meat than the rest of the world (*ibid.*). While meat can be a good source of protein and other essential nutrients, it is estimated that Americans eat about 87.5 kg of beef, pork and/or chicken per capita every year or approximately 1.68 kg/week (Rabobank, 2016). According to the American Dietary Guidelines (2015-2020), the recommended weekly intake of meats, poultry, and eggs, at the 2,000-calorie level is 0.73 kg/week (U. S. Department of Health and Human Services and USA Department of Agriculture, 2015). This shows a clear excessive consumption of meat. Between 1970 and 2000 the per capita consumption of sugars increased by 20% in the USA The consumption of high-fructose corn syrup (HFCS) increased more than 1000% between 1970 and 1990, and currently accounts for over 40% of caloric sweeteners added to food and beverages (Franck et al., 2013). The higher demand of HFCS and meat, nationally and globally, has been a major driver of the expansion of highly specialized, intensive, industrialized production of genetically uniform maize (Miller and Spoolman, 2011; IPES-Food, 2016).

As discussed earlier in the section 2 key message 14, maize subsidies have deeply transformed the food system, not only in the U.S but globally. Federal agricultural subsidies focus on financing the production of corn and other cereals. A substantial proportion of these subsidized commodities are transformed into meat, dairy products, high-calorie sugar-sweetened beverages and processed and packaged foods (Franck et al., 2013). Between 30% to 40% of the subsidized maize in the USA is used as feed for cattle and livestock, and approximately 5% of the maize is used to produce HFCS (Siegel et al., 2016a). Since the USA produces about 80% of the total food consumed internally, and imports only 20%, domestic production is determinant of the local diet (*ibid*). The low cost of feeding animals translates into lower costs of raising them, which in turn has an effect on the relative prices of meat products (Franck et al., 2013). We have argued that soda producers who use HFCS in their products have largely benefited from maize subsidies in the USA (see sections 2 message 14). These and other large-scale food processors that also benefit from such savings translate them to the consumers (Franck et al., 2013). The low cost of maize allows retailers to increase calorie density at an insignificant cost (Nestle, 2003, Jackson et al., 2009, quoted in Franck et al., 2013). One of the main justifications of the 1973 Farm Bill was to guarantee to consumers a plentiful supply of food at a reasonable price. Indeed, maize subsidies have played an important role in providing plentiful amounts of processed foods and beverages containing HCFS and other food additives and ingredients derived from maize, as well as meat from maize-fed animals.

Health impacts associated to the consumption of subsidized maize

There is a substantial amount of evidence regarding the negative impacts of excessive meat consumption, particularly red and processed meats on heart disease and stroke (Sinha et al., 2009; Micha et al., 2010; Kaluza et al., 2012; Pan et al., 2012), but also on obesity (Wang and Beydoun, 2009; Vergnaud et al., 2010), type 2 diabetes (Micha et al., 2010; Pan et al., 2011), and certain cancers (Chao, 2005, Cross et al., 2007, Ma and Chapman, 2009, Pan et al., 2012; World Cancer Research Fund International, 2016, quoted in Johns Hopkins University, 2016). Sugar-sweetened beverages (SSB)[39] contain a high dose of calories from added sugars while delivering little or no nutrition. It is estimated that just the consumption of one soda per day increases the probability of being overweight by 55% for children and 27% for adults (American Heart Association, 2015). Evidence shows that the consumption of SSB is also related to metabolic dysfunction, diabetes, heart disease (Malik et al., 2010; Stanhope et al., 2015) and dental decay (Li et al., 2012)[40].

A recent study by Siegel et al. (2016a) investigated the impacts of higher consumption of foods and beverages derived from subsidized maize and other cereals on the development of cardio-metabolic risk factors in the USA Using data from the National Health and Nutrition Examination Survey (NHANES), the authors estimated an individual-level subsidy score that reflects individuals´ consumption of subsidized food commodities, including processed maize, as a percentage of their total caloric intake. It is estimated that about 56.2% of the total calories consumed by the 10,308 participating adults were derived from the main subsidized commodities. Results show that, controlling for sociodemographic and lifestyle factors, a higher consumption of calories from subsidized maize and other food commodities was associated with a greater probability of cardiometabolic risks. Consumers in the highest quartile of subsidized food had a 14% to 41% higher probability of cardiometabolic risks measured by BMI, abdominal adiposity, CRP level, and lipid levels.[41] In a previous study (Siegel et al., 2016b) it was shown that diets of individuals with higher subsidy score have lower nutritional quality, too.

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[39] SSB include soda, fruit drinks (other than pure fruit juice), sports and energy drinks, prepared teas and coffees that contain added caloric sweeteners like sugar or HFCS.

[40] Two meta-analyses have shown that studies funded by the industry are between 4 to 8 times more likely to conclude that SSB are not linked to negative health impacts (Bes-Rastrollo *et al*., 2013; Lesser *et al*., 2007).

[41] Given the incomplete nutritional and ingredient information for foods reported in the NHANES, the study could not directly calculate the amount of high-fructose corn syrup in foods or the exact proportion of subsidized meat that is consumed as processed vs. unprocessed.

The cost of treating obesity-related cardio-metabolic disease in the USA ranges between $150 billion-$300 billion USD per year, when considering indirect costs (Siegel et al., 2016a). Moreover, between 1995 and 2010, the USA government spent approximately $170 billion USD subsidizing the production of foods that were associated with obesity (*ibid.*). In the absence of obesity, Medicare spending would have been approximately 8% lower and Medicaid 12% lower between 2001-2006 (*ibid.*). Reducing the consumption of subsidized foods will not end with obesity but individuals whose diets contain lower proportions of subsidized foods have a lower probability of being obese (*ibid.*). Siegel et al. (2016a) urged to align agricultural and nutritional policies to improve people´s health, and propose a shift of agricultural subsidies for the production of fruits and vegetables. Over the past twenty years, the North American Free Trade Agreement has led to important changes in the consumption and production of maize and, in general, has transformed food systems in the United States and Mexico. Pre-NAFTA, Mexico had a stringent regulation of maize and other grain imports. Duty-free sorghum was, with maize, the leading feed grain imported by Mexico. Taxes maintained the trade of processed foods at low levels. Pre-NAFTA, trade of sugar and HFCS was negligible. Currently, maize is the leading feed commodity imported by Mexico from the USA. Since NAFTA, USA meat imports to Mexico doubled in volume; HFCS imports increased 863%; and USA investment in Mexican food manufacturing tripled. Mexico is currently facing a public health crisis due to overweigh and obesity: official statistics reveal that 35% of children and teenagers, and 73% of the adults are either obese or overweigh (Secretaría de Salud, 2012). Approximately 14% of adults are diagnosed with diabetes. Only the costs related to diabetes represent between 4.4 and 5.3 billion USD, equivalent to 73% and 87% of the programmed total public expenditure on health in 2012 (IMCO, 2015). Soda producers are the main consumers of HFCS (Harvie and Wise, 2009) and Mexicans are some of the main consumers of soda worldwide. The consumption of sugar-sweetened beverages (SSB) represents 70% of the daily intake of added sugars by Mexicans (Sánchez-Pimenta et al., 2016). It is estimated that Mexico has the greatest number of SSB-attributable disability-adjusted life years (DALYs) with 3,960, per million adults (1,516-13,990) (Singh et al., 2015). In the USA there were 2,087 (2050-5180) DALYs per million adults attributable to the consumption SSB in 2010 (*ibid.*).

In sum, maize plays an important role in the diet of these three maize-producing countries, but in different ways. Even though maize is produced for self-consumption in Ecuador, most of the maize production in the country is used by the poultry industry. In Mexico, maize for human consumption is mostly based on the preparation of dough. The per capita daily calorific intake from maize grain in Mexico, mainly in the shape of tortillas and other traditional maize-based foods and drinks, is over one thousand kilocalories, compared to 97 in the U.S and 36 in Ecuador. Maize also plays a fundamental role in the US diet, but in the shape of feed, sweeteners and other processed foods.

5. EXTERNALITIES OF MAIZE SYSTEMS: NON-MONETARY VALUATIONS

5. Externalities of Maize Systems: Non-Monetary Valuations

5.1 Dependency of global systems on maize genetic diversity

Authors: Caroline Burgeff, Alicia Mastretta-Yanes and Francisca Acevedo

Introduction

Maize is fundamental in Mesoamerican cultures and has played a key role in the development of these civilizations, becoming a keystone species and a pillar of the *milpa* traditional production systems (Benitez et al., 2014). In places such as Mexico, it forms the base of human food systems and their cultural expressions which are tightly aligned throughout the country. Food security and food sovereignty have relied heavily on the temporal and spatial availability of maize. A very strong interrelationship between these plants and humans has been created over thousands of years, leading to a positive and very fruitful interdependency, particularly where the greatest genetic diversity is present in both the cultivated and wild expressions, especially in Mexico (for recent revisions see Kato et al., 2009 and Aguirre-Liguori et al., 2016). At the world level, some cultures, such as in several countries in Latin America and Africa have used maize as a staple food. Others have used it as a cereal for food, feed and also recently for fuel. Its important role at a global level is undeniable, and it is present in all markets, geographies, economies, environments, cultures and households.

Maize was domesticated in Mexico around 9000 years ago, most likely from Balsas teocintle or teosinte, a tropical lowland grass (*Z. mays* ssp. *parviglumis*; Matsuoka et al., 2002; van Heerwaarden et al., 2011) in a process that involved crossing with a highland teosinte from the Transmexican Volcanic Belt (*Z. mays* ssp. *mexicana*: van Heerwaarden et al., 2011; Hufford et al., 2012). Around 5000 years after its initial domestication, maize spread from its center of origin and genetic diversity in Mesoamerica to the rest of the American continent, and subsequently to the rest of the world (Vigouroux et al., 2011) where, thanks to its productivity, plasticity and adaptability, it has become one of the three most commonly used cereals. The result of this history is that, considering landraces and modern maize lines, maize is one of the most commonly grown crops worldwide and is adapted to both tropical and temperate environments, from sea level to close to the timberline and from 400 to 3,555 mm in growing season rainfall (Ruiz Corral et al., 2008; Fig. 5.1). Such a range of adaptation was possible for two main reasons. Firstly, the genetic diversity extant at the time of domestication in Balsas teosinte (*Zea mays* ssp. *parviglumis*) and the new genetic features provided by the early introgression with its more temperate highland relative (*Z. mays* ssp. *mexicana*); it may therefore be no coincidence that, of all the major crops, maize is the species that retains more of the genetic diversity present in its wild relative following domestication (80%; Hufford et al., 2012). It is interesting that, to date, in some parts of Mexico, maize is grown in a system that allows gene flow with the teosintes (Wilkes, 1977). Secondly, from the local adaptation that arises through natural selection from maintaining landraces in a wide range of environments. In other words, the maize germplasm has adapted along geographic and climatically diverse distribution areas for at least 9000 years in the case of maize as a crop, and for millions of years in the case of its wild relatives (For a review on the genetic and evolutionary principles implied in domestication and modern plant breeding see Box 5.1). As a consequence, the huge range of maize phenotypes and the total genetic potential for yield increase that has been achieved by modern breeding came from developing new arrangements of the native genetic diversity (Smith et al., 2015). To this dependency, we must add that while breeding has focused on producing "pure" lines, breeding programs have continuously introduced exotic materials for their ability to provide beneficial genetic responses, especially to new or unusual sources of stress, but also to produce increased yields (Lewis and Goodman, 2003; Duvick, 2005; Smith et al., 2015).

BOX 5.1. Genetic and evolutionary principles implied in domestication and modern plant breeding

Author: Alicia Mastretta-Yanes

Human management of crops through domestication and modern plant breeding is an evolutionary process that modifies the genetic diversity of the species involved. In particular, two main evolutionary forces influence the genetic diversity of crop species: artificial selection and genetic drift. The influence of artificial selection and genetic drift was highest at two main points; firstly, during the early stages of domestication and, more recently, during modern plant breeding. In this section, we explain the genetic basis behind artificial selection, genetic drift and other evolutionary mechanisms that take place in agriculture.

Domestication, traditional agriculture and modern plant breeding imply the human selection of plants with desired traits (*i.e.* selection of specific phenotypes) that are generated by given genetic characteristics (genotypes). In other words, domesticated plants were and still are subject to an artificial selection. At the same time, crops also undergo natural selection, since survival rates still depend to some extent on how the plant responds to environmental conditions, day length, pathogens and other external conditions that are beyond human control. Both artificial and natural selection represent evolutionary mechanisms that tend to reduce the genetic diversity of a given population by promoting the reproduction (and hence the transmission of inheritable genetic characteristics to their offspring) of certain genotypes but not others.

Domestication and plant breeding also imply genetic drift, i.e. random fluctuations in genotype proportions. This occurs because the selection process does not involve all individuals in a population, but only a sample of them (*i.e.* farmers chose only a batch of seeds to use in the next cycle and not the entire complement of seeds produced) and seeking only the desired traits while disregarding others. Such "disregarded traits" may be of no interest to the human making the selection, or may be "invisible" if they do not imply something that is visually apparent (for example, the presence of plant chemicals useful to combat pathogens). As a consequence, by a random process related to frequency (more abundant genotypes have higher probabilities to pass by simple chance), some genotypes will be present in the next generation but not others.

…Box 5.1 continued

Genetic drift and selection also affect genomes in different ways due to the loci they can act upon. Specifically, genetic drift acts at the same rate on all loci in a genome, while selection proceeds largely independently at different loci. This means that few loci can be under strong selection while the rest of the genome varies. For example, Hufford et al. (2012) identified 484 candidate loci associated with the domestication of maize, in which the strength of selection is more than an order of magnitude higher than that found across the rest of the genome. Another important factor determining how selection modifies a genome is the fact that, physically speaking, genes are part of the threads of DNA arranged in chromosomes and hence some loci are in close proximity to these threads while others are more distant. This means that if one gene becomes under artificial selection and thus increases its frequency in the next generation, the neighboring DNA regions will also be transmitted to the next generation as if they too under selection. When this happens, loci are said to be under linkage disequilibrium. This phenomenon can be broken by recombination, a process that occurs during the cell division necessary for sexual reproduction, in which pieces of DNA are broken and recombined to produce new combinations of alleles. In general, the closer genes are to one another, the more likely it is that they are linked and the more crosses would be necessary for recombination to break such a linkage. This can have an important effect on genetic diversity in the context of plant breeding, to the extent that some traits are present in cultivars not because they were desired, but because the genes responsible for these traits are linked to others under strong selection.

The evolutionary and genetic phenomena described here occur naturally in wild populations, but agriculture has changed the speed and magnitude in which they can affect the genetic diversity of the species.

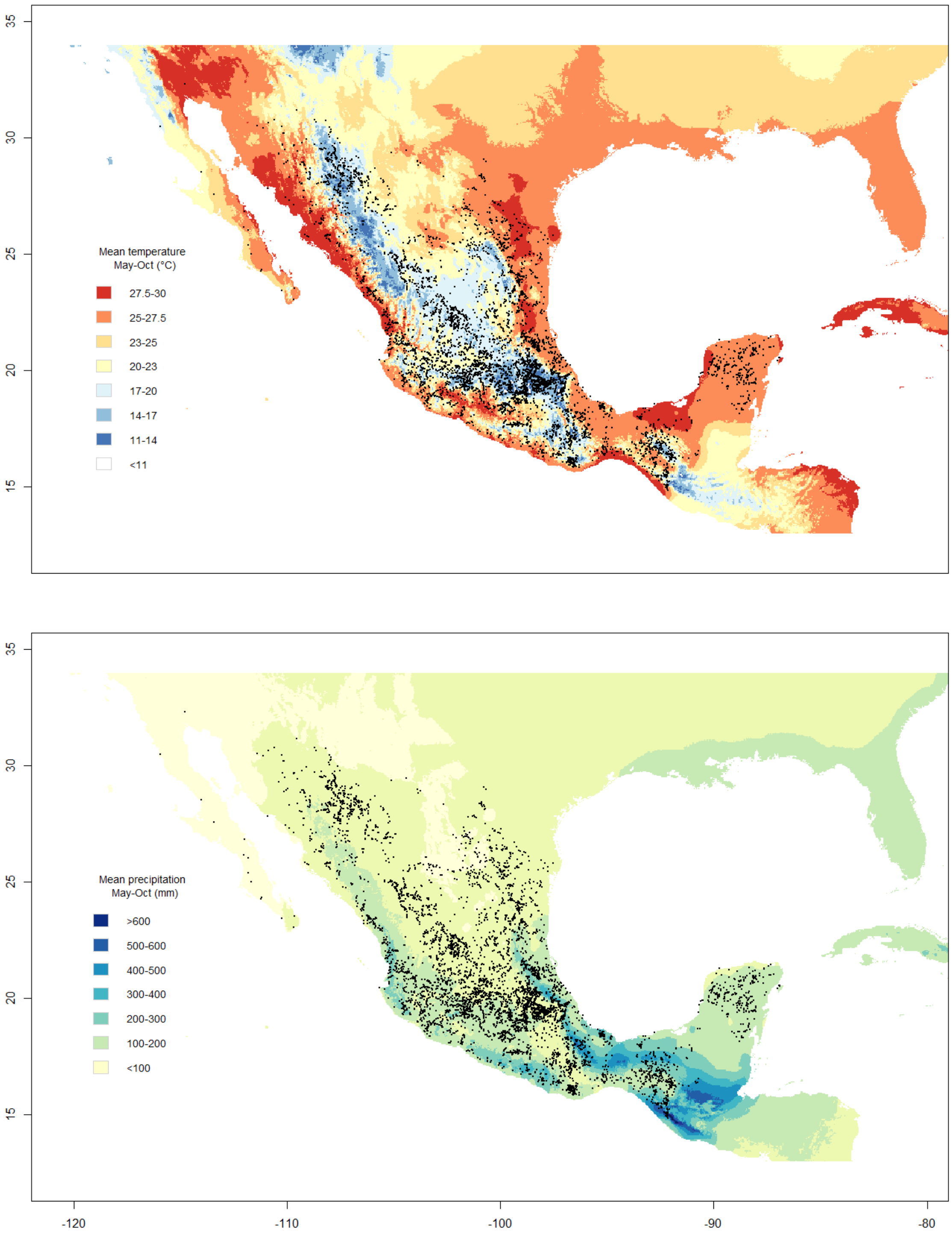

Figure 5.1 Mexican maize landraces (black dots) are grown in a wide range of environmental conditions, as illustrated by mean temperature (top) and precipitation (bottom) during the months of rainfed agriculture. Data from Cuervo-Robayo et al. (2014) and the Global Maize Project (CONABIO, 2011b). Note that some points fall within areas with <400 mm mean precipitation rainfall; this could be due to incomplete sampling of studies reporting the environmental conditions of maize cultivation, or to the presence of residual humidity or the use of particular landraces and management practices.

As with any other globally cultivated crop, maize must cope with ever changing climatic and productive conditions, and this depends on existing and future sources of genetic variability; i.e., the diverse genetic combinations that are produced by and required to confront both biotic and abiotic stresses. The necessary genetics are present in the wealth of maize diversity that exists both in the crop wild relatives and in the cultivated form (maize), which exceeds that found in any other species known to man (see Goodman, 2011) and represents a priceless biological, cultural, social, and economic heritage for humanity. This genetic variability preserved and used by traditional smallholder maize farmers represents a global public good and as such must be valued (Bellon et al., 2015).

Maize wild relatives, teosintes and the grasses of the *Tripsacum* genus, are present in natural environments and constitute a wealth of genetic diversity to be saved, conserved, understood and potentially used (see a brief summary of a monetary valuation performed by Price Waterhouse Cooper of the potential significance of conserving crop wild relatives). Nevertheless, their extension and habitats, especially for the case of the teocintle populations which are principally present in Mexico (see CONABIO's webpage on teosintes), are being greatly reduced particularly due to human activities (Sánchez, 2011).

Maize production systems have been presented through a typology earlier in this document (section 3). Although every single system depends on the availability of genetic diversity, the extent of that dependency is different in relation to maize genetic diversity, for example, in terms of the nature of the diversity required for the crop in each setting, as well as in terms of the way in which the farmer accesses the diversity to propagate (i.e. seeds in the case of maize). The nature and degree to which each system depends on genetic diversity will be illustrated through the following two most contrasting and divergent maize production systems: i.- intensive maize production and ii.- smallholders using maize traditional practices (Fig. 5.2).

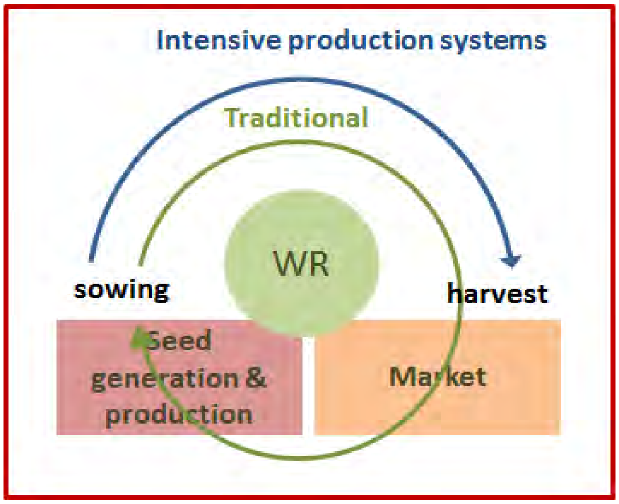

Figure 5.2 Schematic representation of the "life cycle" of maize seeds in intensive vs traditional smallholder production systems, where the former has a starting and a finishing point while the latter is cyclic, retaining part of the production to start a new cycle (WR are "wild relatives").

The dependency of intensive maize production on maize genetic diversity

Intensive maize production systems as we know them now, are linked to the generation of hybrid maize lines first developed in the US during the first half of the last century (for a review on maize hybrid history see Box 5.2, and Crow, 1998). Maize production with hybrids relies on hybrid vigor, which is obtained through the genetic crosses of two or four inbred lines whose combination allows the expression of exceptional characteristics in the maize plants produced. The development of this technology modified maize production in the USA in just few years, where at the half of the 20th century most of the crop was produced with hybrids. This kind of seeds are usually the result of breeding programs that seek predominantly to enhance yield, permitting the use of mechanization, high plant density, fertilizer and agrochemical inputs; they are suitable for well controlled environments and their production is very uniform and has characteristics related to the global uses of the crop (*i.e.* feed and industrial uses). Nevertheless, other characteristics such as resistance to certain pests and pathogens, and adaptations for example to temperate latitudes have also been fostered in some cases. Hybrid seed production has been coupled to the development of modern plant breeding and in field experimentation programs, held by the public or private sectors. To maintain hybrid vigor and its yield advantage, seed has to be bought each planting season because seed recycling will lead to a decrease in yields. A strong incentive to purchase seed every season exists, and thus a larger market than if seed was recycled.

BOX 5.2. A brief history of modern maize breeding and hybrid maize

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Around 9,000-10,000 years ago, the pre-Hispanic inhabitants of Mexico domesticated maize from a lowland tropical teosinte (*Z. m. ssp. parviglumis*) and mixed it with a highland more temperate teosinte (*Z. m. ssp. mexicana*: Doebley, 2004; Hufford et al., 2012), eventually producing the 59 landraces currently recognized in Mexico (CONABIO, 2011). Derived from Mexican maize landraces, Flint Corn arrived to the southwestern US about 3,000 years ago and Dent Corn arrived to the southeastern US 500 years ago (Troyer, 1999). At the end of the 19th and beginning of the 20th century, modern plant breeding of maize began in the US using the Flint and Dent corns as base material. At first, this was mostly done by farmers who performed mass selection of open-pollinated landraces (era 0 of maize breeding history, according to van Heerwaarden et al., 2012). The first southern Corn Belt of the 1830s (Tennessee, Kentucky, and Virginia) then moved northwest (Iowa, Illinois, and Missouri) by 1880, and therefore shorter-season, more drought tolerant cultivars were developed (Troyer, 1999). Around 1000 open-pollinated cultivars were produced from natural and artificial selection in flint x dent backgrounds, from which a few cultivars were widely adapted and became popular. The adaptation of these cultivars was shaped by natural selection based on climate and soil type as well as by artificial selection based on personal experience and cultural preference (Troyer, 1999).

Scientific research then came into play, focusing on developing early inbred lines, i.e. lines of genetically similar individuals that are bred with each other, producing uniform progenies (Crow 1998; van Heerwaarden et al., 2012). This allowed selection of certain desired agronomic traits and produced more uniform fields, which was desirable in terms of ease of labor. However, yield was not very responsive, and moreover it became evident that inbred lines deteriorate considerably in yield and vigor over a few generations (East, 1908; Shull, 1908). This occurs because inbreeding increases the homozygosity of individuals, which in turn allows detrimental recessive alleles to produce deleterious phenotypes and increases the homozygosity for alleles at loci with a heterozygote advantage. However, Shull (1908, 1909) discovered that hybrids (the product of crosses between different inbreed lines) recovered or even increased in yield. This phenomenon is known as heterosis or hybrid vigor. Heterosis leads to enhanced growth and uniformity, increased total biomass, resistance to several sources of stress and increased grain yield. The genetic basis behind heterosis involves different mechanisms, but the key aspect is that crossing genetically distinct individuals generates heterozygosity and introduces new combinations of alleles (Chen 2013; Schnable and Springer, 2013).

The hybrid method was widely adopted across experiment stations by the 1920s, and started to spread to agricultural fields during the 1930s (era 1; van Heerwaarden et al., 2012a). At the beginning, Jones' (1922) method of double-cross hybrids (crossing two inbred lines and crossing that hybrid with the hybrid of two other inbred lines) was used because it produced abundant seeds in a more practical way than could be produced with single-crosses of the inbred lines of the time, since their yields were too small (Crow, 1998).

...Box 5.2 continued

However, single-cross hybrids were higher yielding than double-crosses and even more uniform (Cockerham, 1961). Therefore, inbred lines were selected for high seed production, eventually allowing the cost-effective production of single-cross hybrids (Crow, 1998). Hybrid maize began to be rapidly accepted, not only because of its high yield, but also because: 1) a severe drought hit the US during 1934-36 and the open-pollinated varieties in use at that time were susceptible to drought, but some the hybrid lines proved to be more resistant, and 2) hybrids tend to be phenotypically uniform, which is useful for the machine harvesting that replaced human labor that was required in the factories and military during World War II (Crow 1998; Hoegemeyer 2014). As a result, by the end of the 1950s, most of the maize grown in the US was hybrid. However, producing the parental inbred lines involves considerable effort (Crow, 1998) and when hybrids in a field are allowed to pollinate amongst themselves, the resulting offspring lacks most of the desired effects of heterosis, thus making farmers dependent on the external provision of seed. This is the basis of the hybrid corn seed industry and explains why maize breeding moved from being based on public inbred lines (1950-1980, era 2) to elite commercial inbred lines (post-1985, era 3; van Heerwaarden et al., 2012a).

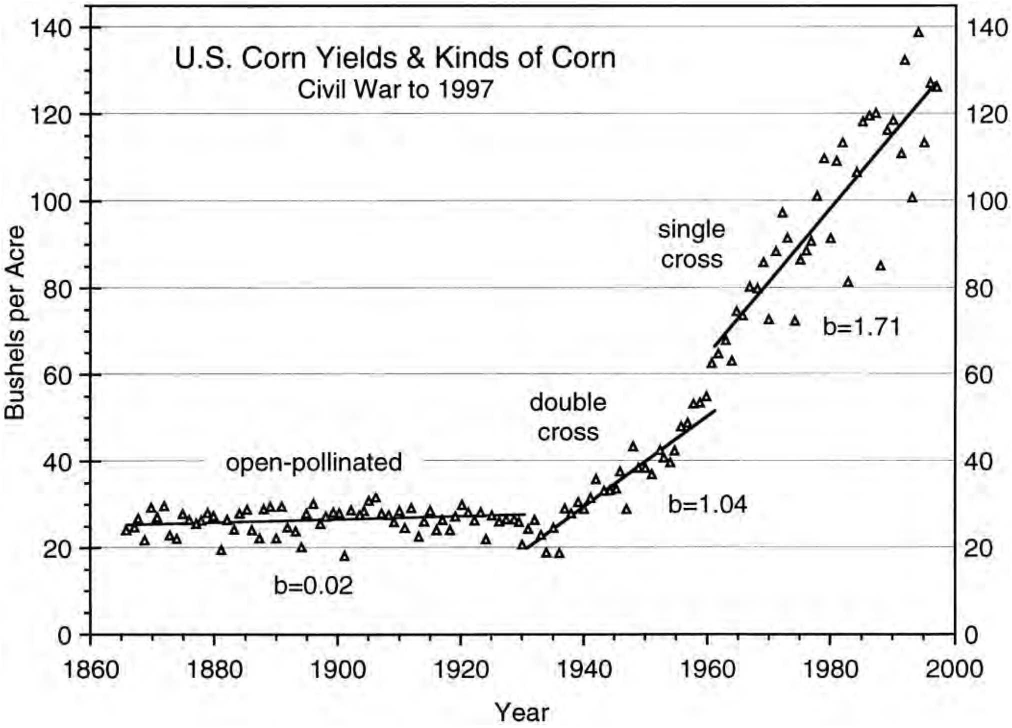

Figure B.5.2.1. Maize yield in bushels per acre in the United States of America. The periods dominated by open-pollinated, four-way crosses, and two-way crosses are indicated, along with regression coefficients (bushel/acre). Taken from Crow (1998), originally draw by Troyer (1999) with data compiled by the United States Department of Agriculture.

...Box 5.2 continued

The development of maize hybrids allowed a considerable increase in the productivity of maize yield per acre in the United States (fig. B.5.2.1). This increase has been the main argument of the advocates of maize hybrids and the associated high-input agriculture. However, we must highlight that crop and farming practices evolved together. As a result, around 50-60% of this yield improvement is due to the genetics, while the rest is explained by the use of fertilizers and herbicides, and by having a greater density of plants (Duvick, 2005), which implies that the slopes from Fig. B.5.2.1. are considerably less dramatic (Fig. B.5.2.2) and has also incurred an associated environmental cost through promoting such high-input type of agriculture.

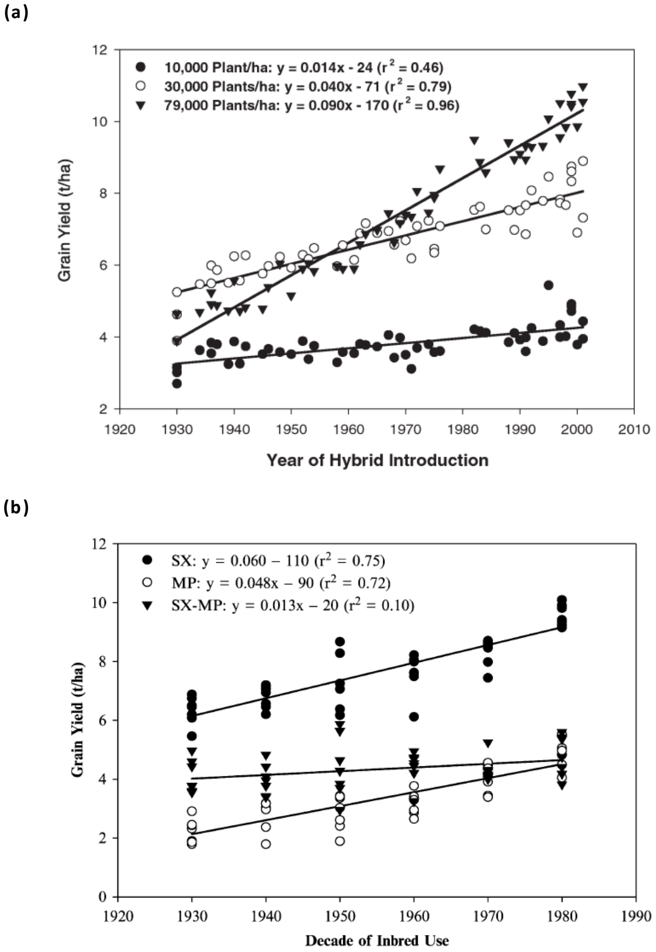

Figure B.5.2.2. Comparison of representative single crosses (SX) and their parental inbreds (MP) representing successful Iowa hybrids for 1930-1980. (a) Grain yield per hybrid regressed on year of hybrid introduction at each of the three plant densities (10, 30 and 79 thousand plants/ha) based on trials grown in 1991 to 2001. There is a strong interaction between the time when the hybrid was developed and plant density in regard to their effects on grain yield. (b) Grain yield of trials grown in different locations and times (three locations in 1992 and two in 1993) at several densities (30,000, 54,000 and 79,000 plants per ha). Yields of inbreds and their single crosses (as averaged across densities and years) increased simultaneously and by nearly the same amount in each decade and absolute heterosis (SX-MP) increased minimally. Taken from Duvick et al., (2003).

Nevertheless, from a genetic point of view, these kind of breeding programs generally have relied on a low initial genetic variability compared to more traditional producing systems. In the USA, for example, only around half a dozen open-pollinated varieties of Corn Belt Dent have had a significant contribution to the current inbred lines (Goodman, 1990; Nass and Paterniani, 2000; Troyer, 2004; Lee and Tracy, 2009). The uniformity of genetic background of crops makes them vulnerable to pests, pathogens and other stressing factors (NAS, 1974, 1975). In some of these extreme situations, genetic resources from landraces and wild relatives have contributed to the recovery of pre-existing production levels. Such is the case of genetic resistance genes to the Southern corn blight (Maxted et al., 1997; Redden et al., 2015). The low variability present in intensive maize agriculture, its consequences and externalities will be further developed in the section 5.3 Genetic externalities of maize production in intensive and smallholders systems.

The dependency of smallholders using traditional practices on maize genetic diversity

In Latin America around 220 maize landraces have been formerly described (Goodman and Bird, 1977), 59 of these have been identified and described as native to Mexico, where 64 are currently grown (Anderson, 1946; Wellhausen et al., 1951; Hernández and Alanís, 1970; Sánchez, 1989; Sánchez et al., 2000; CONABIO, 2011). The extent of the distribution and morphological variation of these landraces can be better visualized in the online Explorer of the Global Maize Project developed by CONABIO as well as in CONABIO's web page on Mexican maize landraces.

In Mexico maize landraces are mainly produced by smallholders that have agriculture fields of no more than 5 ha, who represent around 85% of the total maize farmers in the country (estimated by some publications in a range of 2 to 3.1 millions) (Polanco and Flores, 2008; SIAP, 2008). Most of their production is carried out in rain dependent fields which constitute ca. 85.5 % from the total average surface cultivated with maize in Mexico, (covering an average of 8.4 million ha between 1996-2006) (SIAP, 2008). This kind of smallholders generally follow traditional practices that have generated and rely on these landraces for their subsistence.

Ancestors of these traditional farmers in prehispanic Mexico domesticated maize (Piperno et al., 2009; van Heerwaarden et al., 2011). Maize became a fundamental crop for the different Mesoamerican cultures and was adapted to grow in a wide range of environments under traditional management systems using open-pollinated varieties for thousands of years, producing most of the maize landraces that we know today (the effects on genetic diversity of this are discussed in section 5.1 Genetic externalities of maize production in intensive and smallholders systems. After the discovery of the New World and conquest of Latin America, maize was introduced in multiple occasions to different parts of the world, and through time local landraces & varieties of maize were also generated in regions as Europe or Africa, although in some cases their use has decreased with the adoption of intensive farming practices (Gouesnard et al., 2005; Westengen *et al.*, 2012).

Small traditional production, conducted in multiple climatic contexts and in many cases in marginal settings, is the extreme example of how maize copes with ever changing climatic and productive conditions, and to do so, depends on existing and future sources of genetic variability, that is, the diverse genetic combinations that result from and are needed to confront biotic and abiotic stresses. At a local level small scale producers exploit genetic diversity, making use of it at the species, cultivar and "intra cultivar" level, which is a way to dilute the risk of variable abiotic or biotic stresses (Ceccarelli et al., 2013).

The selection goals of smallholders might be very different depending on the particular characteristics of the local environment and producer's interests, and may not be necessarily focused on yield maximization; other traits, such as color or grain quality, might be more appreciated. In the case of Mexico, for example, local landraces present great ranges of variability in morphology and physiology (plant and ear height, number of ears per plant, size and number of husks, ear size, number of grain rows; grain size, texture and color; life cycle length) agronomical traits (yield, pest and disease resistance, combining ability), as well as adaptation to diverse environmental conditions (altitude, soil types, slope, luminosity, humidity, precipitation, temperature) and uses (CONABIO 2011b; see examples in table 5.1).

Table 5.1 Examples of characteristics of some Mexican landraces. Many of the descriptions in this table come from information gathered in the Proyecto Global de Maíces Nativos (CONABIO, 2011), CONABIO's webpage on Mexican maize landraces and one workshop that was held with maize experts during the project.

Characteristics	Examples of landraces exhibiting such characteristics	References (non exhaustive)
	Adaptation to particular growing conditions	
Low altitude	Nal-Tel, Dzit-Bacal, Zapalote Chico, Tuxpeño	CONABIO, 2011
Intermediate altitude	Celaya, Olotillo, Elotes Occidentales	CONABIO, 2011
Highlands	Olotón, Cónico, Palomero Toluqueño, Apachito, Azul	CONABIO, 2011
Limiting environmental conditions where hybrids and other improved materials cannot prosper	Chalqueño, Cónico, Cónico Norteño, Conejo, Apachito, Cristalino de Chihuahua, Nal-Tel, Olotillo, Tepecintle	Bellon and Risopolous, 2001; Muñoz 2003; Ramírez et al., 2005; Widstrom et al., 2003; CONABIO, 2011
Cloudy o high relative humidity mountain regions	*Arrocillo, Olotón, Coscomatepec, Tepecintle*	CONABIO, 2011
High humidity or flooded soils	Tuxpeño, Jala	CONABIO, 2011
Resistance to pests and pathogens	Zapalote chico, Tuxpeño, Olotón	Bellon and Risopolous, 2001; Muñoz, 2003; Ramírez et al., 2005; Widstrom et al., 2003; CONABIO, 2011
Drought resistance or drought escape mechanisms	Nal-Tel, Conejo, Ratón, Cónico Norteño (population ZAC-58), Chalqueño (population MICH-21) have been used in breeding programs	Wellhausen et al., 1951; Muñoz, 2003; Avendaño et al., 2005; CONABIO, 2011
	Particular agronomic characteristics	
Short life cycle	Nal-Tel, Zapalote Chico, Conejo, Ratón. These landraces can be cultivated and harvested more than once in a year; Precocious crops can be used for early consumption while long cycle landraces are ready to harvest.	Muñoz, 2003; CONABIO, 2011
	Specific grain or ear uses	
Corn on the cob	Cacahuacintle and Elotes Cónicos in Central Mexico; Dulce, Elotes Occidentales and Elotero de Sinaloa in the west, Comiteco in Chiapas	Hernández-Xolocotzi, 1985; Muñoz, 2003; Aragón et al., 2005; SOMEFI, 2007; Vidal et al., 2008;

Pinole	Chapalote, Reventador	SOMEFI, 2009; CONABIO, 2011b.
Ponteduro	Dulce, Dulcillo del noroeste	
Coricos	Blando	
Pozoles o menudos norteños	Gordo, Blando, Elotes Occidentales and Bofo in the west, Cacahuacintle in the centre; Ancho in Morelos, Guerrero, Michoacán and Jalisco	
Tortillas blanditas, tlayudas gigantes	Bolita, Tepecintle	
Pozol	Tuxpeño tepecintle, nal-tel, olotón	
	Uses of other parts of the plant	
Forrage	Zamorano Amarilo, Cónico Zapalote chico	*ibid*.
Use of husks	Pepitilla, Chalqueño, Jala	
Chemical compounds of colored maize grains (anthocianins, flavonoids, beta caroten and xantophylls)	Colored varieties from several landraces	Neri et al. 2007, Sánchez-Villafuerte et al., 2007; CONABIO, 2011b

Local landraces tend to have a better performance in the areas where they are traditionally grown, than improved varieties, in terms of nutritional value, forage quality, local appreciated taste, or precocity (Perales 1996; Muñoz, 2003; Rodríguez et al., 2007; SOMEFI, 2007, 2009; Gonzalez-Amaro, 2016). These kind of limiting conditions, do not meet the minimum requirements improved maize hybrids need to grow and produce. In other words, under suboptimal and even marginal agronomic conditions maize can only produce thanks to the adaptation of these landraces to such growing conditions, and the maize produced that way plays an important role in the diets of local communities.

The need of genetic diversity in traditional productive settings has been self-maintained through time thanks to the practices of seed selection and exchange and in field experimentation that have been held by farmers for centuries (Bellon and Brush, 1994; Badstue et al., 2006; Ceccarelli et al., 2013) submitting the crop to both artificial and natural selection, as well as genetic drift (See Box 5.1). Through these practices small traditional producers have been ensuring the process of diversity generation. This aspect will be further developed in 5.1 Genetic externalities of maize production in intensive and smallholders systems.

Wild relatives of maize, in particular teosinte, present mainly in the western and central regions of Mexico, have contributed recurrently to broaden the genetic diversity of cultivated maize (Wilkes, 1977; Matsuoka et al., 2002; Hufford et al., 2013). Still nowadays, in some regions traditional farmers tolerate or foster the presence of teosintes in their fields to allow genetic exchange with their landraces (Wilkes, 1977; Sánchez, 2011).

The use of local landraces is in some cases associated to polyculture production in traditional agroforestry systems such as the milpas in Mexico (Moreno Calles et al., 2012; 2013). The level of associated diversity is higher in traditional polyculture systems than in more intensive production settings where the use of agrochemicals has a negative impact for example in insect diversity (Ceccarelli et al., 2013).

On the other hand, agrobiodiversity is used as a natural insurance because it complements and facilitates the required beneficial interactions between planned and associated biodiversity (Altieri, 1999; Ceccarelli et al.,

2013) contributing to agricultural production through the nutrient cycling, pest and disease control, and pollination (Wood and Lenne, 1999; Cassman et al., 2005).

Genetic diversity and the interdependency of maize production systems

The two examples of production systems considered in the previous sections show that their relationship with maize genetic diversity is the result of a particular historical, social, productive, geographical and environmental context.

Traditional production systems remain to this day thanks to the empirical practices of farmers where recurrent selection and experimentation have shaped the crop to their needs. On the other hand, intensive production systems depend on improved seeds generated by the public or private sector and are responsible of most of the world maize production for feed and industrial uses. "What makes the landraces and wild crop relatives valuable is exactly what separates them from seeds that satisfy the various seed laws. Whereas commercial seeds have to be genetically stable, land races are genetically dynamic. Moreover, this feature is more valuable the wider the range of environmental conditions in which landraces are grown. Having large numbers of small-scale farmers growing landraces in many different environments is likely to help generate the raw material for plant breeding to meet the challenges posed by climate change" (C. Perrings, pers. comm.).

Small traditional maize producers have been able to feed and nurture themselves and others during thousands of years thanks to: i) the genetic diversity present in the local maize landraces that allow the crop to adapt to different environmental conditions, as well as ii) by allowing the simultaneous use of multiple landraces in the same field, in some cases in combination with other crops and as well as with maize wild relatives. This exists in many different regions where maize production is primarily directed to self-consumption.

Global maize production depends on genetically diverse germplasm; in other words, the huge range of maize phenotypes and the total genetic potential for yield increase, as well as other useful traits introduced that have been achieved by modern breeding come from developing new arrangements of native genetic diversity (Lewis and Goodman, 2003; Duvick, 2005; Smith et al., 2015) generated through traditional production systems and crop wild relatives. Even the Corn Belt maize hybrids were initially possible thanks to two local US landraces that provided the necessary adaptation to the daylight and temperate conditions of the US, and with which still share most of their genetic background (Troyer, 2004; Duvick, 2005). The dependency of maize on genetically diverse germplasm and the potential of pre-existent local adaptation need to be further valued in order to count with a wide range of genetic options to face scenarios of climatic change.

Efforts to preserve genetic diversity have been directed through field plant collections and genebanks that integrate the seed samples of interest for *ex situ* conservation and use in breeding programs.[42] The broader the germplasm representation in genebanks, the wider the potential possibilities for breeding programs, although in

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[42] See recent collections performed as part of the Global Maize Project for Mexico as well as *ex situ* collections maintained both at the international (e.g. CIMMYT Germplasm Bank and Svalbard Global Seed Vault) and national levels (see SINAREFI's Maize Network as an example in the case of Mexico).

many cases germplasm banks are underutilized (Perales, 2016). These materials mainly come from local landraces, breeding programs, and to some extent from wild relatives (still underrepresented) (Castañeda-Alvarez et al., 2016). However, gene banks represent a fixed sample of the evolutionary process, because they do not capture the continuous changes that occur in the field as the crop is subjected year after year to natural and artificial selection. *In situ* conservation of genetic diversity including maize wild relatives, the maize landraces, and the existing intricate relationship of farmers and users with the biological resources, through their traditional practices, must be strongly supported as a very important complementary strategy to the efforts in *ex situ* conservation so as to assure the continuous generation and evolution of the necessary genetic combinations to feed future maize production worldwide.

Maize germplasm has been used and exported to the world as the genetic basis for a high percentage of what is used both in the public and private sector in relation to new varieties, from Research & Development to commercial seed production worldwide (Salhuana et al., 1997; Morris and López-Pereira, 1999; Morris, 2002; Pollak, 2003). Morris and López-Pereira (1999) indicated that in Latin America nearly three quarters of the varieties and the hybrids released generated by national breeding programs and 80% of those materials generated by private-seed industry (these latter without considering Argentina) contained germplasm from the CIMMYT maize collection, whose use was mainly concentrated in lowland tropical materials. It can be argued that investments in research and development show the minimum costs society has been willing to undertake to use and conserve maize varieties (See Box 5.3 for some of the information generated in this subject). Many additional aspects are missing; additional data should be gathered in the future and efforts should be undertaken as to attempt to measure and value the contribution made by existing maize genetic resources used in breeding and the diverse production efforts.

Box 5.3 Investment and research performed in maize breeding and Mexican landraces and teosintes studies

Authors: Caroline Burgeff and Francisca Acevedo

Global breeding efforts

While it is difficult to have a clear estimate of what the financial investment for the establishment and maintenance of maize germplasm collections, as well as maize improvement, breeding and research programs worldwide, have represented (in monetary costs), some data have been gathered that might help towards an initial (non-exhaustive) approximation. Different estimates of the investment into maize research and improvements made between 1966 and 1998 have been proposed in CIMMYT publications (Morris, 2002). The data indicate that, during this period, the institution invested between US $8 and US $18 million per year in the genetic improvement of maize (for details of the estimation, see Morris, 2002).

Another interesting estimate made is that of the expenditure on maize research personnel in the regions of Latin America, Africa and Asia, which totals US $ 21.3 million per year in the public sector, and US $ 38.7 million per year in the private sector. This also indicates that direct personnel support accounts for around 40-50% of the total operating costs of a maize breeding program. Therefore, doubling the previous amounts can provide a rough approximation of the level of investment made in maize improvement in these regions of the world (Morris, 2002).

Maize breeding and improvement programs have been developed around the world. The limited genetic base of US germplasm and the vulnerability this represents (NAS, 1975) have motivated efforts such as the Germplasm Enhancement of Maize project (see GEM project), a public/private cooperation effort that was directed towards improving the germplasm base of maize hybrids by including “exotic” germplasm from the Latin American Maize Project (LAMP) as a source for breeding programs in the US (Pollak, 2003). In the LAMP, twelve Latin American countries cooperated to evaluate their native maize landraces for characteristics such as yield and agronomic type, and received funding of US $ 1.5 million in 1987 from Pioneer Hi-Bred International (Salhauna et al., 1997, quoted in Pollak 2003). Since the LAMP project, other breeding efforts involving Latin American materials have also been undertaken (see Taba et al., 2005).

...Box 5.3 continued

Information on Mexican maize landraces and wild relatives

The goal of the "*Proyecto global Recopilación, generación, actualización y análisis de información acerca de la diversidad genética de maíces y sus parientes silvestres en México*" (also known as the "*Proyecto Global de Maíces*" or Global maize project) was to update the information about the diversity of maize and its wild crop relatives in Mexico in order to provide data for determination of the centers of genetic diversity in the context of the National Biosafety Law. The project was financed by SEMARNAT (*Secretaría del Medio Ambiente y Recursos Naturales*), CIBIOGEM (*Comisión Intersecretarial de Organismos Genéticamente Modificados*) and SAGARPA (*Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación*), with a total of 15 million Mexican pesos (*ca.* US $ 1 million). The project, which was led by CONABIO (*Comisión Nacional para el Conocimiento y Uso de la Biodiversidad*) in coordination with the INE (*Instituto Nacional de Ecología*), and INIFAP (*Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias*), was conducted from 2006 to 2010, and developed 12 specific projects. The results, including a database containing 24057 records (22931 from native landraces, 599 from teosintes and 527 from *Tripsacum* grasses) are publicly available. Furthermore, the distribution of these records, pictures of each landrace and geographic extent of the sampling can be analyzed dynamically at the online Explorer of the Global Maize Project, as well as on CONABIO's web page on Mexican maize landraces.

One follow up of the Global Maize project is the genetic analysis of several recently collected maize landraces and teosinte samples using SNP markers. The results show, among other findings, that the distribution of the genetic variation is better explained by the interaction of altitude and latitude than by landrace identity, implying the existence of potential for local adaptation among populations of the same landrace grown at different locations (Arteaga et al, 2016; project financed by SEMARNAT). The result of this analysis can also be interactively explored at the Mexican maize landraces genetic diversity explorer. Analysis of a second set of samples is currently underway.

CONANP (*Comisión Nacional de Áreas Naturales Protegidas*) has a program for the conservation of maize landraces (Promac or *Programa de conservación de maíz criollo*), directed towards the promotion of conservation and recuperation of varieties and landraces of native maize and its wild relatives in their natural environment. Through subsidies, this program supports groups of farmers in efforts to conserve the genetic diversity of native landraces of maize in priority regions. A complementary project to Promac is *Acciones Complementarias al PROMAC*, which aims to evaluate the efficacy of Promac and strengthen these conservation activities. This project currently supports several groups of farmers that work in collaboration with researchers in four different regions of the country, promoting the exchange of experiences regarding the use, conservation and production of native landraces of maize and the agrobiodiversity associated with their production systems.

…Box 5.3 continued

Studies of the relationship between maize diversity, seed selection, use and consumer preferences have been also undertaken in certain communities in Oaxaca. These have shown for example that women have an influence on local diversity of landraces through their choice for the preparation of particular dishes, even if their seed selection procedure is no different to that followed by the men (Project LE011 "*Usos locales y preferencias de consumo como factores de la diversidad del maíz nativo de Oaxaca*") (González-Amaro, 2016). Laboratory analysis showed that the landraces studied presented better characteristics for the preparation of particular food preparations (tejate, totopos) (González-Amaro et al., 2015; González-Amaro et al., 2017)

Currently, an important effort is being made in Mexico, through a collaboration between the University of Guadalajara (Dr. Jesús Sánchez), SEMARNAT and CONABIO, to characterize the existing wild teosinte populations present in the country (see a video of its natural distribution in Mexico) in order to better direct conservation efforts and monitoring and to build knowledge regarding their potential use in maize breeding.

Genetic diversity present in maize landraces and wild relatives constitute the primary gene pool of maize and it certainly will continue to be of tremendous utility in order to incorporate particular interesting traits into present and future breeding programs. Interestingly, incorporating such traits could potentially be done faster and more precisely than before by using genomic data, such as in genomic selection (Neeraja et al*.,* 2007; Heffner et al., 2009). Interesting agronomic, adaptative and special use related characteristics have been identified in landraces, but such landraces have hardly been incorporated into breeding programs[43] (see table 5.1). This is also the case for wild relatives; for example, striga parasitic weeds are an important problem in Africa in regions where maize production is held in suboptimal conditions. Resistance to this root parasite has been characterized in maize wild relatives such as *Tripsacum dactyloides* and *Z. diploperennis*, where inbred lines with resistance traits have been generated (Amusan et al., 2008; Rich and Ejeta, 2008). There is also the fact that many landraces can already be adapted to marginal environments by having the right genetic background, so that they could be used as base material for breeding instead of as donors.

We, as a maize consuming worldly society, depend on the traditional agricultural practices followed by millions of farmers, which year after year, cycle after cycle, favor and select those genetic combinations that best adapt to the extremely diverse climatic and geographic conditions present in millions of hectares where maize cropping is performed. It is to these farmers to a large extent that we owe the magnificent genetic variability present in maize and key to the crops future resilience. Small scale farmers play a key role by cultivating maize through traditional agricultural practices and positively impact human development; nevertheless national statistics do not necessarily reflect their contribution in national accounts and wellbeing nor are they

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[43] An aspect that should be explicitly considered in any genetic material exchange and/or incorporation in breeding programs is access and benefit sharing in the light of the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits arising from their utilization (under CBD) and the International Treaty on Plant Genetic Resources for Food and Agriculture ITPGRFA (under FAO).

recompensed accordingly. We aim through this effort to make the invisible, visible and assure the traditional agricultural practices which add genetic value be rightfully quantified and valued, so as to positively impact their existence through time.

5.2 Genetic externalities of maize production in intensive and smallholders systems

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In this section, we discuss the potential negative effects of promoting genetic uniformity and breeding in intensive production systems on crop production and further breeding. First, we focus on the rapid spread of pests and diseases, which is probably the most immediate consequence and for which there are some historical examples. We then describe what the effects of modern breeding are on the genetic diversity of the species and how it impedes opportunities for local adaptation and new variation for use.

The first externality is that promoting genetic uniformity allows for mechanization and more efficient harvest timing, but it also makes crops susceptible to the rapid spread of pests and diseases. Southern Leaf Corn Blight, caused by Race T of the fungus *Bipolaris* (*Helminthosporium*) *maydis*, is a classic example of the dangers of genetic uniformity. In the 1970s, this pest struck the US maize causing yield losses of up to 50–100%, with economic losses of about 1 billion dollars (American Phytopathology Society, 2014). The fungus was able to spread rapidly and infect large areas because most hybrid maize at that time was uniform for a condition called cytoplasmic male sterility (CMS). These CMS plants were popular because they avoided the need for manual detasseling (removing the male part of maize plants - a painstaking job necessary to generate the desired hybrid). However, as a coincidence, the maize variety where CMS was found and used for breeding, turned out to be susceptible to this blight. The lesson was clear. ”*Never again should a major cultivated species be molded into such uniformity that it is so universally vulnerable to attack by a pathogen, an insect, or environmental stress. Diversity must be maintained in both the genetic and cytoplasmic constitution of all important crop species*” (Ullstrup, 1972).

Was this lesson learned? The answer is, partially. The hybrid maize cultivars grown in current US intensive production systems are composed of genetically similar or identical individuals, expanding large monoculture areas. However, there is now a greater awareness of the risk. As a consequence, seed companies are constantly looking to deploy new diversity, which has created a degree of temporal and regional genetic variation across commercial lines (Smith, 2007b; Smith et al., 2015). As discussed in the dependencies section, most of this new variation that “saves the day” has come from sources external to the commercial breeding pool, such as diversity surveyed in landraces and gene banks (Smith et al., 2015). However, examples of pest and diseases impacting strongly on crops due to their genetic uniformity continue to appear (see Box 5.4: Examples of agricultural collapse due to genetic homogeneity). Consequently, while genetic diversity has been introduced and breeding in recent years has started to focus more on pest and disease resistance than was the case previously (Smith et al. 2015), it remains unclear whether the levels of diversity present are sufficient to cope with the risk. Importantly, the main commercial companies have followed very similar strategies in choosing source germplasm for their breeding programs and, as a result, their populations show little genetic differentiation (Romay et al., 2013). The second externality of the history of modern maize breeding and industrial production stems from this fact.

Box 5.4 Examples of agricultural collapse due to genetic homogeneity

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In the face of climate change and phytosanitary contingencies, the fact that agrobiodiversity represents a unique source of alternatives available to any production system has been confirmed by historical cases of agricultural production collapse. This phenomenon has occurred in different regions of the world, with devastating social and economic consequences. Well-known cases are potato blight in Ireland (1845-1849) and Scotland (1846-1857) and also the fungal epidemics of coffee in Ceylon (1870s), wheat in the USA (1917-35), maize in the tropical region of Africa (1950s), tobacco in the USA and Europe (1960s) and maize in the USA (1969-70s). In addition to these cases, however, there are two more modern examples: the viral epidemics in rice that occurred in Indonesia (1970-77), the Philippines (1973-77), India (1972-74), Japan (1978) and Vietnam (2000-2008), and the on-going global threat to bananas (see **http://panamadisease.org/en/map** for a live map) from Panama disease. Collapses in agricultural production are largely the consequence of the vulnerability implicit in the genetic homogeneity that characterizes large-scale agricultural systems since the genetic homogeneity of crops renders them susceptible to the rapid spread of pests and diseases. On the other hand, collapsed systems have been able to re-establish themselves through the availability of on-farm and wild genetic resources found elsewhere. For example, a wild relative of the potato (*Solanum demissum*) that is resistant to the fungus (*Phytophthora infestans*) that caused the epidemic (and famine) in Ireland and Scotland in the 19th century was found in the highlands of Mexico (Maxted et al., 1997).

The development of *Corn Belt* hybrids is the history of adapting a tropical grass to a temperate Northern environment in order to maximize yield under high-input conditions (see Box 5.1 in section 5.3: Genetic and evolutionary principles implied in domestication and modern plant breeding). This process occurred by applying very strong selection very rapidly and in a pragmatic social environment. This has without question achieved large improvements in yield but, as detailed below, modern breeding and high-input agriculture has unintentionally also narrowed the opportunity for further development due to breeding from a limited original source, genetic bottlenecks and loss of local adaptation.

Around 87% of the genetic basis of hybrid maize from the Corn Belt was based on the five most popular cultivars of the time, of which *Reed Yellow Dent* contributes 47% of the gene pool used for the creation of inbred lines and their hybrids (Troyer, 2004). With time, the overall diversity has not changed significantly, but it has been separated across lines and they have become more differentiated (van Heerwaarden et al., 2012a). While there has been incorporation of new variation, it has basically been as donor material for very specific traits and represents a small proportion of the genome (Troyer 2004; Smith et al., 2015). The former process created a set of closely related pedigrees that continued to be crossed together for historical and pragmatic reasons: firstly, they perform reasonably well under a wide range of environments (for the Corn Belt variability standard) and secondly, they have already been “cleaned” through decades of breeding, i.e., they possess a range of traits of interest and are well described and are relatively uniform (Troyer, 2004; Smith et al., 2015). As a result, it is easier and faster to develop new lines from crossing pre-existing elite lines, so very little attention has been paid to breeding new base material (Hadi 2007; Dwivedi et al., 2016).

The problem with failing to breed new base material is that this implies disregarding a wide range of potentially useful diversity that has been discarded early or not used at all. The first consequence of this is that the diversity absent from the breeding panels could be responsible for traits that were not important at the time of selection, but that may be important now or for application in other parts of the world. This is especially important for gastronomy and culture, because most of the effort of maize breeding has focused on increasing yield for animal consumption or industrial processes, thus ignoring the traits that are of interest for human consumption (Troyer, 2004; Perales*,* 2016). The second consequence is that this lack of initial variation is eventually translated into a lack of divergence among inbred parental lines (in general, the more different the parental lines are, the greater is the effect of heterosis in their hybrids (see Box 5.2: A brief history of modern maize breeding and hybrid maize) and hence it is unlikely that future breeding would produce more dramatic yield increases (Duvick, 2005; Hadi, 2007) or adaptation to new conditions, such as those imposed by climate change and new abiotic stresses (Troyer, 2004; Vigouroux et al., 2011; Dwivedi et al., 2016). From here, another evolutionary externality emerges: rare (low frequency) alleles are a crucial source of adaptation to new conditions and pests (Vigouroux et al., 2011), as well as for agricultural traits associated with quantitative trait loci (QTLs, loci Jiao et al., 2012). However, the recurrent rounds of modern breeding selection have caused genetic bottlenecks that tend to eliminate rare alleles (Romay et al., 2013) and decrease nucleotide diversity (Jiao et al., 2012). For instance, a group of current US lines shows 11% less nucleotide diversity than their ancestral lines (Jiao et al., 2012). Nevertheless, in more recent breeding (during the last 25 years) an increased presence of rare alleles has been documented in elite lines (Jiao et al., 2012).

Going back to the history of maize breeding in the *Corn Belt*, both artificial and natural selection occurred and still occurs in farms and research stations that present suitable conditions for high yield levels (Troyer, 2004). The places where selection and seed production occur are therefore relatively few and scattered across the Corn Belt, while the area where the resulting maize is grown is much larger and variable. This means that wide adaptation was preferred instead of local adaptation, simply because plants that performed well across different research stations were preferred, even if they were bettered in some stations by another more locally-adapted one (Troyer, 2004). Finally, part of the reason why high-input agriculture emerged was because it modifies the local environment (through the use of agrochemicals and irrigation) where seeds are grown in order to make it more similar to the place where seeds are developed and produced (Ceccarelli, 2009, 2015). In the end, therefore, wide adapted lines that require high-inputs were preferred and developed and local adaptation ceased to be relevant. Unfortunately, high-input agriculture has turned out to have diverse negative consequences for the environment, as discussed elsewhere in this document, and the diversity of environments, particularly marginal environments, turned out to be beyond the range of adaptation of even the widest adapted lines. If the current hybrids are not grown under high-input conditions or are taken to marginal environments, their survival rates and yields significantly diminish, and they are often outperformed by local landraces (Perales et al. 2003; Aragon, 2016; Perales, 2016; Fig. 5.3; Box 5.5).

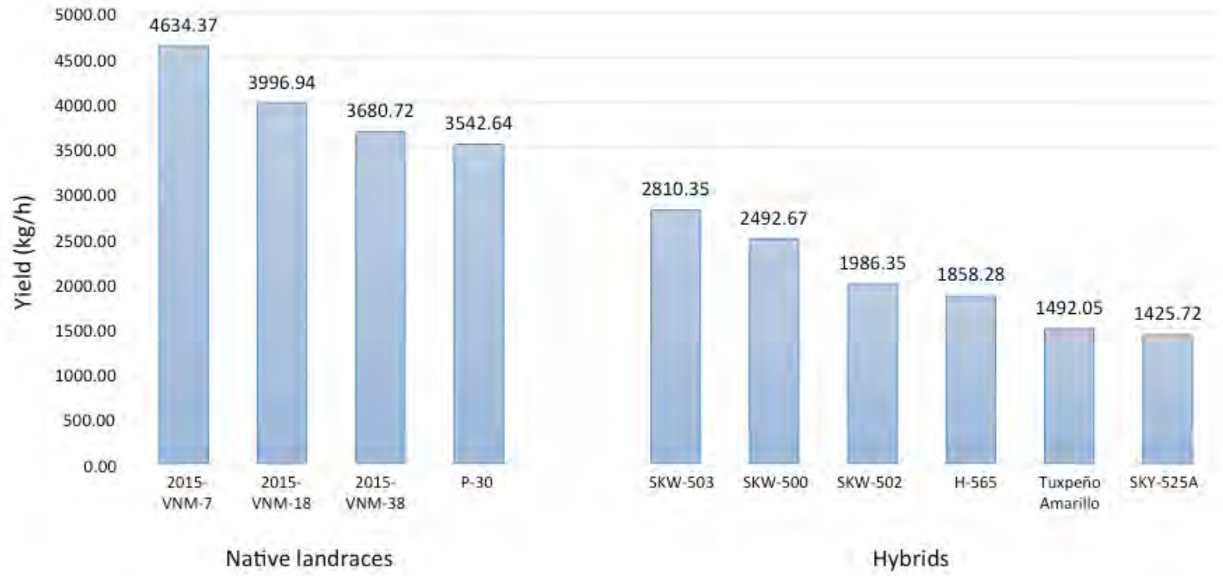

Figure 5.3 Example of native landraces outperforming breeding lines. Data comes from an *in situ* experiment to characterize native landraces in Valle Nacional in Oaxaca, Mexico during the rainfed cycle of 2015. The environmental conditions were stressful, since there was a drought during the flowering period and excess rain during the grain formation phase. Taken from Aragon (2016). See more examples in Perales (2016).

Landraces can outperform hybrids in marginal environments and under low-input conditions because they are better adapted to such circumstances. Therefore, a promising solution to improve yield in challenging environments without relying on an intensive use of agriculture is exploring the local adaptation of native landraces, and using these as base material for local breeding, instead of using them only as donors for lines that would be used elsewhere (Hadi, 2007; Vigouroux et al., 2011; Dwivedi et al., 2016).

Box 5.5. Yield differences between maize landraces and improved varieties of maize in Mexico.

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In spite of the considerable economic value of the cultural services provided by maize landraces, research and public policy tend to focus exclusively on yields. Field experiment studies to determine the benefits of using improved seeds have been carried out mostly on irrigated lands or areas with favorable climatic conditions (Turrent Fernández et al., 2012). These studies are therefore insufficient to make decisions in marginal land, where most of the agricultural plots of smallholders are located (*ibid*.). Turrent Fernández et al. (2012) estimate that the national rate of adoption of improved varieties of maize (hybrid and open pollinated varieties) has remained in the order of 30%, showing insignificant growth over the past two decades. The authors consider that the limit of adoption may have been reached. Evidence shows that yield differences between improved maize seeds and maize landraces depend on the context. If trials are established where hybrids have optimum conditions for growth, the landraces cannot compete. If hybrids are tested in environments where traditional varieties have adapted and evolved, they cannot compete.

Some studies show that yields of improved maize seeds under optimal conditions in different regions of Mexico can reach up to 9-21 ton/ha (Martínez Gomez et al., 2004, Gaytán Bautista et al., 2005, Sierra-Macías et al. 2005, Tosquy-Valle et al., 2005, Coutiño-Estrada et al., 2006, quoted in Turrent Fernández et al., 2012). Espinosa et al. (1999) estimated that improved seeds could increase maize yields by up to 40%, compared to the landraces used as progenitors. Miguel et al. (2004) compared the yields of twenty-four varieties of Chalqueño race blue kernel found in the State of Mexico with the white hybrid H-139. Yields of the landrace varieties ranged from 2.9 to 5.4 ton/ha, compared to the hybrid, which yielded 6.5 ton/ha, approximately 17-22% more than the best yielding native varieties.

Other studies have found that some landraces and open pollinated varieties produce similar or higher yields than those of hybrid seeds. Arellano and Arriaga (2001) carried out a study in the Toluca valley of Mexico and found that the two tested hybrids, H-28 and H-30 produced 5.25 and 5.32 ton/ha, respectively, while the three open pollinated seeds yielded 5.37, 5.06 and 4.45 ton/ha. The local varieties analyzed yielded 4.16 ton/ha.

….Box. 5.5 continued

González et al. (2007) compared yields of the landraces *Palomero Toluqueño* (4.2 ton/ha), *Cacahuacintle* (4.6-5.3 ton/ha) and *Chalqueño*[1] (7.57-8.22 ton/ha) with those of the hybrid *Cónico-Chalqueño* (7.76-9.04) as well as hybrids such as AS-722 (7.4 ton/ha), H-40 (8.05 ton/ha), and *Condor* (8.08 ton/ha). The study was carried out in the localities of El Cerrillo Piedras Blancas, Metepec and Jocotitlán, situated in the valley of Toluca-Atlacomulco, Estado de México, México.

As stated above, it is unusual to find studies comparing hybrid seed yields to landraces under the socioeconomic and biophysical contexts in which the latter have evolved (Turrent-Fernández et al., 2012). In regions where different kinds of seeds are planted simultaneously, including hybrid and landraces, producers do not perceive one type as superior to the others. Instead, they realize that different classes of maize have contrasting and complementary characteristics. Recognizing that all have advantages and disadvantages, smallholders make compromises according to their particular circumstances (Bellon and Risopulos 2001;Bellon et al., 2006).

Bellon and Risopoulos (2001) surveyed about 100 farmers to investigate the expected yields of improved varieties and landraces. The results showed that experienced farmers expected nearly the same level of yields from the creolized variety *Tuxpeño Criollo* (1.77 ton/ha) as from improved varieties (1.93 ton/ha). While landraces had lower expected yields (*Olotillo Blanco* 1.5 ton/ha, and *Olotillo Amarillo* 1.4 ton/ha), they provided farmers with other benefits that neither the improved nor the *Tuxpeño Criollo* supplied in terms of food and feed quality, resistance to insects in storage, and sturdiness.

More recently, Aragón et al (2016) collected native maize seeds from around 150 smallholders of two regions in Oaxaca: the Mixteca and the Papaloapan region. One hundred and sixty six samples of landraces were collected. In order to develop an *in situ* conservation program, the collected seeds were used to establish a field experiment in 2015. For each of the genetic materials collected, two furrows of 5 meters were established. Each furrow had 11 plants with three grains per planting point, resulting in a density of 55,000 plants/ha. Yield estimates of the different landraces showed great variation, with a range between 0.58-9.7 ton/ha and an average of 5.1 ton/ha. Sixteen of the landraces collected in the Mixteca region surpassed 7 ton/ha and two reached up to 9-9.5 ton/ha. In the Papaloapan region, the top sixteen landraces yielded over 3 ton/ha; five of these yielded over 4 ton/ha and one (*Olotillo* x *Tuxpeño*) over 6 ton/ha. These results were compared to those of five improved varieties. Only one surpassed yields of 2 ton/ha, reaching over 5.5 ton/ha, but no hybrid variety performed better than the native white grain of the race Olotillo x Tuxpeño (over 6 ton/ha). This experiment demonstrates the potential of landraces under adequate agronomic management in the context of smallholder traditional production systems.

Continuity of the evolutionary process by on-farm cultivation of maize landraces

Maize landraces retained around 80% of the teosinte genetic diversity after the domestication bottleneck (see Box 5.1 for definition) and gained variation from introgression with a highland teosinte (Hufford et al., 2012). From this genetic diversity base, the pre-Hispanic cultures were able to introduce maize to a wide range of different environments by promoting local adaptation and artificial selection, eventually generating the huge phenotypic diversity of maize we know today and reflected in the hundreds of maize landraces present in Latin America. In Mexico, the domestication of maize continues and actively shapes genetic diversity because of the characteristics and cultural preferences that smallholders continue to employ. Firstly, they select and save their own seed from each cycle, sometimes exchanging it locally or regionally (van Heerwaarden et al. 2012b). Secondly, they often grow more than one variety per cycle because growing landraces with different vulnerabilities ensures a yield even under adverse conditions (Rice et al., 1998; Bellon et al., 2003a; Lazos-Chavero, 2014) and also allows them to obtain all of the types of grain required to meet their cultural and gastronomical needs (there are 600 different dishes of maize (Bourges, 2002), and many depend on specific landraces). Third, in some parts of Mexico, landraces are grown in sympatry with wild teosinte subspecies, sometimes on purpose. These management characteristics create diverse opportunities for gene flow and promote adaptation by subjecting crops to *in situ* natural selection (Arteaga et al., 2016). From a genetic perspective, this has important consequences when we consider the scale at which this process takes place.

In 2010, 4.6 Million ha[44] were grown in Mexico with 59 native landraces (Fig. 5.4) in a wide range of environments covering 11 biogeographic regions and environmental conditions (Perales and Golicher 2014; Fig. 5.5). Considering densities of around 30,000 plants/ha, an estimated 1.38 x 10^{11} individual plants are being grown each year. Mexican native maize is characterized by being genetically diverse, with important differentiation within what is defined as a landrace (Arteaga et al. 2016, and see the Mexican Maize Landraces Genetic Diversity Explorer). Therefore, in contrast to intensive production systems that promote genetic uniformity, here we are contemplating 1.38 x 10^{11} genetically different individual plants. On each of those individual plants, new seeds are formed after open-pollination with neighboring plants, further increasing diversity through recombination. The resulting seed of 30,000 mother plants/ha are mostly destined for human consumption, but around 20 kg of seeds are set aside to be planted per ha in the next cycle. These seeds are commonly selected by choosing around 290 ears of the harvested material, each with 400 kernels (van Heerwaarden et al., 2012b). Since seeds from the same ear share the same mother, this reduces the population to 290 effective families (this is an underestimate, considering that the fathers of each kernel would likely be different) that could pass on to the next generation. This may seem like a strong bottleneck, but consider again the scale at which this process takes place: 290 maize families per ha in 4.6 Million ha means 1.33 x 10^9 plants contributing their background genetic diversity, along with rare alleles, to the next generation. Consider also that selection of these ears is performed independently by around 3 million smallholders[45], in different environments and in a process in which both men and women make the decisions based on their own criteria.

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[44] Area planted with yields equal or less than 3 ton/ha; obtained from the Sistema de Información Agroalimentaria de Consulta (SIACON, www.siap.gob.mx). This is a low estimate, as landraces can produce more than 3 ton/ha.

[45] Estimated from 2 million production units (farms), each with 1.5 people involved in the selection process.

Therefore, there are local and regional differences regarding which types of ears are looked for and which individual plants would survive to produce seed, those making the pool of 1.33 x 10^9 mother plants a diverse sample of the population.

Figure 5.4 Mexican native landraces (57 of 59) and teocintles growing in Mexico. Top part shows maize landraces cobs and one teocintle (center). Made with data from the Global Maize Project (CONABIO, 2011) and pictures from: Guillermo Aguilar Castillo, Luis Alonso Borunda Paquot, José Alfredo Carrera Valtierra, Eliud Castaño Suárez, Roger Iván Díaz Gallardo, Noel Orlando Gómez Montiel, José Cruz Jiménez Galindo, María del Carmen Loyola Blanco, Cecilio Mota Cruz, Alejandro Ortega Corona, Rafael Ortega Paczka, Oscar Palacios Velarde, Hugo Perales Rivera, Beatriz Rendón Aguilar, Froylán Rincón Sánchez, José Ron Parra, José de Jesús Sánchez González, Miguel Ángel Sicilia Manzo, Víctor Antonio Vidal Martínez. CONABIO Images Bank. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Information on Mexican maize landraces can be consulted at CONABIO's website on maize landraces and CONABIO's poster on maize landraces.

Having 1.33 x 10^9 mother plants of maize each year in a place like Mexico implies a rich genetic diversity, because here is the center of origin and domestication of this crop, thus the Mexican native maize germplasm represents the current picture of an evolutionary history of around 9,000 years. However, other parts of Latin America also hold important genetic diversity because maize was introduced there little after domestication (Vigouroux et al., 2011), and therefore their genetic variation may differ to the one cultivated in Mexico. In particular, maize reached South American around 6,000 years B.C. and has continued to be cultivated there in different environments (Piperno 2006, Perry et al. 2006 and Vigouroux et al. 2011). Interestingly, the maize that first reached the lowlands was the one domesticated from *Z. m.* spp. *parviglumis,* without introgression with the highlands teosinte *Z. m.* spp. *mexicana.* Therefore, when maize was introduced to the Andean region (Peru, Bolivia, Ecuador and part of Colombia and Chile), it needed to adapt to the highland conditions by convergent evolution, reaching a similar phenotypic result than the Mexican highland landraces out of a different genetic background (Takuno et al. 2015). As in Mexico, an important amount smallholders of South America continue to grow their native landraces. Although we currently do not have data on the total area planted in this way, we can estimate that it is large, and that therefore the amount of genetically different individual plants is equally important.

The extent and scope at which maize is grown by smallholders in Latin America becomes more revealing and significant under the light of evolution. Firstly, heterozygosity (see Box 5.1 for definition) decays more slowly in large populations[46]. For the Mexican maize landraces grown by smallholders, we estimate[47] the decrease of heterozygosity to be 3.75×10^{-10} per generation, which is a very small number, thus preventing genetic drift from wiping out the rare alleles. As explained in previous sections, rare alleles are important sources of adaptation against changing climate conditions and new abiotic stresses (Dwivedi et al., 2016). By planting maize landraces, Latin-American smallholders are therefore conserving allelic diversity in the best way possible. Secondly, in this context, conservation not only means preserving, but also subjecting genomes to *in situ* natural selection. Since natural selection depends on local conditions, and given the wide range of environments where maize landraces are grown (*e.g.* 10 ecological groups distributed in 11 biogeographic regions only in Mexico; Ruiz Corral et al., 2008; Perales and Golicher, 2014; Fig. 5.5), it is likely that different alleles are being favored by different selection pressures. As a result, some alleles can be rare relative to the total population, but important for localized populations in a given environment. Interestingly, the frequency of rare alleles can increase naturally if they prove to be adaptive to the new conditions produced by changing environments (*e.g.* climate change). Empirical examples of this have already been reported for sorghum (Lasky et al., 2015). Rare alleles are rare by definition and we may therefore have been unable to describe them in our genotyped panels; however, our crops may already be using them.

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[46] From classic population genetic theory, we know that due to genetic drift (See Box 5.1 for an introduction to genetic drift*)*, heterozygosity decreases by $1/(2N)$ in each successive generation, where N is the population size. So the larger the size of N, the smaller will be the decay. Two times N is required because, in diploid organisms such as maize, two alleles can exist at the same locus.

[47] Following the population size presented in the text and the formula $1/2N$, hence: $1/(2 * 1.33 \times 10^{9}) = 3.75 \times 10^{-10}$, a very small number.

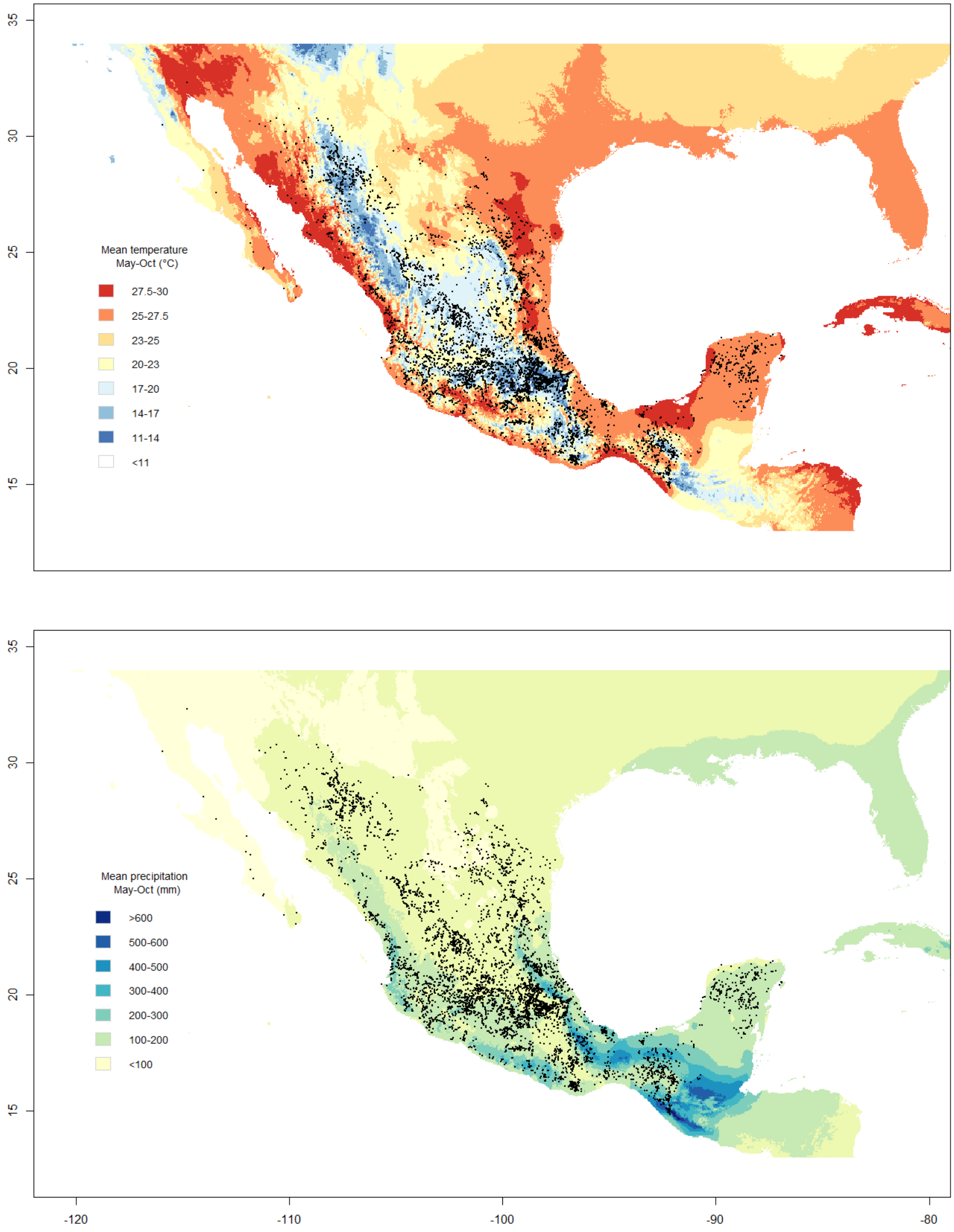

Figure 5.5 Mexican maize landraces (black dots) are grown in a wide range of environmental conditions, as shown by the mean temperature (top) and precipitation (bottom) during the rainfed months of agriculture. Data from Cuervo-Robayo et al. (2014) and the Global Maize Project (CONABIO, 2011).

Lastly, growth of a huge amount of genetically diverse plants with potentially 9,000 years of local adaptation is useful not only for preserving the extant genetic diversity, but probably also for creating new diversity. This can happen because every time an individual reproduces, there is a small chance that its offspring will present a mutation[48]. The large majority of such new variation would be neutral or detrimental for the mutant individual, but a small percentage can be beneficial and, under the right selection pressure, quickly increase in frequency (Gillespie, 1984; Orr, 2003; Eyre-Walker and Keightley, 2007). The probability that a mutation occurs, called mutation rate, is very small: for maize it is estimated to be 1.63 x 10^{-8} base substitutions per site per generation (Jiao et al*.,* 2012). However, since mutations can arise in any individual, the larger the population size the larger the number of new mutations that could arise in the population[49]. Considering this mutation rate and the stated population size, the maize grown by Mexican smallholders could produce 43 new mutations per base per generation. If we then consider the size of the maize genome regions that correspond to genes, that represents a total of 2.3x10^{9} new mutations in total each cropping cycle in the 4.6 million ha of smallholder maize farmers in Mexico[50]. This contribution is significant, as evidenced by the fact that maize genetic diversity seems to be recovering after the domestication bottleneck, and that there are more rare alleles in maize landraces than in teosinte (van Heerwaarden et al., 2012a).

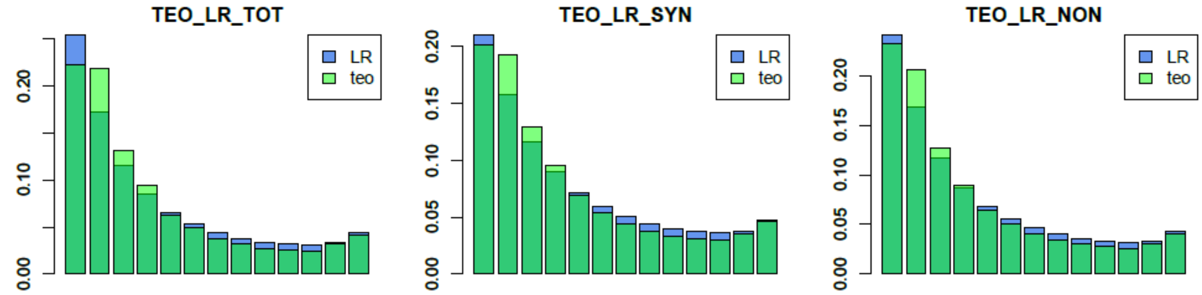

Figure 5.6 Site frequency spectrum (SFS) showing the frequency of alleles in maize landraces (LR) and teosinte *parviglumis* (teo). Columns to the left represent rare alleles (i.e. those of a low frequency in the population, for the leftmost column that is <0.7) and columns to the right represent common alleles (i.e. more frequent in the population, for the rightmost column that is >0.92). Panels show the SFS for all sites (_TOT), for synonymous sites (_SYN; when the alternative allele does not change the amino acid that would be produced by the DNA) and for non-synonymous sites (_NON; when a different amino acid, and hence protein, would be produced by that allele). Leftmost columns show that the landraces present more rare alleles than the teosinte. Taken from Hufford et al. (2012).

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[48] A change in the genetic code, for instance the substitution of one nucleotide (“letter”) of DNA for other, e.g. an A for a G, which can in turn modify the protein produced by a given gene.

[49] The actual number of new mutations is estimated by the formula ų2N, where ų is the mutation rate and N the population size. Two times N is required because, for diploid organisms (such as maize), two alleles can exist in the same locus.

[50] Estimated from a mutation (substitution) rate of 1.63×10^{-8} (Jiao *et al.* 2012) and a population size of 1.33x10^{9} with the formula ų2N, hence 1.63×10^{-8}* 2* 1.33x10^{9} = 43.49 substitutions per base generation. We must then consider the amount of DNA bases in coding regions (corresponding to genes that generate proteins), which for maize is 2% of the 2700 Mb of its genome (Schnable et al., 2009; Rodgers-Melnick et al., 2016). Therefore, 43.49 mutations per base per generation * 5.4x10^{7} coding bases = 2.3x10^{9} new mutations per generation.

A large amount of rare alleles has also been found in modern breeding maize lines (Hufford et al., 2012; Jiao et al*.,* 2012), which probably emerged through mutations in past decades. However, there are three important differences between mutations arising within the Mexican landraces and those within elite breeding lines: 1) in general, the starting material of breeding lines tends to be less diverse than that of the landraces (see section 4.1 and Box 4.2 for details); 2) breeding lines tend to be more similar worldwide; for instance, Chinese and US lines show little differentiation (Jiao et al*.,* 2012), and 3) while breeding lines are tested in several experimental fields and seed production is developed in several different locations, they are still outnumbered in orders of magnitude by the number of small farms where landraces are grown and seeds saved for the next cycle. As a consequence, a) mutations that arise in the context of smallholder agriculture interact with a wider diversity of genetic backgrounds, which is important because the effect of mutations depends on which other alleles are present (Loewe and Hill, 2010); and b) in Mexican maize landraces, mutations are subjected to different selection pressures in different environments, thus making it more likely for mutations to be useful in one condition or another.

The numbers given above only consider one type of mutation, which was substitution of one base for another, but genome changes can include other kinds of mutation. For instance, mutations that leads to structural variation, like indels (insertion or deletion of bases) and duplications (“copy-and-paste” of one segment of DNA to somewhere else in the genome, potentially producing two copies of a gene that can evolve independently). These other mutations (especially gene duplications) are poorly recorded in panels of genomic variation because they cannot be detected with the same methods used for SNPs. Nevertheless, they are also subject to genetic drift and selection, so it is to be expected that these other mutation sources can also lead to genetic differentiation and adaptation.

Regardless of the mutation type, the strength of Mexican native maize lies in its numbers. Large populations grown in several different environments for millennia are of irreplaceable evolutionary value because they hold such a rich genetic pool that is locally adapted to conditions where commercial maize cannot be grown. Since conditions keep changing, this pool cannot be fully preserved in seed banks (*ex situ* conservation), but instead must keep evolving in the same system (*in situ* conservation), i.e., in large differentiated populations and different environments, rather than by a handful of custodians chosen to preserve each landrace (Perales, 2016). However, an important argument against *in situ* conservation is that seed banks are easier to access by breeders and geneticists, so even if important genes and alleles are “out there”, it would be difficult to incorporate them into commercial lines. That, however, is a limited vision, because there remains the value of this maize for the livelihoods of farmers in environments where commercial breeding as we know it today would probably never be successful (Perales, 2016). We should change our mentality to take advantage of that evolutionary process by aiding local breeding of native maize and considering the smallholders as part of the solution.

5.3 Impacts of maize production practices on ecosystem services: agro-ecological, organic and conventional agricultural management

Author: Yatziri Zepeda

Agricultural production systems face the challenge to produce sufficient, safe, nutritious and culturally appropriate food to sustain a population of over 8 billion by 2030, while minimizing negative environmental impacts. It has been claimed that such a challenge could be met by closing yield gaps in order to attain potential yields through intensification (Pradhan et al., 2015). Others argue that the current global food system produces more than enough food calories to feed the global population (Tittonell, 2014)[51] and that the issues to address should be 1) to produce food where it is most needed or consumed; 2) the large amount of calories produced to make biofuels (9%) and feeding animals (36%) instead of directly feeding people; 3) the excessive amount of food wasted along the supply chain (33%) due to the inability of market chains to ensure food access for everyone; 4) the inequitable distribution of food calories and 5) the unsustainability of current agricultural systems and practices (Gliessman, 2014).

The unsustainability of the current agricultural landscape

Maize production has increased twice as much as its harvested area since 1990. This is the result of a generalized yield increase due to intensification, including an increasingly wider adoption of hybrid seeds and other inputs such as fertilizers, herbicides, pesticides, and mechanization. The positive effects of industrialization have been widely acknowledged: during the second half of the 20th century, per capita food production doubled in Southeast Asia and the Pacific, South Asia and in Latin America and the Caribbean (McArthur and McCord 2014 in IPES-Food 2016); high yielding varieties increased the availability of net calories and helped farmers to work their way out of poverty (IFPRI, 2002, quoted in IPES-Food 2016).

However, these improved varieties have not benefited the poorest smallholders or those without access to irrigation (*ibid*.). Smallholders lack access to extension services, credit and markets and often struggle with the volatility of prices for global commodities such as maize (FAO, 2004b, quoted in IPES-Food 2016). As a result, it is estimated that 50% of the world´s hungry are smallholders (WFP, 2015).

Evidence shows that agricultural intensification has increased yields at a significant environmental cost, affecting water bodies, climate stability, natural pest control, pollination and soil health, among others (Milder et al. 2012). Intensive agriculture is a major contributor of greenhouse gas (GHG) emissions through fossil fuel-intensive production of chemical fertilizers and pesticides (Gilbert, 2012, quoted in IPES-Food, 2016). Moreover, approximately 70% of all the water extracted from freshwater bodies is used for irrigated agricultural production–usually at unsustainable rates (FAO, 2013, quoted in IPES-Food, 2016). Intensive agriculture pollutes water bodies and soils with excessive amounts of nitrate and other nutrients, pesticides and soil sediments (Parris, 2011, quoted in IPES-Food, 2016). Soil degradation and biodiversity loss has also resulted from intensive

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[51] 2,700 Kcal/person/day produced vs 1,800-2,100 Kcal/person/day required (FAO, 2015)

systems (Scherr and McNeely, 2012, quoted in IPES-Food, 2016). Current agricultural practices negatively impact the same ecosystem services on which agricultural systems, intensive or otherwise, depend.

In an attempt to make such negative externalities visible, a small number of studies have estimated the environmental costs of agriculture. These studies, undertaken at different times and places make comparison difficult. Pretty et al. (2000) estimated the total external costs of UK agriculture to be approximately £2,343 million in 1996 (range for 1990-1996 £1,149-3,907 millions), equivalent to £208/ha of arable land. The authors included, among others, the annual costs of contamination of drinking water with pesticides (£120 millions), nitrate (£16 millions), cryptosporidium (£23 millions) and phosphate and soil (£55 millions); agricultural costs of damage to wildlife, habitats, hedgerows and drystone walls (£125 millions); costs of gas emissions (£1113 millions), soil erosion and organic carbon losses (£106 millions) and food poisoning (£169 millions).

Tegtmeier and Duffy (2004) carried out a similar exercise for the Unites States in which they evaluated the damage to natural resources, wildlife and ecosystem biodiversity and human health due to agriculture at between $4,969 and $16,151 million per year. Among other annual costs, damages to water resources caused by nitrates and pesticides are estimated at $188.9 million and $119 million, respectively. Damages due to soil erosion are estimated by the costs to the water industry and by the costs to replace the lost capacity of reservoirs, at $227-831.1 million and $241.8–6044.5 million per year, respectively.

At the agricultural landscape level, the effect of agriculture on ES largely depends on the amount of land committed to agriculture compared to other uses. Since agriculture is the main diver of deforestation, it has been claimed that agricultural intensification, and the resulting increased yields, is key to forest protection and thus to biodiversity conservation. In general, the link between increase yields and reduced pressure on the forest frontier is ambiguous. On the one hand, if capital and labour are attracted away from the forest frontier to support intensification of production in other areas with increased yield, pressure on forests will be reduced.

On the other, if there are higher potential land rents from agricultural production in the forest frontier, the pressure on land will increase. Evidence of whether agricultural intensification has alone prevented natural land from becoming agricultural land is mixed. Between 1990-2005 only a few cases where yields increased while land-use change decreased have been reported (IPES-Food 2016). Analyses at national level show that, overall, intensive agricultural systems have not led to the stabilization or reduction of land devoted to agriculture (Rudel et al. 2009; Ewers et al. 2009 in IPES-Food 2016). In general, as yields have increased, croplands have also increased (*ibid*.). Whether the rate of increase in land conversion due to intensification has been slowed or not is yet to be determined. Burney et al. (2010) estimate that as a result of intensification, approximately 1.761 million hectares were spared between 1961 and 2005. However, this is an aggregate figure and the International Panel of Experts on Sustainable Food Systems (IPES-Food, 2016) which assumed that new land was converted to croplands, while other potentially degraded land was taken out of production. Degraded spared land cannot be assumed to provide ES equal to that of pristine natural areas.

There is strong evidence that yields in intensive production systems have begun to plateau. The period 1990-2010 witnessed a prevalent deceleration in the relative rate of increase of average yields of rice, wheat and maize in highly productive countries (IPES-Food, 2016). There is strong evidence of decreasing yield rates in 20%

of global maize production while 5% is under an upper yield plateau (Grassini et al., 2013). Another study that analyzed data from 2.5 million census observations taken worldwide over the past 50 years concluded that, globally, 26% of maize-growing areas are witnessing yield stagnation and 3% have experienced yield collapse (Ray et al., 2012). In high-yield systems, such plateaus can be explained by degraded ecosystem services including soil erosion and soil fertility loss, erratic weather patterns, climatic conditions, as well as policies concerning agrochemical inputs and the yields approaching a biophysical ceiling (IPES-Food, 2016).

Yield plateaus coincide with the decline in real per capita public funding of agricultural research (see sections 2 key message 17). Between 1970 and 1990 real per capita funding in USA increased at approximately 0.8% annually. Between 1990 and 2007 the average rate of change in real per capita funding was around -0.1% per year (Alston et al., 2009). In 2006, aggregate R&D expenditures in all sectors in USA were $10.3 billion. Private spending accounted for 58%, exceeding public spending (federal spending 29%, state spending 13%). The composition of publicly funded research has also changed, moving away from agricultural production and towards health, food safety, nutrition and environmental impacts. In 1975, 66% of state funded research was directed to enhancing farm productivity. By 2007 it had fallen to 57% (Alston et al., 2009).

Sustainable agricultural production systems

It has been argued that agroecology or “the application of ecological science to the study, design and management of sustainable agroecosystems” (Altieri 1995; Gliessman, 2006) has the potential “to improve agricultural systems by mimicking or augmenting natural processes, thus enhancing beneficial biological interactions and synergies among the components of agrobiodiversity” (Altieri, 2002, quoted in De Schutter, 2013). In other words, agroecological management practices aim to minimize negative externalities and enhance the provision of on-farm ecosystem services that, in turn, support yields in a sustained manner even in poor seasons (Milder et al., 2012; Lal, 2015). Among others, they contribute to climate change mitigation and adaptation; reduce soil erosion and improve soil fertility; use water more efficiently, promote watershed recharging, minimize dependence on external inputs, and promote biodiversity and beneficial interactions among species (Gliessman, 2014). Supporters of agroecology also claim that it offers smallholders an alternative to systems that rely on external inputs and technologies, often inaccessible to them, improving their safety-net and resilience (De Schutter, 2011; Altieri., 2012, quoted in Milder et al., 2012). Finally, agroecological systems claim to promote social equality, nutrition security, and financial viability (IPEFS, 2016).

While no single production system works best everywhere (Reganol and Wachter, 2016), site-specific agroecological practices can be adopted in a wide range of contexts and applied in almost any type of production system, from small production units to intensive agricultural systems. In fact, most production units usually combine components from both intensive agriculture and agroecology (Milder et al., 2012). Agroecological practices include: mixed or intercropping, agroforestry, intensive silvopastoral systems, crop rotation, local variety mixtures, cover cropping, green manures, mulching, compost applications, no-tillage, contour farming, grass stripping/living barriers, terracing, check dams along gullies (Altieri and Nicholls, 2012), integrated pest management, limited or no use of synthetic chemicals, water harvesting, transplantation of seedlings at young age, low seedling density and shallow root replacement, optimal plant spacing, intermittent flooding, frequent weeding, precision input applications, and laser leveling (Milder et al., 2012). These are core practices of major agroecological systems including conservation agriculture, organic agriculture, and precision agriculture, in the case of maize production systems.

Most maize production systems around the world, lay somewhere between the intensive and agro-ecological extremes. Actually, the implementation of agroecological management practices in input-intensive and technology-intensive systems as well as the intensification of agroecological systems is an approach that has been endorsed by relevant global reports (FAO 2011c, quoted in Garbach et al., 2017).

The main criticism of agroecological practices is the potential for lower yields compared to those of conventional agriculture (Kirchmann and Thorvaldson, 2000; Connor and Mínguez, 2012, quoted in Reganold and Wachter 2016). However, there is a growing amount of evidence claiming that agroecological practices can provide ES and maintain yields. Milder et al. (2012) reviewed over a hundred studies to evaluate the outcomes, synergies and tradeoffs of different agroecological systems. The majority of studies indicated positive or neutral outcomes for yield and ecosystem services, except for organic agriculture, suggesting that agroecological systems are generally beneficial.

In the case of organic systems, a recent review by Reganol and Wachter (2016) examined the performance of these systems in terms of productivity, environmental impact, economic viability, and social wellbeing. The authors concluded that while organic farming systems do produce lower yields compared to conventional agriculture (6-37% less, being rice, soybeans, and maize the best yielding organically grown crops, and fruits the lowest yielding organic crops), they are more profitable, deliver greater ecosystem services and social benefits and produce at least an equal amount of nutritious foods that contain less or no pesticide residues. According to the authors, with certain crops growing under certain conditions and optimal agronomical practices, the yields of organic systems come close to matching those produced by conventional agriculture.

Objective

The objective of this section is to make visible and compare the biophysical impacts of different maize production systems. More specifically, a detailed description of two major agroecological systems relevant to maize production is developed: conservation agriculture and organic systems. Lack of data impeded a statistical analysis and a monetary economic valuation representative of the typologies. Instead, existing evidence of the impacts on ecosystem services of conventional production of maize, compared to the aforementioned agroecological maize production systems, is examined. First, a thorough literature review of existing meta-analyses and global reviews is presented. Afterwards, studies based on field experimentation carried out in two case studies are reviewed: 1) Conservation Agriculture in Jalisco and other rain-fed and irrigated semi-arid areas of Mexico, and 2) Organic Systems in the *Corn Belt* in the United States.

In the case of Conservation Agriculture, its limitations are discussed. The economic viability as well as the determinants of the adoption of its practices from the point of view of smallholders is reviewed. For this purpose, we focus on the existing literature on two case studies: The Highlands of Ecuador and the slopes of

Chiapas, Mexico, where subsistence native maize is produced. The promotion of conservation agriculture in Mexico is linked to the promotion of improved varieties. However, smallholders have been reluctant to adopt them.

In the case of Organic Systems in the Corn Belt states, more and better data was available. Therefore, the impacts on specific ES in the region are described with more detail. A discussion of the value of negative environmental externalities is included, as well as the existing evidence on the potential benefits and costs of banning atrazine; the potential aggregate economic loss from glyphosate resistance; and approximated benefits of reducing the use of fertilizers.

5.3.1 Conservation agriculture

Conservation Agriculture (CA) is an agroecological system that aims to increase yields by enhancing ES. It can be defined as “a method of managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment” (Corsi et al., 2012, quoted in Bursari et al., 2015). Three core management principles of CA are generally encompassed: 1) minimal or no soil disturbance through conservation tillage (reduced or no-tillage (NT)) 2) permanent organic soil cover by retaining crop residues, and 3) crop rotations (Verhulst et al., 2012; Lal, 2015). Conservation tillage is generally defined as any reduced-tillage system that leaves at least 30% of the soil surface covered with crop residue after planting to reduce soil erosion by wind and water. Reduced or no-tillage has been regarded by some as the most important component of CA (Busari et al., 2015). However, it has been highlighted that the emphasis in CA should not only lie in the tillage system but also on the interaction of the three core management principles described above (Verhulst et al., 2012). Lal (2015) also considers integrated nutrient management as a principle of CA. Other practices that are sometimes included in CA are the use of cover crops, plantation of woody perennials, water harvesting, laser leveling and optimal plant spacing (Milder et al., 2012). For the purpose of this comparative exercise, conventional agriculture (CT) is defined as a system based on extensive tillage combined with removal (or burning *in situ*) of crop residue and no crop rotation.

The practice of CA can modify soil properties and processes compared to conventional agriculture. As soil changes its physical, chemical and biological characteristics, the provision of ES such as food and raw material production, water regulation, erosion prevention and the maintenance of soil fertility, biodiversity and carbon sequestration and storage are affected. However, the magnitude -and in some cases the direction- of these impacts on ES, when comparing CA with CT, varies depending on soil properties, climate, physiography, biome, crop and residue type, duration and characteristics of the intervention, as well as the combination of different CA practices. Therefore, the effects of CA are always location-specific and thus are shaped by the particular socioeconomic and ecological context (Milder et al., 2012). In addition, CA cannot be seen as an indivisible, fixed set of homogenized agroecological practices. Instead, the contribution of each individual component as well as interaction between them in the provision of ES should be evaluated in the specific context of each production unit.

Meta-analyses and global reviews on the impacts of conservation agriculture vs. conventional agriculture on ecosystem services

There has been a substantial amount of research on the impact of CA and its individual components on the provision of different ES. However, no studies have simultaneously evaluated the impact of these practices on multiple ecosystem services. Most of the literature focuses on food provision in terms of variations in yields resulting from the adoption of CA.

Brouder and Gomez-Macpherson (2014) carried out a meta-analysis for Sub-Saharan Africa and South Asia, comparing the impacts of CA and CT on smallholder agricultural yields. The authors included over 20 studies, specifically comparing maize-based systems. The study concludes that, relative to CT, CA increased maize yields, soil water infiltration and soil organic matter, especially when mulch was used.

Rusinamhodzi et al. (2011) use meta-analysis to analyze the long-term effects of CA on maize grain yield under rain-fed conditions in Southern Africa. Their results show that mulch cover under high rainfall conditions results in lower yields as a consequence of waterlogging; a great majority of the data shows that soil texture affects yields in agricultural areas under CA and that it can increase yields in well-drained soils. These authors also find that CA requires inputs that increase N in order to improve yields; rotation is found to increase yields but the calculations often fail to include variations in rainfall within and between seasons. Most of the data shows that reduced tillage with mulch cover increases yields in semi-arid areas.

Sithole et al. (2016) reviewed the evidence of the impacts of CA on soil quality and maize yield in South Africa. The study concludes that soils under CA have an increased capacity to store water and are thus more resilient to rainfall variability compared to those under CT. This is particularly important in agricultural areas with erosion, infertility and, as mentioned before, a scarcity of water. Moreover, the study demonstrates that, beyond its environmental benefits, CA can have positive financial, social and health benefits and it calls for further research on the impacts of CA in different agroecological, social and economic contexts.

Perhaps the most comprehensive global review of the literature regarding the impacts of CA on multiple ecosystem services is a study by Palm et al. (2014). The review presents conclusive evidence that compared to CT, CA increases topsoil organic matter and water quality and reduces soil erosion and runoff. Nevertheless, there appears to be certain degree of uncertainty about the role of CA in carbon sequestration and in the reduction of GHG emissions (ibid.). Baker et al. (2007) argue that CA may alter the distribution of SOC, but not the total balance, with higher concentrations found near the surface in conservation tillage and higher concentration in deeper layers under CT. Palm et al. (2014) found that, of the more than 100 studies analyzed that compared soil carbon sequestration between CA and CT, only half indicated increased sequestration with CT. Results of the effect of CA on GHG, compared to CT, are also mixed. In general, biodiversity is higher with CA than with CT. However, the provision of ES such as pollination and pest control is difficult to evaluate given the limited evidence of cause and effect and the lack of reliable estimates of magnitude of impact and the inconsistency of these effects (ibid). While the evidence that CA promotes C sequestration is not compelling, the significant benefits of the provision of other fundamental ES are clear.

Maize is very sensitive to water stress and demands high amounts of nutrients. This is particularly important to rainfed maize production systems, which must become more resilient in the face of climate change and the expected decrease in average precipitation and increased frequency of extreme periods of drought (Verhulst et al., 2011). Under these circumstances, agricultural practices that encourage adequate water management and soil fertility -such as those embraced by CA-, are fundamental to ensure sustainable production (Scopel et al., 2005).

By 2015, CA had been implemented over 41,000 ha in Mexico, a relatively small amount compared to other Latin America countries such as Brazil (31,811,000 ha), Paraguay (3,000,000 ha), Argentina (29,181,000 ha), Uruguay (1,072,000 ha), Bolivia (706,000 ha), Chile (180,000 ha) or Colombia (127,000 ha) (FAO, 2016b). Globally, over 155 million hectares on both intensive and small farms have adopted practices of CA (Kassam et al. 2014). Adoption of CA has been more successful in the temperate regions of South America, compared to that of smallholders in the Andean region and Central America, where the process has been more challenging (Speratti et al., 2015).

Limitations of CA

Evidently, as with any other agricultural system, CA has limitations and constraints to its adoption and success. It has been claimed that CA has the potential to be implemented and optimized in any agroclimatic zone and that the limiting factors for adoption are mainly socioeconomic, political and cultural (Speratti et al., 2015). The benefits of CA are felt in the long-term (Giller et al., 2009). Therefore, the main limiting factors of adoption by smallholders in Latin America include their short-term priorities, particularly for those who rent their land, or for questions of food security. Limited access to capital and credit, risk aversion, a lack of locally available mechanization, reliance on manual labor and the opportunity cost of using crop residues for covering the soil, foregoing higher value uses such as animal feed, sale of residues and biofuel production are other limiting factors for adoption (*ibid*.).

High demand for residues as animal feed is perhaps the main obstacle for adoption in different regions of Mexico (Van den Broeck et al., 2013) and in the Andean region, particularly in the case of rainfed agriculture (Speratti et al., 2015). However, evidence shows that for CA to benefit the soil, only a portion of crop residues must be left for soil cover. For example, in the highlands of Mexico between 50-70% of the crop residues can be removed for alternative uses (Govaerts et al., 2007). Moreover, the potential increase in yields as a result of CA can in turn add more crop residues for alternative uses (Turmel et al., 2015).

As with any other agroecological system, CA is knowledge-intensive. In order to adopt CA successfully, it is necessary to thoroughly understand farmers' challenges, practices and beliefs and build from that basis. The lack of extension services that tailor practices to local conditions, supporting farmers in the adaptation of CA technology to their particular agronomic and economic constraints, is an important barrier of implementation and success (*ibid*.).

In order to foster dynamic models of research and extension, institutional support is necessary to develop innovation networks that can integrate external (research institutes, universities, governmental agencies and extension services) and internal (farmers and community members) sources of knowledge. The knowledge-intensive nature of CA can even bring social benefits such as community integration, cooperation, and knowledge exchange (Giller et al., 2009).

The implementation of CA has been linked to an increased use of herbicides and pesticides as an alternative to increased requirements for labor or mechanization in order to control weeds. It has been reported that some demonstration programs for smallholders in Africa compare "packages" of CA that include external inputs such as fertilizers, herbicides and improved seeds to farmers´ management practices that lack external inputs (Giller et al., 2009).

The greater incidence of weeds and pests during the transition phase to CA is a significant problem for farmers and can be an obstacle to adoption. However, this is also a very important driver for farmers to adopt organic practices, since crop rotation and enhanced biodiversity can help to control weeds and pests under CA (http://conservationagriculture.mannlib.cornell.edu/pages/aboutca/faq.html#5). Once the system attains a new biological balance under CA, in 4 to 5 years, reduced levels of weeds and pests are reported, resulting in an overall reduction in the use of agrochemicals (*ibid*.).

In fact, CA can be practiced under both intensive and organic production systems. Its adoption in genetically modified systems within the framework of integrated weed management is an alternative that allows a departure from intensive use of herbicides as a result of weed resistance (National Academies of Sciences, Engineering, and Medicine, 2016). In Europe, organic farmers who are adopting CA are addressing weed control either by intensifying mechanical work or regulating weeds biologically with cover crops (Peigné et al., 2016).

5.3.1.1 Impacts of Conservation Agriculture vs. Conventional Systems on ecosystem services: The case of rainfed semi-arid areas of Mexico

Three studies on the biophysical impacts of CA, compared to CT, that affect ES in rain-fed semi-arid Mexico were identified in the literature[52]. Verhulst et al. (2011) compare soil water content, rainfall water productivity and yields in rain-fed maize plots under CA with CT practices. The authors obtained data from a field experiment in the semi-arid highlands of Mexico (*i.e. Estado de México*). This included six permanent management practices based on variation of crop rotation (maize/wheat), tillage/zero tillage (ZT) and residue management. Their results show that CA practices promoted higher soil water content than management practices involving CT and ZT with residue removal. CA with partial residue retention used rainfall more efficiently and produced a more resilient agronomic system than CT practices. During the driest period of the growing season in 2007, 2008 and 2009, CA had at least 20 mm, 25-40 mm, and 12 mm more water than CT, respectively. On average, between 1997 and 2009, CA resulted in a rainfall water productivity of 1.31 k/m^3 vs 1.00 k/m^3 for CT. During the same

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[52] A literature review was carried out using the following search terms in the Scopus database: maize AND tillage AND soil AND Mexico. 15 studies were identified. Only 3 focused on semi-arid regions and the ES of interest.

period, CA had an average yield advantage of 1.5 ton/ha of maize compared to CT, particularly with practices involving full crop residue removal. No significant differences were identified between ZT and partial residue retention vs. ZT and full residue retention. This result is important since, as stated earlier, there are competing uses of residues, such as fodder or fuel, and therefore removal of part of the residue can be a sustainable solution.[53]

A study carried out in the same area by Fuentes et al. (2009) found that 14 years of applying CA to a yearly maize-wheat rotation crop produced improved soil quality and higher yields compared to CT. A maize monoculture crop under CT produced an average (2001-2004) of approximately 3.2 ton/ha compared to 5.6 ton/ha with CA (rotation). The volumetric moisture content of the CA maize-wheat was 289 g/kg compared to 206 g/kg in the CT monocrop. Total N at 0.5 cm depth and soil organic carbon at 0-5 cm depth was 1.6 g/kg under CA, compared to 1 g/kg under CT.

Scopel et al. (2005) carried out a very complete evaluation in terms of the number of ES analyzed. Data was gathered between 1994 and 1998 at three experimental sites in a farmer´s field of about 8000 m^2 in the semi-arid locality of La Tinaja, Jalisco. The sites were located less than 50 m apart. The soil type (Dystric Cambisol) was the same at all sites, and is representative of the soil in this semi-arid tropical region. Slope ranged from 3-7%. The experimental sites compared monocrops of continuous maize production, the most common system in the region, under CT with CA. CA practices included no-tillage and crop residue treatments at 0(CA-0), 1.5(CA-1.5), 3(CA-3) and 4.5 (CA-4.5) ton/ha of added surface crop residues. Monitored ecological process indicators included water runoff, soil erosion, soil carbon changes and maize yield.[54]

Precipitation events can be very intense in the region, reaching 50 mm/ha or more. Agricultural lands thus suffer from substantial water runoff and soil erosion (Scopel et al. 2004, quoted in Scopel et al. 2005). In common with other tropical regions, reduced fertility and inappropriate water usage have led to important maize yield losses in the area (*ibid*.).

Compared with CT, CA reduced water runoff losses by 10-50%, mainly due to increased crop residue. Soil erosion losses were reduced by 50-90% per year. Over a period of 5 years, soil carbon levels under CA increased by 23-29% compared to those with CT. During 1997, under the most intense rainfall, CA maintained about 800kg of C/ha more than CT (2-7 times more). Maize yields were 170-190% larger under CA (Scopel et al., 2005). Results varied depending on the amount of residues, slope, and the intensity of rainfall events.

Results in the Scopel et al. (2005) study show that maize production systems under CT or no-tillage (NT) but no mulching lost about 30% or more of the annual rainfall through runoff on plots with a 7% slope. NT and mulching with 1.5 ton/ha of crop residues (CA-1.5) reduced annual water runoff by 28% in 1997 (when a stormy rainfall occurred) to 57% in 1995, compared to NT and no mulching (CA-O). That is, the larger the amount of crop residue, the larger the reduction in runoff. NT and mulching with 4.5 ton/ha of crop residues (CA-4.5)

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[53] The average approximate value of potential evapotranspiration for the entire season (1991-2009) was 907 mm; the average annual rainfall for the same period was 496mm.

[54] More specifically, the indicators monitored were annual soil erosion (ton/ha), annual runoff (mm), annual average runoff coefficient (%), average annual sediment concentration (ton/ha/mm runoff), soil carbon concentration (%), soil bulk density (g/dm3), average annual maize biomass (ton/ha), carbon input to soil (ton C/ha), annual carbon erosion losses (ton/ha) and grain yields (ton dry matter/ha).

reduced runoff losses to 8-28% of the total rainfall, depending on the year. The effect of higher residue amounts became relatively less important in 1997, when rainfall was high with several intense events. CT had a significant effect on reducing annual runoff compared to the treatment with no tillage and without surface residues (CA-0) in 1996 and 1997. The tillage effect occurred mainly during the first rainfall events, but disappeared later on due to progressive soil hydration with successive rain. In contrast, the effects of surface residue were consistent over the season.

On average, runoff decreased by about 55% on areas with a 3% slope, compared to areas with 7% slope. Treatment effects were still significant on the plots with a 3% slope: mulching reduced runoff by between 40% (under CA-1.5) and 70% (under CA-4.5), whereas tillage (CT) reduced runoff by about 35% compared with no-tillage (CA-0).

Carbon content in the topsoil (0-5 cm) significantly increased after five seasons of maize production under CA. Compared to CT, carbon content (at 20 cm) under CA-1.5 increased by 4.2 ton C/ha (0.84 ton C/ha/year on average), and CA-4.5 increased by 5.3 ton C/ha (1.06 ton C/ha/year on average). Carbon content under CA-1.5 and CA-4.5 were 23% and 29% higher, respectively, compared to CT.

Soil organic coverage by crop residue retention significantly reduced the concentration of sediments in runoff water compared to no coverage with crop residues. Mulching with 1.5 ton/ha of crop residues reduced soil losses by approximately 25, 53 and 72%[55] compared with CT in 1995, 1996 and 1997, respectively. Larger amounts of crop residues had a slightly more significant effect, but absence or presence of mulch was the dominant factor. Annual soil losses were larger on steeper slopes. The larger number of intense precipitation events in 1997[56] had an important impact on soil erosion. Sediment concentrations were more than six times higher in 1997 than in 1995. The treatment and rainfall intensity effects on runoff and sediment concentration were compounded by the effects of soil erosion. On average, soil losses were between 15 to 2.5 times higher in 1997 than in 1995 and 1996, respectively. All these measured impacts of CA and CT have implications on ecosystem services and disservices: soil erosion, water regulation, water quality, the provision of food and raw materials, and soil fertility.

Soil erosion is one of the main threats to conventional agriculture and is a major cause of negative externalities. Soil erosion control is one of the main objectives of CA (Palm et al., 2014). Evidence shows that CA significantly reduces erosion by reducing soil exposure to wind, rainfall and indirectly through the effects of CA on water infiltration and runoff reduction (*ibid*.). However, ranges in erosion prevention with CA compared to CT depend on biophysical characteristics such as soil type, climate -especially precipitation frequency and intensity, and topography.

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[55] The authors estimate that, compared to CA-0, mulching with 1.5 ton/ha of crop residues reduced soil losses by 76, 77 and 68% compared with CT in 1995, 1996 and 1997, respectively

[56] 1997 was the wettest year, with rainfall events exceeding 40 mm accounting for about 40% of the annual total (5 events), compared to 1995 when annual rainfall averaged 359 mm, only 40% of the events were with rainfall greater than 5mm and only one event had rainfall greater than 40 mm.

Table 5.2 Annual estimates of soil erosion, runoff, and yields by CT, compared to CA with minimum mulch[57] under different weather conditions in Jalisco, Mexico.

	Rainfall (mm)	**Erosion CA (ton/ha)**	**Erosion CT (ton/ha)**	**Runoff CA (mm)**	**Runoff CT (mm)**	**Yields CA (ton dry matter/ha)**	**Yields CT (ton dry matter/ha)**
Dry season	359	3	4	30	105	2.75	1.92
Normal season	576	15	32	177	205	4.16	3.12
Intense precipitation	693	32.5	120	320	345	3.69	1.1
Average estimates 1996-1997	634.5			248	275		

Source: own elaboration with data from Scopel et al. (2005)

Moisture retention and infiltration are regulated by factors such as organic matter content, plant coverage and the composition of micro-organisms, all of which can be affected by agricultural management practices (Palm et al., 2014). By increasing soil stability and promoting macropore connectivity through macrofaunal activity, CA enhances water regulation: it increases water infiltration or moisture retention compared to CT. It is estimated that around 80% of the water used by agricultural crops comes from moisture retained by the soil (Molden, 2007, quoted in Power 2010). CA results in more water available to the plant than CT (Palm et al., 2014). It also results in more soil water storage, increase water use efficiency and reduce runoff (Fabrizzi et al., 2005; Silburn, et al., 2007, quoted in Bursari et al., 2015).

Water runoff and the transport of sediments, agrochemicals and nutrients from croplands to water bodies and groundwater are considered a principal cause of nonpoint source pollution (Pimentel et al., 1997). A decrease in runoff and water soil erosion with CA should reduce the negative impacts on water quality by reducing the transportation of herbicides and pesticides, nutrients, and sediments (Palm et al., 2014). Estimates of the reduction of N in sediments and runoff water by CA range from as much as 60% (Kay et al. 2009 in Palm et al. 2014) to 9% (Liu et al., 2013, quoted in Palm et al., 2016). The loss of soluble N varies depending on the timing of precipitation events relative to N application, rainfall intensity and other factors. Richardson and King (1995) estimate that the mean annual loss of soluble N can be reduced by 50% under CA compared to CT in rainfed maize production systems in Texas, USA.

Most studies focus on the provision of food in the form of variations in yields as a result of adopting CA. The literature reviewed for semi-arid areas in Mexico shows that, on average, CA increases maize yields by 26%-190%, depending on weather conditions and the type of CA interventions (Scopel et al., 2005; Fuentes et al., 2009; Martinez-Gamiño and Jasso-Chaverria 2010; Verhulst et al., 2011).

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[57] Considering that there might be competing uses of crop residues, such as fodder or fuel, and that even small amounts of mulch are effective at conserving water under semi-arid conditions, we calculate conservative values of the application of CA with a minimum quantity of mulch (1.5 ton/ha), compared to CT

5.3.1.2 Impacts of Conservation Agriculture vs. Conventional Systems on ecosystem services: The case of irrigated semi-arid areas of Mexico

Martinez-Gamiño and Jasso-Chaverria (2010) conducted an irrigated maize-forage oat rotation system in an experimental site located in San Luis Potosí, Mexico from 1996 to 2007. Their objective was to assess the effect of CA with different crop residues treatments (33%, 66% and 100% of soil cover) on yields of maize grain, stubble and forage oats, compared to CT. Their results show significant increases in irrigated maize grain yields compared to CT. In all treatments with ZT and reduced tillage, the number of irrigations necessary during the maize growing season was reduced by two because of the increased soil water content resulting from the organic soil cover. The higher soil water content measured in CA treatments compared to CT was the reason for the higher maize grain yields. Adoption of CA at 33% of soil cover increased maize stubble production by 3.46 ton/ha compared to CT. By implementing CA, farmers could increase maize grain yields and devote 2 ton/ha to cover at least 33% of the soil surface.

After 14 years of CA at 33% soil cover 6.41 ton/ha of maize grain were produced, representing an increase of 78% compared to CT, which produced 3.6 tons/ha (Martinez-Gamiño and Jasso-Chaverria, 2010). Adoption of CA at 33% soil cover produced 10.49 ton/ha of maize stubble, compared to 7.03 ton/ha under CT, representing an increase of 78% (Martinez-Gamiño and Jasso-Chaverria, 2010).

5.3.1.3 The economic viability of CA and the determinants of adoption in traditional smallholder production systems

It is in extensive systems of maize or in smaller scale systems under intensive farming in flat areas where adoption of CA has increased (Barrowclough et al., 2016). However, as stated above, there is evidence that adoption of CA by the highland smallholder systems of Latin America, such as those in Chiapas and the Andean region, can be a greater challenge (Speratti et al., 2015; Barrowclough et al., 2016). Profitability of the adoption of individual conservation practices in these areas has been demonstrated (Swinton and Quiroz, 2002; Knowler and Bradshaw, 2007, quoted in Barrowclough et al., 2016). This section reviews the evidence for the economic viability of CA adoption, as well as the determinants of adoption of its practices from the perspective of smallholders on the slopes of Chiapas and the Ecuadorian Highlands.

5.3.1.3.1 Costs and benefits of the adoption of CA in the hillsides of Chiapas

The traditional Mexican milpa system is an intercrop of maize, beans and squash. Some milpas include only two of the three elements or only maize (see section 5.4). Evidence shows that, compared to monocrops, there are additional benefits to the application of CA if crops are rotated or at least intercropped with leguminous crops (Thierfelder et al., 2012). Adoption of CA without rotation or intercropping is unlikely to provide the full long-term benefits (*ibid*.).[58]

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[58] The challenges of including crop rotation or intercropping, at least in Africa, include: lack of available seeds, a perceived loss of potential production area to a rotational crop, lack of knowledge about the benefits of crop rotation and

Erenstein and Cadena Iñiguez (1997) interviewed over eighty semi-subsistence farmers in order to investigate the profitability of the CA maize-beans intercrop system and the determinants of its adoption in Motozintla, a municipality located on the slopes of the Sierra Madre of Chiapas. At the time, due to a local law forbidding the burning of crops, smallholders did not burn crop residues but instead left them in the field as mulch and 66% adopted the no-tillage component. However, only 29% adopted both of these components. The results showed that, overall, adoption of CA in a maize-bean intercropping system with local varieties produced higher yields, compared to CT (25% more maize). In a normal year, CA yielded 2.61 t/ha (1.71-3.66t/ha in poor and good years, respectively), compared to 2.12 t/ha (1.40-2.91 t/ha in poor and good years, respectively) with CT. Bean yields were also higher under CA: 148-248k/ha, compared to 104-208 k/ha under CT (*ibid*.).

The promotion of CA in this area encouraged farmers not to burn residues and to replace manual weed control with the use of herbicides[59] (Erenstein and Cadena Iñiguez, 1997). In this particular study, adoption of CA implied a greater use of herbicides, therefore, generating higher input costs. Labor costs (both, family and hired labor) were substantially less for CA, mainly due to the reduced need for labor to control weeds. Most farmers grow native varieties of maize, and seeds are retained from previous harvests so the farmers do not need to purchase them. The opportunity costs of local varieties of maize and bean were estimated using common sale prices for local seeds within the communities. The total variable costs were lower for CA (*ibid*.).

Crop residues are used for feed but there is no market for this product in the area. Residue yields were estimated at 5t/ha and demand for the material as feed at 1.5 t/ha per year. Erenstein and Cadena Iñiguez (1997) assumed that, where weathering of residues during the dry season is less than 10%, 3t/ha would be available to cover the soil. Mulching is the only alternative use of residues and therefore the opportunity cost of crop residues in the area is zero. Given that the practice of free grazing is common in the area and that fencing is a good option to discourage communal grazing, the opportunity cost of 2 tons of residues is estimated as the value of the annual cost of fencing the field to prevent free grazing and secure residues for both feed and mulching. The opportunity cost of land is assumed to be equal for CA and CT and reflects the value of rent paid for the land, as an approximation of the opportunity costs. Fixed costs for CA are higher because they include the cost of depreciation of and interest for the fence and the equipment, including hoes, files, machetes and sprayers. Capital was valued at an interest rate of 2.5% monthly.

Output prices were calculated using the sale price adjusted for transportation costs and the cost of shelling maize. Income, added value (gross benefit minus expenses for inputs) and net benefits (gross benefit minus the cost of resources) were considerably higher for adopters of CA, compared to CT (Erenstein and Cadena Iñiguez, 1997). It is estimated that the profits of the maize-bean intercrop were mainly the result of the bean intercrop, which provided about 20% of the gross benefit; cultivation of maize alone would provide an approximate net benefit of zero.

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associations such as the breaking of pests and disease cycles, improvements in soil fertility, reduced risks of crop failure and additional incomes (Thierfelder et al., 2012).

[59] However, as mentioned before, the use of herbicides is not a core practice of CA. Alternatives to herbicides, such as crop rotations and enhanced biodiversity, can be used under CA.

The study (Erenstein and Cadena Iñiguez, 1997) identified the following barriers to adoption of CA:

1) Farmers in steeper areas are more likely to leave crop residues to cover the soil and to adopt CA in general, since livestock are less likely to graze on crop residues in such fields. Communal grazing reduces the probability of adopting CA.
2) The substitution of manual weeding for herbicides in this case study has important implications on factors that affect the adoption of CA.
    a. Farms with more family labor available are more likely to adopt CA: family labor is related to emigration, since there are opportunities to use the saved labor outside the farm, promoting the decision to implement less labor-intensive systems, such as CA, when herbicides are applied, in this case.
    b. Off-farm income sources facilitate access to external inputs and to adoption of CA. Larger farms are more likely to adopt CA. Since more labor is required, it is more likely that the farmers will adopt a labor-saving mechanism such as CA, in this case.
3) Finally, state agricultural policy, particularly in terms of the distribution of incentives, combined with the local law against burning, also stimulated adoption.

Eighty five percent of the farmers grew local varieties of yellow maize. The rest grew white maize, as well as other, mostly native, varieties (92%). The authors considered that the productivity of the system remained “low” because of the use of landraces. The low rate of adoption of improved seeds is explained by their unsuitability to the conditions of the zone. They acknowledge that the high biophysical variability in the area made it difficult for seeds to adapt and provide materials suitable for each agro-ecological niche. Given such levels of profitability of maize crops, it is argued that farmers are assigning a value to maize for home consumption that is higher than its estimated opportunity cost.

5.3.1.3.2 Costs and benefits of adoption of CA in the highlands of Ecuador

Barrowclough et al. (2016) carried out a study in two watersheds, Alumbre and Illangama, of the Bolivar Province of Ecuador in order to estimate the costs and benefits of CA, determinants of its adoption and willingness to pay for the enhancement of ecosystem services through CA. The area is characterized by maize beans-intercrop systems produced by the mestizo population, who are relatively new to farming, and the incidence of excessive soil erosion, deteriorated soil health and productivity loss. The study combined data from on-farm trials and two household surveys.

Experimental plots were established on the farms of three producers in each of the two watersheds. However, maize crops were only included in the Alumbre watershed. Experiments in the Illangama watershed included potato-oats-vetch-barley and faba beans. Yields, input costs and net value of production were measured for plots under different practices of CA and CT over a five-year period. Costs were estimated for all inputs, including labor and depreciation for fixed inputs. Yields were estimated and valued at market prices, including the costs of shipping to markets. Crop residues removed were valued at local prices for feed. The value of residues left on the field was considered implicit in expected yields; however, no other ecosystem service was valued.

Results showed that the adoption of some components of CA is slightly more profitable than CT (Barrowclough et al., 2016). In the trials of maize/oats-vetch-bush beans/oats-vetch, zero tillage was the preferred option since it produced higher yields of all crops and at the highest net profit. Unlike Chiapas, there is a market for crop residues in the highlands of Ecuador. In this study, therefore, the net benefit was lower with zero-tillage when residues were left as soil cover (USD $4,419/ha), compared to when they were sold as feed (USD $6,623/ha). Residue retention is likely to increase the yields of all crops over time, which may offset the loss of leaving the residues for soil cover. However, soil quality did not improve significantly during the 5 years of the experiment and thus the yield benefits did not offset the lost value of residues for feed.

In the second experimental site of maize/groundcover-bush beans/groundcover, the treatment of zero tillage, residue removal and maize without fertilization had the highest net benefits (USD $4585/ha), compared to the same treatment but with residue retention (USD $2501/ha), which had the lowest profits (*ibid*.). Again, residue retention did not pay for itself. The value of fertilization was limited in this CA production system.

In summary, the implementation of some components of CA is technically and economically feasible in small-scale steep-sloped production systems, but in the period of the experiment, soil quality did not improve sufficiently to see increasing yields. Farmers may be reluctant to maintain soil cover residues due to competing uses for the material and the low benefits that this residue mulching brings in the short-term.

Determinants for the adoption of CA in the highlands of Ecuador

In order to understand the determinants of adoption of CA as well as to measure farmers´ willingness to pay for different attributes of CA, two surveys were carried out (Barrowclough et al., 2016). One survey was randomly applied to 319 households located in the two watersheds during 2011. This determined that the adoption of CA is not dictated by farm size or household labor availability but by the perception of farmers regarding soil loss on their farm. Households where soil loss is perceived as severe are 10% more likely to adopt CA compared to these who believe soil loss is a minor or moderate problem. There is a positive but weak relationship between visits of extension agents and CA adoption. Farmers with irrigation and more diversified crops are more likely to adopt CA, compared to specialized farms. An increase in one unit in the number of crops is associated with a 4% increase in the probability of adoption. Farmers with more years of formal education were less likely to adopt CA, perhaps because they are less dependent on the farm income and therefore less likely to adopt a complex set of practices. Gender was not a determinant of CA adoption. Risk-averse farmers are unwilling to adopt new practices unless the returns increase over time.

Willingness to pay for the attributes of conservation agriculture in Ecuador

The second survey collected data from 233 smallholders located in the two watersheds in order to conduct a discrete choice experiment (Barrowclough et al., 2016). Willingness among farmers to pay for the following CA attributes was estimated: 1) four-year yield: 2) one-year yield; 3) planting labor days; 4) weeding labor days, and 5) soil erosion. The choice experiment showed that smallholders are mostly interested in aspects such as increasing yields and reducing costs. Significant willingness to pay values were found for all four attributes, except for that of one-year yield, indicating that the farmers are willing to tolerate small changes in the short-term in exchange for higher returns in the future. Smallholders are willing to pay 1.77% in additional current production costs to obtain a 1% increase in yield within four years (*ibid*.).

Smallholders are more interested in saving labor at key points during the growing cycle. “Planting labor” had a mean WTP value of 1.03%, compared to “weeding labor” which had a WTP value of 0.4%. This shows that labor markets are tightest during planting and that producers value the higher skills necessary for planting, compared to the more straightforward task of weeding.

While producers stated that erosion was an extremely important issue, their willingness to pay for low and medium erosion was not high: 0.27% and 0.11%. This reflects the fact that farmers are concerned about the on-farm effects of soil erosion but not about the off-farm effects associated with it.

Conclusion

Adoption of CA in traditional maize rotation and intercropped systems located on the steep slopes of Chiapas and Ecuador is technically and economically feasible. Different studies estimate the net benefits differently and include different combinations of CA practices in the analysis. Some include opportunity cost while others do not. The rotation and intercropping systems evaluated are composed of different crops. However, the net benefits of CA were higher in both countries compared to CT. Crop residue retention reduces gross income or increases opportunity costs and, in the short-term, reduces net benefits. However, in the longer-term, yield increases can offset the lost value of residues for feed.

Adoption of the three core practices of CA (no-tillage, organic soil cover and rotation), or adoption of some of them, produces higher yields. In Chiapas, it implied a greater use of herbicides, increased input costs but decreased labor costs. In both Chiapas and Ecuador, crop residues are used as feed. However, in Chiapas, communal feeding is common and there is no market for feed, while in Ecuador there is.

The two studies looked at different determinants of the adoption of CA. Both studies analyzed the effect of farm size and off-farm income or side businesses. Farm size only affected the total adoption of CA (the three core practices) but did not affect the adoption of individual components. Having an additional income has a positive effect on the adoption of CA.

5.3.2 Organic maize systems

We have previously drawn a typology of world maize production systems where we characterize intensive and organic systems (see section 3). The difference between organic and intensive production systems lies in the agricultural inputs used. Organic systems are defined as small and large-scale production units bonded by a set of rules that ban the use of GM seeds, synthetic fertilizers, insecticides and herbicides. Both, intensive and organic maize production systems in the United States are commercially oriented. On average, the size of conventional enterprises in this country is 328 ha and the size of organic farms is 187 ha (Foreman, 2014). All phases of the organic production process are mechanized at different levels, just like the intensive systems are.

Despite their high profit potential and the strong interest that organic maize is generating in USA, its overall adoption remains at less than 1% of the total planted area of maize (McBride and Green, 2015). Most organic maize is used for livestock and poultry feed (77% of the total area planted of organic maize) rather than food (15% of the area planted). Eight percent is used for other or unknown purposes and none of it is used for ethanol (Foreman, 2014). United States, the main producer of maize worldwide, imports yellow organic maize. Based on 18-month data (2013-2014), it is estimated that organic maize imports have an annual growth rate of over 85% in USA. According to the USDA, U.S. imports of organic maize more than tripled in 2015 compared to 2014, reaching 303,645 tons (Durisin, 2016). In 2014 the main exporters of organic maize to USA were Romania, Turkey, the Netherlands, and India (Jaenicke and Demko, 2015).

The predominant maize production system in USA is intensive and in the last decades has incorporated the use of genetically modified (GM) seeds. In 2015, it accounted for 93% of the total planted area of maize in USA. In this sense, GM systems have become the conventional way of current maize production in the country. In the marketing year September 2015-August 2016, GM and intensive non-GM maize combined were mostly used for fuel ethanol (38%) and for feed (37%). About 10% was used for food, seed, and industrial uses, and 14% was exported (USDA, 2016 c).

For the purpose of this section, and following the characterization of our typologies, organic systems (OS) are characterized by the adoption of three core practices: no use of GM seeds, no use of synthetic agrochemicals, and the application of crop rotations. Conventional production (CNV) of maize is defined as a system that emphasizes maximum productivity and profitability and is characterized by the use of synthetic fertilizers and pesticides, and monocultures. Please note that this definition of conventional production is different than the definition of conventional agriculture (CT) previously defined in section 5.3.1 when analyzing 5.3.1 Conservation agriculture. Conventional production (CNV) of maize is defined as a system that emphasizes maximum productivity and profitability and is characterized by the use of synthetic fertilizers and pesticides, and monocultures.

As the following section shows, when comparing the impacts on ES of maize organic systems (OS) versus CNV, most of the meta-analyses, reviews, and field experiments that we analyzed did not specify whether the conventional system was GM or non-GM. Most likely, studies analyzing pre-1998 data analyzed conventional non-genetically modified maize. Post-2008 analysis most likely addressed GM entirely, since over 80% of the total maize production was GM by then. Large studies and data in between are most likely including both systems.

Therefore, unless stated otherwise, we do not differentiate between GM and non-GM intensive systems as the conventional or baseline farming system against which we compare the value of organic systems in the provision of ES in USA study.

Meta-analyses and global reviews on the impacts of Organic Systems vs. Conventional Systems on ecosystem services

Existing evidence on ES outcomes of different agroecological systems shows that conservation agriculture (CA) (*i.e.* the agroecological system previously evaluated) tends to enhance or maintain both provisioning (crop yields) and regulating ES, compared to conventional systems –a win-win or a win-neutral situation. On the other hand, organic systems can also increase the provision of regulating ES, reduce negative externalities resulting from the avoidance of synthetic fertilizers and pesticides, and deliver greater social benefits. However, it is often presumed that OS have a negative impact in the provisioning of raw materials (feed, fuel) and food in the form of lower maize yields, compared to CNV. Unsurprisingly, most of the literature focuses on the evaluation of yield differences.

In order to identify general trends on the ES generally impacted by OS, compared to CNV, we reviewed existing meta-analyses and reviews of the outcomes of both provisioning and regulating ES. We found three studies that comprehensively evaluated the multiple impacts of OS on ES for several countries and crops.

Garbach et al. (2017) carried out a vote-counting meta-analysis comprising 104 studies for different agroecological systems and crops including conservation agriculture, holistic grazing management, organic systems, precision agriculture and a system of rice intensification. Thirty-three studies specifically on OS were analyzed. They compared data on outcomes for yield and nine regulating ES relative to CNV. The conventional system against which they compared OS mostly represented external input-intensive agriculture. The nine regulating ES (or environmental impacts underpinning ES) included were: pest control, pollination, soil structure and fertility enhancement, weed control, biodiversity and habitat provision, carbon sequestration, erosion control, water flow regulation, and water purification. The first four benefiting farmers, while the last five also support broader public goods.

Most of the studies included in this meta-analysis showed that, compared to CNV, OS tend to enhance pollination, soil structure, biodiversity, erosion control, and water flow regulation. OS tend to have neutral impacts, compared to CNV, regarding pest control. Win-win outcomes of increased yield and regulating ES were found in 17% of all the comparisons made in OS for diverse crops. For example, increased yields paired with enhanced soil carbon, enhanced soil nitrogen, greater microbial mass and better respiration, and greater soil water retention. OS were mostly characterized by trade-offs between reduced yields and increased ecosystem services including higher biodiversity, higher biological control potential, and better soil quality. Lose–lose outcomes included mostly significantly reduced yield paired with increased weed competition, lower concentrations of available phosphorus in soil and higher levels of phosphorus leaching. However, these results are highly dependent on the management practices adopted and the adequacy of their implementation, both in OS and CNV, according to the authors. Outcomes also varied depending on the type of CNV system against which the comparison is made. The generalization of OS outcomes, compared to CNV is therefore challenging (Garbach et al., 2017). The evidence on positive outcomes of OS relative to CNV is conclusive for three ES: soil structure and fertility enhancement, including increasing soil organic carbon, biodiversity, and water flow regulation.

Reganold and Wachter (2016) reviewed 52 studies to qualitatively assess multidimensional aspects of OS, compared to CNV. They developed sustainability metrics representing aspects of production, environmental and economic sustainability, and wellbeing. They concluded that while OS did produce lower yields, they better balanced all areas of sustainability. Their metrics showed that OS performed better than CNV in soil structure and fertility enhancement, biodiversity and other ES. OS also reduced water pollution, improved energy use, were more profitable, reduced total costs, promoted employment, reduced worker exposure to pesticides, and produced equally or more nutritious foods that contained less or no pesticide residues.

Finally, a report by the National Academies of Sciences and Engineering, the Institute of Medicine, and the National Research Council carried out an extensive review on the evidence for the strengths and weaknesses of different production systems to improve agricultural sustainability and reducing the costs and unintended consequences of agricultural production. The report concluded that existing scientific studies on multiple dimensions of agroecological systems, including OS, "suggest that they represent viable approaches to raising crops in a way that can improve the sustainability performance of U.S. agriculture along a number of important measures" (National Research Council, 2010b).

This study found that, in general, OS produced lower yields than CNV in developed countries. OS also resulted in better overall soil quality measured by more organic matter, better structure, less compaction, more earthworms, greater microbial activity and diversity, compared to CNV (Reganold et al., 1993; Pimentel et al., 2005a; Mäder et al., 2007). Regarding soil nutrient leaching, they found evidence of significantly lower leachable nitrates (Stolze et al., 2000; Shepherd et al., 2003; Kramer et al., 2006), and phosphorus (Lotter, 2003). This is explained because such nutrients come from compost and manure and because OS require lower levels of nutrients, generating smaller levels of nutrient surpluses in OS, which reduce nutrient pollution from agricultural lands to water bodies (Sanchez et al., 2004; Han et al., 2009). Soils in OS store N more efficiently (Clark et al., 1998) and reduce runoff and erosion (Lotter, 2003). The authors considered weed control the greatest challenge to OS yield and profitability (Cavigelli et al., 2008). Finally, they claim that OS could have lower greenhouse gas emissions since the use of synthetic fertilizers and pesticides that require fossil fuels to be produced is forbidden. However, excess N input can create N_2O emissions in both OS and CNV but best management practices under any agricultural system can reduce soil carbon loss and N_2O emissions (Meisterling et al., 2009).

Meta-analysis and reviews on maize production in USA

Studies that simultaneously evaluate multiple impacts of OS on both yields and regulating ES are even more limited when specifically addressing maize in USA. Therefore, we first analyzed reviews and meta-analyses focusing on yield differences between OS and CNV maize in order to identify patterns in the magnitude of the impacts in the region of interest.

Badgley et al. (2007) carried out a review that compared organic and semi-organic systems to conventional and low-input subsistence agriculture around the world. They estimated that, for all crops, OS yielded 8% lower. Fifteen studies comparing organic maize yields to CNV maize in USA from 1979 to 2005 were included in their study. Using their yield ratios for these studies, we estimate that the organic maize yield in USA is 97% that of conventional, or that organic maize is 3% lower than conventional. The study suggests that yield differences between OS and CNV is smaller in rainfed than in irrigated agriculture and that, overall, OS yields are higher than CNV yields in the developing world and lower in developed countries. The authors claimed that, globally, OS could produce enough food per capita to sustain the entire human population without expanding the agricultural frontier, and that leguminous cover crops could fix enough nitrogen to replace synthetic fertilizers.

Seufert et al. (2012) carried out a meta-analysis to compare the yields of those organic systems that truly follow the standards of organic certification bodies to conventional agriculture of different crops at a global scale. Seventy-four specific comparisons of organic vs. conventional maize yields were included, out of which seventy were for USA. Their results show that organic maize yields are approximately 14% lower than conventional maize, ranging from 10-20%. The authors considered CNV as either high –or low- input commercial systems, or subsistence agriculture. The study claimed that, in general, yield differences are highly contextual. Their results also show that OS perform better in rain-fed systems (-17% yield difference), compared to irrigated crops (-35% yield difference). When best management practices are adopted to particular crops and under specific growing conditions, OS can perform as well as CNV. Finally well-established OS perform better than recently converted systems.

De Ponti et al. (2012) analyzed a meta-dataset of 362 estimates comparing organic and conventional crop yields including 34 studies on maize, of which 26 were carried out in North America. They defined conventional agriculture as any agricultural system in which chemical inputs are used. The authors concluded that in the specific case of maize, on average, yields were only 11% lower than conventional systems, with a range of ±40% (*ibid*.).

Table 5.3 Average yield differences between OS and CNV maize from meta-analysis and reviews in USA

Author	**Average yield difference relative to CNV**	**Compared systems**	**Region**	**Period**
Badgley et al., 2007	-3% (-16 to +30%)	Organic and semi-organic vs. conventional and low-input	USA	1979-2005
Seufert et al., 2012	-14% (-10 to -20%)	Organic following standards vs. high -or low- input commercial systems and subsistence agriculture	USA	1975-2009
De Ponti et al., 2012	-11% (-40 to +40%)	Organic following standards vs. agricultural systems in which chemical inputs are used	Mostly North America	n.a.

Evidence shows that, at the individual crop level, maize is one of the crops that performs significantly better than the average crops in terms of relative yields (De Ponti et al, 2012; Reganold and Wachter, 2016).

5.3.2.1. Impacts of Organic Systems vs. Conventional Systems on ecosystem services: The case of the Corn Belt states

A literature review of existing long-term field experiments estimating yield differences between maize OS and CNV in Corn Belt States and Pennsylvania[60] was carried out. The results of field experiments on the provision of regulating ES from maize OS were reviewed afterwards. Posner et al. (2008) estimated that, on average, from 1990 to 2002, OS maize in Wisconsin yielded 13% less than a CNV maize-soybean rotation. The authors found that during wet years, favorable for weed growth, OS maize yields were lower (16-28%) and in years when weather conditions kept weed pressure low, OS yields were comparable to low-input CNV. Porter et al. (2003) reported the results of two trials from 1993 to 1999 in Minnesota, A 2 and a 4-year maize-soybean rotation were evaluated under four management practices, including CNV and OS. They concluded that OS maize in Minnesota yielded 9% less than a CNV. Pimentel et al. (2005a) used data from field experiments carried out from 1981 to 2002 at the Rodale Institute in Pennsylvania. They compared the performance of CNV against organic animal-based cropping and organic legume-based cropping and found that, relative to CNV, organic yields perform better after the transition period and in drought conditions. Their results showed that during the first five years of the experiment (1981-1985) maize yields were 20-28% lower for OS, compared to CNV (CNV yielded 5.9 ton/ha; organic legume-based cropping yielded 4.7 ton/ha; organic animal-based cropping yielded 4.2 ton/ha). After the transition period, maize yields were similar across systems: organic animal-based cropping yielded 6.4 ton/ha, organic legume-based cropping yielded 6.3 ton/ha and CNV 6.5 ton/ha. When comparing OS and CNV maize yields under drought conditions, the authors found that OS yields were significantly higher than CNV. Animal-based cropping yielded 6.9 ton/ha and organic legume-based cropping 7.2 ton/ha. CNV yielded 5.3 ton/ha for a difference of 28% for organic animal and 34% for organic legume.

Table 5.4 Average yield differences between OS and CNV maize from field experiments in USA

Author	**Average yield difference relative to CNV**	**State**	**Period**	**Notes**
Posner et al. 2008	-13% (-16-18% in wet years)	Wisconsin	1990-2002	Maize-soybean rotation. In less wet weather yields are comparable
Porter et al. 2003	-9%	Minnesota	1993-1999	Maize-soybean rotation
Pimentel et al 2005a	-20-28% during the first 5 years; similar yields afterwards	Pennsylvania	1981-2002	Yields are significantly higher after the transition period and under drought

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[60] We include Pennsylvania because the longest-running side-by-side field experiment comparing the impacts of maize OS on regulating ES relative to other agricultural systems in USA is hosted by the Rodale Institute

When recent studies that rely on national data for a specific year were analyzed, yield differences appear higher. Foreman (2014) used data only from the 2010 Agricultural Resource Management Survey and the Economic Research Service cost of production accounts to estimate production costs and actual yield of organic maize compared to conventional systems in the United States. In 2010 the actual yield of organic maize was 7.6 ton/ha (121 bushels/acre) vs. 9.9 ton/ha (159 bushels/acre[61]) of conventional maize: organic yields were 23% lower. Data from USDA´s 2011 Certified Organic Production Survey and USDA´s 2011 Crop Production Report show organic maize yields to be 7.4 ton/ha (119 bushels/acre), compared to 10 ton/ha (160 bushels/acre) for conventional maize, or 26% lower (McBride and Greene, 2015). Given that the data for these studies is nationally representative for 2010 and 2011, and that by the time almost all maize in USA was GM, we assume these numbers represent GM. The study did not specify whether the analyzed OS were in transition or well established systems either.

Evidence from the trials at the Rodale Institute, the longest-running side-by-side field experiments in USA showed that improved soil water retention in OS maize not only resulted in higher yields during periods of water scarcity, but also in increased groundwater recharge after the dry periods (Lotter et al., 2003; Pimentel et al., 2005a). OS maize also enhanced soil carbon, soil nitrogen and resulted in greater populations of mycorrhizal fungi (*ibid*.).

OS can sometimes adopt best management practices that are core to other agroecological systems, including minimal or no tillage, permanent organic soil cover of retained crop residues, cover crops, biological N fixation, pollinators management, etc. (Milder et al., 2012). Evidence of trials at the Rodale Institute shows that no-tillage in OS increased weed competition, reducing yields (Drinkwater et al., 2000). A similar concern regarding weed competition was found in a study carried out in Maryland (Teasdale et al., 2007). In the long term, maize OS that rely on a minimum level of tillage can enhance soil structure and fertility more than conventional conservation agriculture (no-tillage) (*ibid*.). Therefore, the strategic use of tillage and crop rotations can increase organic maize yields and reduce negative environmental impacts.

Water storage

Organic systems have higher water retention abilities (Liebig and Doran, 1999; Wells et al., 2000, quoted in Lotter et al., 2003), which may be the main mechanism with which they increase their tolerance to drought (Lotter et al., 2003). Beyond the promotion of better yields during drought, the improved water retention of OS increases groundwater recharge. Pimentel et al (2005b) compared levels of water percolation[62] between 3 maize production systems: 1) a 5-year conventional crop rotation of maize, maize, soybeans, maize and soybeans, typical of the Corn Belt region; 2) a typical livestock operation producing maize for animal feed consisting of a 5-year rotation of maize, soybean, maize silage, wheat and red-clover alfalfa hay plus a rye cover crop before corn silage and soybeans, and, 3) a production unit for grain without livestock, relying on nitrogen-fixing green manure crops as the primary source of nitrogen with a final rotation system that included hairy

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[61] 1 bushel/acre=0.0627 ton/ha

[62] Water percolation is the process by which water moves downwards after the rain or the irrigation has stopped (Brouwer et al. 1985)

vetch (a winter cover crop used as green manure), maize rye, soybean and winter wheat. Through the use of lysimeters, the authors collected water volumes percolating through each of these systems between 1991-2002. Their results showed that the average annual volume of percolated water was 15-20% higher in the legume-based and the animal-based organic systems, respectively, compared to the CNV.

Between 1996 and 2000, Lotter et al. (2003) collected data, from eight replications of similar maize systems: a 5-year maize-soybean rotation conventionally grown, an organic manure-based maize-soybean rotation, and an organic legume-based 3-year maize-soybean-wheat-green manure. The author installed steel cylinder lysimeters in four of the eight replications in order to collect WP and leachate for each maize system. Their results showed that the OS improved soil´s water-retention capacity, infiltration rate and water capture efficiency. The legume-based OS maize reported soil water content 13% higher than CNV, and 7% higher in soybean plots[63]. The average percolated water was 30% higher in both OS, relative to CNV in 1999, when a severe drought in the northeastern US was followed by heavy rains. In September, following high rainfall, both OS captured about 200% more water than CNV. The only time when CNV had more percolated water than OS was in May, meaning that OS retained more water in the soil for maize to use when water was scarce. During the 5-years of measurements, animal-based OS captured 25% more water than CNV, significantly more than the water captured by legume-based OS (16% more). Their estimates showed that the average annual percolated water harvest between 1996-2000 was approximately 190 l/m^2 for CNV, 220 l/m^2 for legume-based OS and 238 l/m^2 for animal-based OS.

Climate regulation from soil organic carbon

Pimentel et al. (2005a) estimated soil organic carbon (SOC) in 1981 and 2002. According to their results, animal-based OS and legume-based OS retained 200-300% more SOC, compared to CNV. The authors report an annual SOC increase of 0.98 ton/ha and 0.57 ton/ha versus 0.29 ton/ha in the CNV[64], respectively.

Delate and Cambardella (2004) compared CNV and OS using identical crop varieties during the 3-year transition period and the fourth year following a full rotation of maize-soybean-oat-alfalfa in Iowa. Their results showed that during the 3 years of transition to OS and one year beyond the transition, SOC concentration in the top 15 cm of soil increased 9% in the OS (from 24.1 g C/kg in 1998 to 26.2 g C/kg in 2001), whereas the increase was 3.3% in CNV (from 24.1 g C/kg to 24.9 g C/kg in the same years). During the 4 years, OS accumulated 5.4 ton C/ha.

Gattinger et al. (2012) carried out a meta-analysis including 74 studies comparing SOC concentrations and stocks between OS and CNV globally and for different crops. They found that, over a period of approximately 14 years, OS lead to SOC 3.5 ± 1.08 ton/ha higher than CNV in the upper 20 cm of soil. When considering only the highest quality studies containing OS with zero net input[65], the difference was smaller but still significant at 1.98 ± 1.50 ton SOC/ha. The authors estimated the net carbon gain due to conversion from CNV to OS by the difference

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[63] Animal-based OS was no part of this anaysis.

[64] Assuming approximately 4000 ton/ha of soil in the top 30 cm

[65] C inputs from organic fertilizers in the form of stacked manure, slurry or compost.

between initial and final SOC stocks for studies for which such data was available. They concluded that OS led to an annual carbon gain of 0.55 ton C/ha and CNV to a gain of 0.090 ton of C/ha. The results of five studies in the Corn Belt region and Pennsylvania included in their database[66] are presented in table 5.5 (Liebig and Doran 1999; Fraser et al., 1988; Delate and Cambardella, 2004; Hepperly et al., 2006; Grandy and Robertson, 2007). The average carbon stock in the OS of these studies was 49.05 ton, compared to 41.75 ton/ha for CNV[67].

Table 5.5 Annual soil carbon differences in OS and CNV

	SOC (ton/ha)	**CO_2 equivalent (ton/ha)**
Animal-based OS	0.98	3.60
Legume-based OS	0.57	2.09
Average OS	0.78	2.84
CNV	0.29	1.06

Source: own elaboration with data from Gattinger et al. (2012)

Soil fertility

Compared to CNV, OS perform better in preserving or enhancing soil´s biological and biophysical qualities (Reganold et al., 1987, Reganold, 1995, Clark et al., 1998, Drinkwater et al., 1998, Stölze et al., 2000, Mäder et al., 2002, Lotter et al., 2003, Delate and Cambardella, 2004, Pimentel et al., 2005a, Liu et al., 2007, quoted in Gomiero et al., 2011).

Pimentel et al. (2005a) estimated nitrogen levels in 1981 and 2002 in animal-based OS, legume-based OS, and CNV maize. Initially, all the systems had similar concentrations of N (0.31%). By 2002, the percentage of soil nitrogen in CNV remained unchanged while both animal-based and legume-based OS had increased significantly to 0.35% and 0.33%, respectively.

Teasdale et al (2007) compared the performance of no-tillage CNV maize to OS in a 9-year trial. The authors compared records of minimum-tillage practices for maize and other grains in a steep, dry, and erodible land from 1994 to 2002. The systems compared were different CNV no-tillage systems with a chisel-plow based OS. Their results show that despite the use of tillage, OS resulted in higher N concentrations at all depth intervals to 30 cm. Three tests of N availability confirmed that OS resulted in higher N available to maize in OS. The three tests are: 1) Yield differences between subplots with no applied N relative to nearby subplots treated with N were lower in OS than in CNV; 2) a pre-sidedress nitrate test[68] in subplots without applied N showed higher soil nitrate in OS than in CNV; 3) Corn ear leaf N at silking was also higher in OS.

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[66] Iowa, Nebraska, Michigan, and North Dakota

[67] According to EPA, the social cost of CO_2 in 2015 was $11/ton, $36/ton and $56/ton with an average discount rate of 5%, 3% and 2.5%, respectively.

[68] An in-season test that can determine if additional fertilizer N is needed for maize. This test should be applied in on soil samples taken just prior to sidedressing or the period of major N demand by maize

Table 5.6 Comparison of total nitrogen averaged over 2001 and 2002 at different soil depths

	Soil depth, cm			
	0-7.5	7.5-15	15-30	0-30
CNV No-tillage (g/kg)	1.29	0.93	0.58	2.8
OS (g/kg)	1.59	1.3	0.87	3.76

Source: own elaboration with data from Teasdale et al. 2007

Box 5.6 The premium price of organic maize

Author: Yatziri Zepeda

There can be several reasons for which organic maize is more expensive than conventional maize. It has been claimed that marketing and the distribution chain for organic crops is relatively inefficient and costs are higher because of the relatively smaller amounts that are commercialized. Higher prices have also been attributed to higher production costs. However, in the case of maize, there is evidence that the average operating costs per hectare were not statistically different between organic and conventional maize (Foreman, 2014). Actually, an analysis of the USDA showed that mean operating and capital costs per hectare of maize production were generally less for OS than for CNV (McBride and Greene, 2015). Total operating costs and operating plus capital costs per hectare for organic maize were about $32 and $20 per hectare lower with respect to conventional maize. The study found that the mean difference in total economic cost per hectare was insignificant but the composition of costs varied substantially for conventional and organic maize. Organic systems have lower costs in seed, fertilizer and pesticides than conventional growers, while conventional systems had lower costs in fuel, repairs, capital and labor (ibid). Most importantly, prices of organic crops also reflect the willingness to pay of the society for some characteristics that are not captured in the price of conventional maize, including their contribution to the enhancement of ecosystem services analyzed here, higher standards for animal welfare, reduced health risks to farmers and rural development by improving farmers´ income (FAO, 2016a). Considering similar production costs, it is likely that organic maize is more expensive than conventional because its supply might be limited compared to its demand (Foreman, 2014).

5.3.2.2 The value of negative environmental externalities of conventional maize systems

Beyond the provision of ES, OS can reduce negative externalities or prevent “dis-services” from agriculture. An extensive amount of literature demonstrates that intensive systems that depend on synthetic agrochemicals to sustain yield have significant negative impacts on water quality and quantity, the emission of greenhouse gases, soil fertility, biological control and pollination (Matson et al., 1997, Klein et al., 2007, Diaz and Rosenberg, 2008, quoted in Garbach et al., 2017).

In terms of management practices, the fundamental difference between OS and CNV is the use of synthetic fertilizers, insecticides and herbicides, which are banned in OS. In USA, GM maize has exceeded 80% of the total planted maize since 2008, currently accounting for over 92% of the total planted area of maize (USDA, 2016d). According to the latest Agricultural Chemical Use Survey, for the 2014 crop year, maize producers in USA applied approximately 8.9 million tons of fertilizers and 68 thousand tons of herbicides. The most widely used fertilizer was N (applied to 97% of planted hectares of maize), at an average rate of 161 kg/ha. Herbicides were the most extensively used pesticides (applied to 97% hectares). Atrazine was the most used active ingredient (applied to 55% of planted area, followed by glyphosate isopropylamine salt (applied to 38% of the maize area). Insecticides and fungicides were applied to 13 and 12% of the planted area, respectively. The most widely practice used to manage pests in maize areas was scouting for weeds (used on 92% of maize planted hectares), followed by crop rotations (82%), no-tillage or minimum tillage (67%), and the implementation of soil cover, mulching or other physical barriers (47%) (USDA, 2015a).

Table 5.7 Fertilizer and main herbicides applied to maize planted areas in 2014 in USA

		Fertilizer	
	% of planted hectares	Average rate for year (kg/ha)	Total applied (million tons)
Nitrogen (N)	97	161	5.08
Phosphate (P_2O_5)	80	71	1.8
Potash (K_2O)	65	91	1.95
		Herbicides (active ingredient)	
	% of planted hectares	Average rate for year (kg/ha)	Total applied (thousand tons)
Atrazine	55	1.14	20.5
Glyphosate isopropylamine salt	38	0.99	12.3
Acetochlor	29	1.4	13
Mesotrione	27	0.12	11.3
S-Metolachlor	27	1.23	10.7
Glyphosate potassium salt	24	1.3	10.2
		Fungicides[a] (active ingredient)	
Pyraclostrobin	9	0.137	66.2
Propiconazole	7	0.059	22.2
		Insecticides[a] (active ingredient)	
Tebupirimphos	4	0.008	2.2
Bifenthrin	2	0.08	10.8

Source: own elaboration with data from the Agricultural Chemical Use Survey 2014 (USDA, 2015a)

a = data for Iowa. In this state, the main herbicides used are Atrazine, Acetochlor, and Mesotrione.

A complete review of long-term data on the use of insect and herbicide-resistant GM maize revealed that the use of synthetic insecticides to maize has decreased in large-scale farms since the introduction of insect-resistant maize (Bt)[69], even in fields with non-Bt varieties of maize (National Academies of Sciences, Engineering and Medicine, 2016). Through a meta-analysis, Klümper and Qaim (2014) estimate that, around the world, the use of insecticide has been reduced from the adoption of Bt maize in 37%[70]. In USA, there has been a pattern of decreasing use of active insecticidal ingredient applied per hectare of maize from 1996 to 2010 (National Research Council, 2010a; National Academies of Sciences, Engineering and Medicine, 2016). In 1996 the amount of active ingredient of insecticides applied was 0.25 kg/ha of maize. This amount decreased to 0.08 kg/ha in 2001, 0.006 kg/ha in 2004, 0.04 kg/ha in 2007, and 0.025 kg/ha in 2010 (*ibid*.).

While the overall use of insecticide on maize in USA has decreased, there has been a dramatic increase in the use of neonicotinoid insecticides in maize fields since 2003 (Thelin and Stone, 2013, Douglas and Tooker 2015, quoted in National Academies of Scineces, Engineering, and Medicine, 2016), most likely, as a complementary pest-management approach (Petzold-Maxwell et al., 2013, Douglas and Tooker, 2015, quoted in National Academies of Sciences, Engineering, and Medicine, 2016). The average amount of neonicotinoid used per hectare is 0.001 kg of active ingredient (The National Academies of Sciences, Engineering, and Medicine, 2016).
There has also been a reported decrease in the total amount of all types of herbicides applied per hectare since herbicide–resistant crops (Hr)[71] were adopted (*ibid*.). However, there is evidence that such decrease has not generally been sustained and that it could be simply reflecting a transition towards high-efficacy herbicides. In the specific case of maize, a meta-analysis by Klümper and Qaim (2014) found that pesticide reductions were larger for Bt crops than for Hr crops. While Hr had reduced the quantity of herbicide used in some situations, they contributed to the increase in the use of broad-spectrum herbicides, such as glyphosate, elsewhere. Overall, the amount of herbicide applied to Hr maize did not change, compared to no-GM, they concluded. Fernandez–Cornejo et al. (2014) found that the use of active herbicidal ingredient in maize decreased from approximately 2.9 kg/ha in 1995 to less than 2.2 kg/ha in 2002, but increased to 2.5 kg/ha in 2010. The USDA estimates that 2.1 kg/ha of active herbicidal ingredient were applied to maize crops in 2014 (The National Academies of Sciences, Engineering and Medicine, 2016).

Information on the total amount of pesticides used in GM maize is insufficient to make conclusions on their impacts to human health and the environment though (National Academies of Sciences, Engineering, and Medicine, 2016). The use of smaller amounts of more potent herbicides is not necessarily desirable. A case-by-case evaluation is therefore necessary (*ibid*.).

Bourguet and Guillemaud (2016) carried out a global review of the environmental and health costs of pesticides and their evaluation. Over 60 studies and 30 datasets published between 1980 and 2014 were analyzed. The authors updated and, in retrospective, analyzed studies on the external costs of pesticides in USA according to

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[69] Insect-resistant GM maize contains genes from *Bacillus thuringiensis* (Bt), a soil bacterium that gives maize plants the ability to generate a toxic protein to eliminate targeted insects that feed on them

[70] Nevertheless, insect resistance outbreaks to these Bt GM constructs in plants in different regions of the world have occurred over time and are documented in the scientific literature.

[71] Herbicide-resistant maize is genetically modified to survive glyphosate, a powerful herbicide.

four categories: regulatory costs, human health costs, environmental costs and defensive expenditures[72]. Economic costs due to regulations governing pesticide use are estimated to have reached USD $4-US$22 billion per year in the 2000s[73]. In 2005, health costs from pesticides were evaluated at USD $1.5-15 billion, depending on whether fatalities due to chronic exposure are included or not. Overall estimated hidden and external costs probably reached the value of USD $39.5 billion per year at the end of the 80s, beginning of the 90s. A very important limitation of these studies is that many of them were carried out over 30 years ago. Since then, rapid changes in technologies, regulations and standards have completely shifted the landscape of agrochemical use.

Evidence of the potential benefits and costs of banning atrazine

Atrazine is currently the most widely applied herbicide in maize planted areas in USA. The states that applied the largest amounts of the active ingredient are located in the Corn Belt (Illinois 17%, Iowa 11%, Nebraska 10%, Indiana and Kansas, 9% each) (Farrugia et al., 2016).

Unsurprisingly, atrazine is also the pesticide most frequently found in groundwater (Ackerman, 2007), and even in rain (Hayes et al., 2002). A vast amount of research has studied its toxicity and effects on plants and animals. So far, the evidence has been mixed. It has been claimed that, when used in accordance with federal regulations, atrazine is harmless (Coursey, 2007). However, the EPA (Farrugia et al., 2016) carried out a recent ecological risk assessment analyzing hundreds of studies on the exposure and effects of atrazine as well as monitoring data of surface water for over 20 years. The study concluded that “aquatic plant communities are impacted in many areas where atrazine use is heaviest, and there is a potential chronic risk to fish, amphibians, and aquatic invertebrates in these same locations. In the terrestrial environment, there are risk concerns for mammals, birds, reptiles, plants and plant communities across the country for many of the atrazine uses. EPA levels of concern for chronic risk are exceeded by as much as 22, 198, and 62 times for birds, mammals, and fish, respectively. Terrestrial plant biodiversity and communities are likely to be impacted from off-field exposures via runoff and spray drift”.

By the time we were developing this study, the EPA´s ecological risk assessments for atrazine and other triazines was a draft going through a public consultation. Until conclusive evidence is confirmed, the economic valuation of the effect of atrazine and other pesticides on human health and ecosystems is challenging.

Ackerman (2007) suggested that the difference between the current value of U.S. maize production using atrazine and the next-best alternative to producers if atrazine were banned could reflect the value of atrazine for maize production. The author reviewed existing studies analyzing several aspects of farm revenues if atrazine were banned, including changes in herbicides used, in yield per hectare under new herbicides, in planted hectares if maize production became less profitable, in maize market price if production decreased, and changes in cultivations of crops from withdrawn hectares from maize production (Ribaudo and Bouzaher, 1994; EPA

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[72] The studies included for USA were Pimentel 2005a; Pimentel 2009; Pimentel and Burguess 2014; Pimentel and Greiner 1997; Pimentel and Hart 2001; Pimentel et al. 1980a; Pimentel et al. 1980b; Pimentel et al. 1991a; Pimentel et al 1991b; Pimentel et al 1992; Pimentel et al 1993a; Pimentel et al. 1993b; Steiner et al. 1995; Tegtmeier and Duffy 2004

[73] 2013 dollars

2002; Fawcett and Huxley, 2006; Coursey, 2007). Ackerman´s review found that, if contrary to claims from studies like EPA´s (Farrugia et al., 2016), atrazine turned out to be harmless and mistakenly banned, the costs would be relatively small. The author found that a ban of atrazine in USA would reduce yields by 6% to 1%. Actually, Italy and Germany, two countries that banned atrazine in 1991, have maintained the same yields. In that case, the economic impact would be an increased price of herbicides of less than 1% (*ibid.*).

In 2015, the total value of maize production in USA was USD $49 billion dollars approximately (USDA, 2016 c). A loss of 1-6%, which would reflect the cost of banning atrazine, is estimated at USD $490 million-$2.9 billion. The economic value of negative externalities caused by atrazine, such as those recently found by EPA, is to be compared to this number.

Evidence of the potential economic loss from glyphosate resistance

There is a similar ongoing debate regarding the impacts of glyphosate on human health and ecosystems. In 2015, the International Agency for Research on Cancer (IARC) of the WHO assigned a new classification to glyphosate as probably carcinogenic to humans. After that categorization, agencies focusing on public health issues like the European Food Safety Authority or Canada's Health Agency or EPA carried out their own evaluation and concluded that glyphosate is unlikely to pose a carcinogenic risk to humans, that direct food and dermal exposure to glyphosate should not be a health concern as long as federal regulations are followed when using it, and that it does not interact with hormones or the thyroid system (National Academies of Sciences, Engineering, and Medicine, 2016). The effect of glyphosate on insects like bees and butterflies has also been debated. Balbuena et al. (2015) conclude that the exposure of honeybees to levels of glyphosate commonly found in agricultural landscapes affects their navigation, impairing "(their) cognitive capacity needed to retrieve and integrate spatial information for a successful return to the hive…with potential long-term negative consequences for colony foraging success". The impact of glyphosate on monarch populations is also controversial and there is no consensus among researchers (National Academies of Sciences, Engineering, and Medicine, 2016).

However, there is consensus in that weeds have been evolving resistance to glyphosate in many locations, creating a major agronomic problem and costs (*ibid.*). According to the largest and most recent study on pesticide use in USA.,[74] over the period 1998-2011, on average, adopters of Hr maize used 1.2% (0.03 kg/ha) less herbicide than nonadopters, and adopters of Bt maize used 11.2% (0.013 kg/ha) less insecticide than nonadopters. When weighed by the environmental impact quotient (EIQ)[75], adopters of Hr maize used 9.8% less

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[74] The study collected annual farm-level data from over 5000 maize producers in USA during the period 1998-2011.

[75] In order to estimate the environmental impact of different herbicides, the authors weighted each active ingredient by its EIQ value. The limitations of the EIQ procedure have been acknowledged (Knoss and Cobur 2015). However, in the context of this study, the authors found it useful since it allows them to convert an array of attributes specific to each herbicide and insecticide into a single value that summarizes the toxicity of the chemical. The EIQ index in this study is formed by three components: 1) farmer exposure to dermal and chronic toxicity; 2) consumer exposure to chronic toxicity and potential groundwater effects, and 3) the environmental impacts on fish, birds, bees and beneficial arthropods.

maize herbicides, relative to nonadopters, and adopters of Bt maize used 10.4% less insecticides[76] (Perry et al., 2016). However, when investigating the gradual use of herbicide by Hr, particularly, glyphosate-tolerant maize adopters, there is clear evidence of an increase in herbicide use, which might be explained by the emergence of glyphosate weed resistance. Over time, glyphosate-tolerant maize adopters progressively used more herbicide relative to conventional maize producers. By 2008, this difference was positive and statistically significant. By 2011, weighing by the environmental impact quotient, Hr adopters used more herbicide per hectare than nonadopters (*ibid*.), with potential negative environmental implications.

Instead of looking for new chemicals to combat weeds, the National Academies' report encourages the adoption of agroecological weed management techniques such as cover crops and crop rotations, particularly in agricultural areas that have not been exposed to constant applications of glyphosate yet. Such practices can reduce the amount of chemical herbicides applied on farm, reduce farmers' production costs, reduce negative externalities off-site, and foster resilience in agriculture (National Academies of Sciences, Engineering, and Medicine, 2016).

A USDA study used data from the USDA´s Agricultural Resource Management Survey (ARMS) and an independent Benchmark Study to carry out a simulation to estimate the economic impacts of glyphosate. The study found that glyphosate resistance resulted in a significant reduction in total returns that affected maize producers (Livingston et al., 2015). Through a propensity-score matching approach, the authors estimated the impact of glyphosate resistance on maize in 2010 and 2012. The results showed that maize producers that reported a glyphosate resistance infestation in 2010 realized significantly lower total returns due to lower yields and higher agrochemical and fuel costs than similar maize producers who did not report the infestation. However, yield differences and input costs were not statistically different.

Maize yields for farmers that reported a glyphosate-resistance weed infestation (GR) were 8.4 ton/ha (133.74 bushels/acre)[77], compared to 9 ton/ha (143.29 bushels/acre) of farmers who had not reported GR. The total returns of farmers reporting GR were USD $166.23/ha lower (-$67.26/acre). The potential aggregate economic loss from glyphosate resistance is not trivial. About one-third of the farmers in Iowa reported to have glyphosate-resistant weeds, according to a survey carried out in 2012 (Arbuckle, 2014).

Evidence of the benefits of mitigating the use of fertilizers

The severity of low oxygen in coastal waters can be the combined result of many causes. However, eutrophication and hypoxia in the northern Gulf of Mexico have been mostly attributed to nitrogen loadings from the Mississippi River (Bricker et al., 1999). Agricultural inputs such as synthetic fertilizers and manure contribute about 65% of the nitrogen loads entering the Gulf from the Mississippi Basin (Goolsby et al., 1999). It is estimated that as much as 15 % of the nitrogen fertilizer applied to cropland in the 31 states of the Mississippi River Basin, ends up in the Gulf of Mexico (Ribaudo and Johansson, 2006, National Research Council, 2010b). It is estimated that organic rotations using compost leached an average of 35 kg/ha of N/year, compared to 53 kg/ha

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[76] For the case of soybean herbicides, the adoption of GM had a detrimental effect.

[77] 1 bushel/acre of maize = 63 kg/ha

N/year for CNV, a 34% reduction (Sánchez et al., 2004, quoted in National Research Council, 2010b). According to the Action Plan for Reducing, Mitigating and Controlling Hypoxia in the Northern Gulf of Mexico estimated that a 30% reduction in the N load would achieve the total goal of reducing the size of the Northern Gulf´s hypoxia to 5,000 km^2 (Rabotyagov et al., 2014). The adoption of OS management practices could contribute to such goal.
1991

Studies on the economic effects of hypoxia in the Gulf of Mexico are very few, most likely given the lack of conclusive evidence on the short and long-term impacts of sustained hypoxia on ecosystems, including the impacts on major fisheries (Rabotyagov et al., 2014). There is also a notable lack of studies evaluating lost nonuse or existence values associated with hypoxic conditions and eutrophication (*ibid.*). Using benefit transfer methods, Jenkins et al. (2010) estimated the benefits of restoring wetlands in the southern part of the Mississippi River, an intervention that could help reduce the amount of nitrates entering the river and eventually the Gulf of Mexico. The estimated value of N mitigation per hectare of land considered was between USD $900 and USD $1,900.

5.4 The cultural value of maize diversity

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The Millennium Ecosystem Assessment (MEA) defines Cultural Ecosystem Services as “the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience” (MEA, 2005). Cultural ecosystem services are usually included under non-consumptive use values (Sarukhán and Whyte, 2003). Even though they are commonly recognized as important, they are usually poorly defined, poorly quantified and poorly integrated into the ecosystem services framework and management plans (De Groot et al., 2005; Daniel et al., 2012). The physical, mental and emotional benefits provided by ecosystems are often subtle and intuitive (Kenter et al., 2011) and their value, which lies within the realm of subjectivity, depends on individual or collective perception of the contribution of these services to wellbeing (Eickenet et al., 2009; Scullion et al., 2011; Milcu et al., 2013). This attribute may be the reason why many consider that the value of most cultural ecosystem services cannot be assessed using methods of neoclassical economics. Nevertheless, some researchers consider their value to be measurable since they are expressed in human action (Chan et al., 2012). In order to capture the importance of ecosystems services and to incorporate these into economic and other policy decision-making, it is necessary to establish the link between a given ecosystem and its goods and services, and the value placed on these by individuals. This has been one of the main challenges in valuing cultural services (Vejre et al., 2010, quoted in Hernández-Morcillo et al., 2013).

The most frequently studied cultural ecosystem services are those most easily quantifiable, further widening the gap between counting that which matters to people and that which is easily measured. Hernández-Morcillo et al. (2013) conducted a review of current publications assessing or valuing cultural ecosystem services. These authors included a total of 200 studies in their review, of which the majority focused on ecotourism (54%), aesthetic services (14%), sense of place (13%), education services (9%), spiritual and religious services (7%) and inspirational services (3%). Another review from Miclu et al. (2013), which included 104 publications from 2005 to 2012, found a similar trend in the services assessed, in that the most common services assessed (in descending order and using a different classification scheme) were recreation and ecotourism, aesthetic values, spiritual and religious values, educational values, cultural heritage values, bequest, intrinsic and existence values, inspiration, sense of place, knowledge systems, social relations and cultural diversity (*ibid*.). The most commonly used methods to estimate these services were contingent evaluation, market price or cost approaches, travel cost method, hedonic pricing method, benefit transfer, choice experiments and deliberative economic valuation (Miclu et al., 2013). Nevertheless, given the inherent problems of monetary valuation, many authors increasingly focus on noneconomic deliberative techniques such as Delphi surveys or the Q method (Daily et al., 2009). Some authors specifically argue for using methods that reflect the relationship between a specific cultural service and its user, including personal experience, imagination, expectation, and preference, thus achieving an explicit psycho-cultural perspective (Martín-López et al., 2009; Kumar and Kumar, 2008). An increasingly popular alternative to evaluation is spatial representation of ecosystem services, which is frequently associated with participatory mapping or photo-based methods (Kumar, 2010; Sherren et al., 2010).

The aim of the present section is to provide a general perspective of the paramount importance of maize diversity as a key provider of cultural ecosystem services for smallholder maize systems. We review the importance of maize and maize landraces for Ecuadorian and Mexican societies, emphasizing the cultural centrality of this crop as expressed in its diversity of uses, especially for culinary purposes.

Cultural value of native maize and agrobiodiversity in Ecuador and the Andes

The Andes mountain range from Colombia to northern Argentina is one of the eight centers of origin of domesticated plants in the world. For thousands of years, numerous ethnic groups living in a myriad of Andean micro-environments have been adapting crops to their ecological and cultural needs, which has led to the richness of species and varieties so characteristic of Andean agriculture today (Tapia and Carrera, 2011). In the same plot, it is common to find different potato varieties, along with several varieties of maize, quinoa, beans, roots, tubers and fruit. Agronomic knowledge and management practices have been passed down from generation to generation. The estimated number of peasant communities growing native crops in Ecuador, Peru and Bolivia alone amounts to 10,000 (Tapia, 2008). The diversity of crops that characterize these holistic cultures is the result not only of crossbreeding practices, but also of attention given to local water, soil and climate conditions. For example, the celebration of Inti Raymi (the June solstice feasts) and Koya Raymi (fertility feasts) coincide with the harvest and planting of maize and other crops, and are an opportunity for the community to share chicha, tamales and other maize-based preparations (Carrera, 2012; Tapia, 2015).

Ecuador, one of the countries with the highest agro-biodiversity per unit area in the world, is home to a large variety of ecosystems and cultures. In the 1960s, 29 maize races and several complexes were identified in the country (Timothy et al., 1963) and additional races have been found in the last two decades (Yánez et al., 2003). The conservation of maize landraces described half a century ago has been confirmed by collection and characterization studies such as that of Tapia (2015). According to this author, the factors that have made conservation possible include the practice of subsistence agriculture, limited penetration of improved varieties (3%) and the preservation of ancestral traditions by rural communities (*ibid*.). Another contributing aspect is the wide variety of uses to which the maize is put (Tab. 5.8). For example, *kcello*, an Ecuadorian maize race, is used to prepare as many as 18 different dishes, while the *grape cluster* variety has more specific uses, such as preparation of *colada morada*, a beverage common throughout the mountains on the Day of the Dead festivities. The diversity of uses for maize among rural communities is manifested in the many dishes prepared with this staple in everyday life as well as for religious festivals (such as the Corazas, an ancestral celebration centered on the annual cycle of the crop) (Coba, 1989, quoted by Tapia, 2015), and entertainment events in both urban and rural settings (Figs. 5.7 and 5.8). However, while most races found in the 1960s still exist, some like *chillo* have begun to dwindle due to the advance of urbanization, or have shifted to new areas (Tapia, 2015).
There are 35 indigenous peoples in Ecuador, 14 of which live in the mountains and depend on maize cultivation. Mestizo communities also maintain a close relationship with their environment and benefit from the knowledge and uses of different maize varieties. Most producers (54%) plant from two to seven maize varieties along with other associated crops, mainly beans (50%), and 98% of the production is for their own consumption. It has also been documented that, on average, about 35% of maize seeds for replanting are obtained from the family harvest, 32% from relatives, 15% from neighbors, while only 18% is purchased in the market. Seed exchange is

rare (24%) and is practiced mostly by younger producers (< 30 years old), although usually it is older people who are responsible for the farm or for maize cultivation (Tapia, 2015).

Maize is of great importance to the Ecuadorian diet, and the many uses given to this staple in both rural and urban settings have ensured the conservation of its genetic diversity. Table 5.8 shows the great diversity of culinary maize uses of different maize landraces present in Ecuador. Lima and Tapia (2010) also mention other food (*mazamorra, uchu jacu* and *chuchuca*) and medicinal uses (infusions of maize stigmas).

Figure 5.7 Maize at the entrance of Sangolquí and Pallatanga, Ecuador. (Picture by Edison Sylva)

Figure 5.8 Local festivities related to maize. (Picture by Edison Sylva)

Table 5.8 Diversity of food uses per maize landrace in the highlands of Ecuador (Taken from Tapia, 2015)

Landrace name	**Food uses**	**Number of uses**
Kcello Ecuatoriano	Milk, chaquis, chichi, cob, colada, envueltos, flour, humitas, machica, mollete, morocho, mote, motepata, soup, tamales, tortas, tortillas, toasted.	18
Mezcla	Milk, roasted, chichi, chivil, choclo, colada, envueltos, flour, humitas, morocho, morochillo, mote, bread, sango, tamales, tortillas, toasted.	17
Zhima	Chanquita, chichi, chivil, cob, chumalita, colada, flour, humitas, machica, morocho, mote, bread, sango, tamales, tortillas.	15
Chillo	Maize balls, cauca, chitos, cob, colada, flour, humitas, morocho, mote, bread, soup, tortillas, toasted.	13
Cuzco Ecuatoriano	Chicha, cob, colada, flour, humitas, machica, mazapanes, morocho, mote, sango, tamales, timbulos, tortillas.	13
Mishca	Maize balls, cauca, cob, tanda cob, colada, flour, humitas, mote, bread, sango, soup, tortillas, toasted.	13
Morochón	Chicha, cob, flour, morocho, mote, humitas, bread, soup, tamales, timbulos, tortas, tortillas, toasted.	13
Blanco Harinoso Dentado	Milk, cauca, cob, flour, humitas, machica, mote, sango, soup, tamales, tortillas, toasted.	12
Guagal	Maize balls, buñuelos, chiguiles, cob, flour, humitas, morocho, mote, tamales, tortillas, toasted.	11
Blanco Blandito	Cauca, cob, mote cob, colada, flour, humitas, machica, mote, tamales, toasted.	10
Cónico Dentado	Cob, flour, humitas, machica, morocho, mote, sango, tamales, tortillas.	9
Complejo Mishca-Chillo	Chicha, cob, colada, flour, humitas, popcorn, mote, tortillas, toasted.	9
Sabanero Ecuatoriano	Cob, flour, humitas, morocho, mote, quimbolitos, soup, tosted.	8
Complejo Mishca-Huandango	Colada, flour, humitas, mote, bread, tamales, tortillas.	7
Uchima	Chicha, flour, machica, mote, tamales, tortillas.	7
Montaña Ecuatoriana	Cob, flour, humitas, pollada, tamales, tortillas.	7
Racimo de Uva	Colada, purple colada, cuchichaqui, flour, humitas.	6
Patillo Ecuatoriano	Arepas, cob, flour, mote.	4
Chaucho	Chicha, cob, flour.	3
Chulpi Ecuatoriano	Purple colada, tosted, flour.	3
Complejo Chillo-Huandango	Flour, toasted.	2

Cultural value of native maize and agrobiodiversity in Mexico and Mesoamerica

For Mexico, and Mesoamerica in general, maize is a cultural object and not simply a commodity as in other regions. It could be argued that it is a “cultural keystone species”, *i.e.*, a culturally salient species that has a major influence on the cultural identity of a people (Garibaldi and Turner, 2004). Maize’s role in Mexican cultural identity is unrivaled by any other crop, even though the country is also the center of origin of about one-tenth of the most important crops of the world (Perales and Aguirre, 2008). Maize is a fundamental element of the myths of origin of Mesoamerican cultures: the human being is made from maize or comes from this plantation, and its appearance marks a before and after in human history, it is a metaphor for life itself, especially the birth, growth, reproduction and death of human beings (Carrillo, 2010). To this day, the people of Mexico consider themselves “men and women of maize” and maize endows Mexicans with a sense of place and a shared identity, as described by Huff (2006) for the Mayas of Guatemala. Despite all economic and cultural changes undertaken by Mexico in the past decades, maize remains a defining feature of Mexican culture as it has been for several thousand years.

Maize’s key role in defining cultural identity for Mexicans materializes through its prevalent place in the landscape, its essential and irreplaceable place in daily nourishment and cuisine, its multiplicity of use, as well as in narratives and ceremonial roles. Cultural goods can be measured within a standard economic model as “economic value” (not synonymous with commercial value) and as “cultural value”; this seeks to reflect the worth of the good assessed in cultural terms (Throsby, 2003). Cultural value is multi-dimensional, unstable, contested, lacks a common unit and may contain elements that cannot be easily expressed according to any quantitative or qualitative scale (Throsby, 2003). Determining the cultural value of maize in Mexico is necessarily challenging because of the qualitative nature of several aspects of this type of analysis. Garibaldi and Turner (2004) and Gandini and Villa (2003) proposed several aspects for the analysis of cultural significance and value for species with cultural value and livestock breeds; these include intensity of use, language, possibility of replacement, antiquity and others. Applying these types of criteria to maize demonstrates its unique position in Mexican culture (Tab. 5.9 and 5.10).

Table 5.9 Estimation of maize as keystone cultural species for the three countries studied (following Garibaldi and Turner 2004)

Element	**Aspect**	**Mexico**	**USA**	**Ecuador**
Intensity	Is the species used routinely and/or in large quantities	5	5	3
Intensity	Does the species have multiple uses	5	5	4
Naming and terminology	Does the language incorporate names and specialized vocabulary relating to the species	5	1	3
Role in narratives, ceremonies or symbolism	Is it prominently featured in narratives, ceremonies, etc.	5	2	3
Persistence and memory of use in relationship to cultural change	Is the species ubiquitous in the collective cultural consciousness and frequently discussed	5	1	3
Level of unique position in culture	Would it be hard to replace this species with another native species	5	3	3
Extent to which it provides opportunities for resource acquisition from beyond the territory	Is this species used as a trade item for other groups	5	5	3
Total		35	22	22

Table 5.10 Estimation of the cultural value of maize for the three countries studied (following Gandini and Villa 2003)

Element	**Aspect**	**Measure**	**Mexico**	**USA**	**Ecuador**
Value as historical witness	Antiquity	Period crop present	5	3	3
Value as historical witness	Agricultural systems	Systems historically linked to crop	5	2	2
Value as historical witness	Role in the landscape	Extent of contribution to rural landscape	5	3	2
Value as historical witness	Role in gastronomy	Historical role in development of typical agricultural products	5	2	3
Value as historical witness	Role in folklore	Historical role in local folklore	5	1	2
Value as historical witness	Role in handicrafts	Role in local handicrafts	3	0	1
Value as historical witness	Presence in forms of higher artistic expression	Extent of crop as typical component of rural farming in arts	5	0	1
Value as custodian of local traditions	Role in maintaining the landscape	Percentage of farms that contribute crop in farming landscape	5	2	2
Value as custodian of local traditions	Role in maintaining gastronomy	Presence of linkages between crop and local products or recipes	5	1	2
Value as custodian of local traditions	Role in maintaining folklore	Presence of folklore and religious traditions in area linked to crop	5	2	2
Value as custodian of local traditions	Role in maintaining handicrafts	Presence of handicrafts in the area linked to crop	2	0	2
Total			50	16	22

In Mexico, maize is prevalent throughout the landscape. With about 8 million ha planted annually, it has more acreage than the next 9 crops together; it is planted from sea level to over 2600 masl, from the south of the country to the north, no other crop is sown under such diverse conditions. While maize is used primarily as a staple in Mexico, it has multiple uses and is the species with more uses reported in the Florentine Codex, written by Francisco Hernández several decades after the Spanish conquest (Estrada, 1989). The antiquity of maize as a domesticate is presently calculated at about 9000 years B.P. (Matsuoka et al., 2002; Piperno et al., 2009), although its prevalence in Mesoamerican culture might only have some 3000 years (Smith, 1967). The importance of maize before Columbus is expressed in a large number of words in the more than 60 native languages present in Mexico, including words for parts of the plant, its phenology, cultivation and food preparation (Stross, 2006). Maize is also present as deities, images and glyphs of ancient Mexico and is a central protagonist in the myths of the creation of humans, maize dough was used to form them (Florescano, 2003; Lopez, 2003).

Mexico’s iconic milpa system is constructed around maize. In its normal form, the milpa is the cultivation of maize, beans and squash in the same field and season. Some milpas have only two of these three elements, in some regions the beans are planted well into the season after the maize. Milpas are also commonly planted only with maize, but many have other crops in addition to beans and squash, such as chili peppers, husk tomato, sweet potato, tobacco, banana or citrus fruits. As such, the milpa is prevalent throughout the landscape and typical of Mexican agriculture. The milpa as a socio-cultural system is composed of various elements, such as the family, community, political organization, worldview, knowledge, values, ritual manifestations (*i.e.* cultural practices) and customs implied in the preparation and consumption of food, among others. Each social or cultural milpa system in different regions has its own dynamics, its objectives, its organization, but the productive system works and reproduces (Terán, 2011). Historically, rural communities had ceremonies or rituals for maize and the milpa; these can extend from rituals to ask for a good year for the milpa, to the blessing of maize seed in church. Although these practices have apparently decreased in frequency, they are still not uncommon and in many regions and communities form part of the year’s festivities.

The importance of maize as a central component of Mexican cuisine is well known, the number of dishes based on maize is in the hundreds and more continue to be developed. All this is possible because of nixtamalization, the cooking of maize in an alkaline solution, commonly calcium hydroxide, which was discovered several thousand years ago. Nixtamalization improves the nutritional quality of maize and, without this process; diets based on maize can incur alimentary problems. It is rare to eat a proper Mexican meal without maize products such as tortilla or tamale and maize is consumed in rural areas in almost every meal. Even the corn smut, a disease of the maize ear, is consumed as a delicacy. Handcrafts of maize are not too common, but figurines of people and other objects are made with the corn husk. Maize can be found in multiple forms of artistic expression, from poetry to paintings, and rural life in Mexico would be unrecognizable without the ubiquitous presence of maize.

Undoubtedly, cultural preferences play a significant role in the maintenance of maize landraces, not only in countries such as Mexico and Ecuador with a high diversity of maize, but also in regions where this crop is not of central importance in terms of food production. Gastronomic uses are related to the conservation of landraces, since these present the correct flavors and textures for the preparation of traditional dishes (Bellon et al., 2003b; Magorokosho, 2006; Vaz Patto et al., 2007; Knežević-Jarić, 2009; Kneţević-Jarić et al., 2010). Hilgert et al.

(2013) found a meaningful relationship between maize diversity and the gastronomic use diversity associated with maize in traditional communities of Argentina's Northern region. In the East of Serbia, local maize is grown in reduced areas of less than 1 hectare in order to produce flour that is used to prepare several traditional dishes (Kneţević-Jarić et al., 2010). Among the Mayan people in Mopan, Guatemala, white varieties are grown unripe in order to prepare tamales, and ripe to prepare tortillas' or to feed animals (Steinberg, 1999). Black and red maize are not for sale, as these have religious and spiritual connotations and are preferentially consumed during festivities. Finally, black maize is believed to promote physical strength and resistance to hard labour or when people experience a long period of fasting (*ibid.*). Among the Yungas from Argentina, the Culli variety (black/red maize) is grown to protect lodging and plots, in the preparation of chicha (a fermented beverage) and for purifications (Hilgert et al., 2013). For Steinberg (1999) and Chambers et al. (2007), landrace diversity loss is not a direct result of the expansion of MVs, but rather of social change related to generational replacement in the context of rising urbanization and industrialization. Replacing landraces implies not only a worsening of genetic diversity of crops, but also loss of the diversity of associated crops, agro-ecological interrelations, the diversity of herbaceous and wild related species and the traditional knowledge that sustains and modifies these (Brush, 2000), for all these reasons there is an imperative to create public policies aimed at the preservation of such richness.

The importance of cultural ecosystem services provided by traditional maize smallholder systems is demonstrated by the paramount place of maize in the cultural matrix of hundreds of generations that have depended on it for their survival and expansion: the system demanded the development and continuous improvement of countless techniques to cultivate, store and transform; led to the emergence of a cosmogony and religious beliefs and practices that make it a sacred plant; It allowed the development of a culinary art of surprising richness; it marked the sense of time and space ordered according to its own rhythms and requirements; it gave rise to the most varied forms of aesthetic expression; and carried the necessary background to understand forms of social organization, ways of thinking and the knowledge and lifestyles of the widest strata (CONACULTA, 2005).

6. EXTERNALITIES OF MAIZE SYSTEMS: MONETARY VALUATIONS

Adán Arana/CONABIO

6. Externalities of Maize Systems: Monetary Valuations

6.1. Valuation of ecosystem services for maize production in Ecuador, Mexico and USA

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Agriculture is always a joint production system yielding multiple crops that depend on a set of agricultural inputs, and a set of biophysical conditions and ecosystem processes, conceptualized here as ecosystem services (ES). Even though it has long been recognized that ecosystem services are crucial for agricultural production, the value of these environmental inputs has seldom been estimated. Agricultural production depends on supporting services, such as those underlying soil fertility and nutrient cycles; regulating services, such as pest and disease control, crop pollination, water purification and weather regulation; and provisioning services, such as the supply of water (Zhang et al., 2007; Power, 2010). Without these services, agricultural production simply could not exist. Among these services, two have been recognized as critical for crop production: water provision and soil fertility (Mueller et al., 2012). However, other variables such as solar radiation, temperature, weeds and diseases may also seriously affect productivity (van Ittersum et al., 2013).

Production functions define the relation between a production input and the produced output. In simple terms, a production function is a mathematical function that relates the various inputs involved in the production of a good with the amount of goods produced. The production function method has been used as way to uncover the value of specific attributes of the environment, or of particular ecological functions and processes (Barbier, 1994; Barbier, 2007; Kumar, 2013). As clearly stated in a document of The Economics of Ecosystems and Biodiversity (TEEB): “Production function-based approaches (PF) estimate how much a given ecosystem service (e.g., regulating service) contributes to the delivery of another service or commodity which is traded on an existing market” (Kumar, 2010).

The use of production functions to value ecosystem services has one main advantage over stated preference methods. Stated preference methods rely on the respondents’ understanding of the benefits to them of the service in question, whereas production functions evidence the relationship between the ecosystem service and an output that has an established market price. Therefore, any change affecting the ecosystem service related to the marketed good is transferred to individuals “via changes in the costs and prices of the final goods and services” (*ibid*.). An example of the use of production can be found in Sparling et al. (2006) who generated a pasture production model based on soil chemical and physical characteristics in order to derive the monetary value of soil organic matter to crop production in three contrasting New Zealand soil orders (Gley, Melanic, and Granular Soils). To monetize the value of soil organic matter, pasture productivity was converted to an equivalent weight and financial value of milk solids (*ibid*.). Another example about the use of a production function to assess the value of an ecosystems service input can be found in Núñez et al. (2006) who estimated the economic value of south Chilean temperate forests as they contribute to maintain fresh water supply.

6.1.1 Methodology

6.1.1.1 Objective

The aim of the present study was to identify the relation between a set of ecosystem services and maize production in our three case study countries, in order to value their contribution to maize production. As mentioned in the introduction these case study countries were selected for different reasons: Mexico for its role as a center of origin and diversity of maize, Ecuador for its significant maize diversity, and USA because it's the world's largest maize producer and marketer.

First, we identified the relationship between the factors of production - ecosystem services and inputs - and the quantity of maize produced. We then estimated the value of the marginal physical product of all inputs using the price of maize at farm level. For this we developed a Cobb-Douglas production function to estimate the value of the marginal product (VMP) of ecosystem services for maize production among high-yield irrigated, high-yield rainfed, mixed and low-yield rainfed municipalities/counties in Mexico and USA, and among Ecuadorian cantons located in the Amazonia, Andean and Coastal region.

6.1.1.2 Selection of variables

- *Ecosystem services and their proxies*

Ecosystem services are abstract constructs that refer to the benefits people obtain from ecosystems (MEA, 2005). As such, they cannot be measured directly but rather through variables that act as proxies of the services. The selection of ecosystems services to include in the regression models to assess their contribution to maize production was done with the help of expert knowledge and the availability of data for the three case study countries.

It is widely recognized in the literature that among the main abiotic limiting factors for crop growth are water, solar radiation and soil nutrients (Grassini et al., 2009; van Ittersum et al., 2013). To capture these, we chose the following proxy variables for ecosystem services: **1)** Annual precipitation and irrigated maize area were selected as proxies for provision services for agriculture. Even though irrigated might be considered a management factor given the obvious importance of hydraulic infrastructure for the allocation and extraction of stored water to the agricultural fields, the main resource for agricultural production is ultimately water; **2)** Rainfall seasonality and maximum temperature were selected as regulation services for agriculture. Rainfall seasonality refers to the intra-annual variation in precipitation rather than the year to year variation in rainfall; as such it reflects how rainfall is distributed along the year. The rainfall seasonality coefficient was originally developed by Walsh and Lawler (1981) after Ayoade (1970) and represented "the sum of the absolute deviations of mean monthly rainfalls from the overall monthly mean, divided by the mean annual rainfall…" This coefficient varied from 0 (rainfall is equally distributed in all months) to 1.83 (annual rainfall occurs in a single month). The coefficient used here (Hijmans et al., 2005) is calculated in a similar way but the resulting number is multiplied by 100. Clearly, rainfall seasonality has important implications for agricultural production since crop growth depend not only on the quantity of rainfall but also on its distribution throughout the year (see discussion); **3)** Sown area and soil organic carbon were considered proxy variables for supporting services. Soil organic carbon could also be considered a proxy for carbon sequestration or nutrient cycling (Finvers, 2008), but here we used it as a support service for agriculture given the important role that the presence of soil organic carbon has for plant productivity (Lal, 2006).

- *Management variables*

In addition to these ecosystem services, management practices represent important production factors that have been instrumental in increasing maize yields during the past five decades (Duvick, 2005; Stewart et al., 2005). We thus include them also in our regression models (see below). It should be noted that the main aim of this study was to estimate the contribution of ecosystem services to maize production; as such we only used agricultural inputs as covariates to control for their contribution to this production. For this reason we do not deal with them in detail neither in the results nor the discussion sections.

6.1.1.3 Data collection

Data for the multiple regressions comprised both ecosystem services and management variables. The variables, measurement units and periodicity of the available data for each country are defined in tables 2.1 to 2.4 in annex 2.1. Annual precipitation, maximum temperature and rainfall seasonality were obtained from Hijmans et al. (2005) and represent interpolations of observed data for the period 1960-1990. Soil organic carbon content (SOC) in the first 30 cm of soil was taken from ISRIC[78] at a resolution of 250 meters. The environmental variables used were obtained from spatial data sources originally presented in a raster format with a resolution from 250 m to 10 km. Spatial data was extracted and aggregated at the administrative unit (county, canton, municipality) using the mean of all pixels contained within the administrative polygon in question.

Management variables were collected from different sources and periods for each country. Management variables for each country were not identical but represent the same inputs to a certain extent. The data for Ecuador was obtained from the *National Agricultural Census* of 2000. Management practices are reported at the farm level and are specific to maize production. Data for four different types of maize are provided (soft dry maize, hard dry maize, soft *choclo* maize and hard *choclo* maize). We only used the information for dry maize, which is the equivalent of the maize grain in USA and Mexico.

Management data from Mexico was obtained from the *Agricultural and Ejidal Census* of 2007. Note that these variables reflect agricultural management practices in the municipality but are not specific to maize production. We assume that management practices that characterize agricultural production in a municipality also characterize maize production since maize is the main crop in almost all of Mexico. Given that management variables were expressed in hectares in the original database, we calculated the percent of agricultural area in which these were utilized and employed this percent to calculate the equivalent surface of maize.

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[78] SoilGrids: https://www.soilgrids.org/#/?layer=geonode:taxnwrb_250m

In the case of the USA, data was obtained from the *USDA Agricultural Census* from 2012. Maize production data were transformed from acres and bushels into hectares and tones. Data pertaining to the use of herbicides, insecticides and fungicides were taken from Baker and Stone (2015)[79]. These data are also not specific to maize production. Nevertheless, we only included pesticides listed in the USDA Chemical Use Survey from 2012 and 2014 that are used on maize. Pesticide data were transformed from pounds to kilograms and summed within each pesticide category (herbicide, insecticide and fungicide).

Before running the regressions we transformed all variables into their natural logarithms using the LN function in Excel Office. To manage the zeros we added 1 to all the variables in the database prior to the logarithmic transformations. Additionally, since precipitation and temperature are a quadratic function of maize yield (Schlenker and Roberts, 2006; Lobell et al., 2011; Lobell et al., 2013; Ren et al. 2014), we included a quadratic term in the original Cobb-Douglas function.

6.1.1.4 Data analysis

The Cobb Douglas production function defines the relationship between the amount of output produced and the amount of inputs used in a production process as follows:

$$Q = AK^{a}N^{b}$$

Where Q is the amount of product and K and N the amount of non-environmental and environmental inputs respectively. Linearization of the Cobb-Douglas production function by transforming the dependent and independent variables into a logarithmic scale yields:

$$\ln Q = \ln A + a \ln K + b \ln N$$

in which a and b denote the output elasticities of non-environmental and environmental inputs.

To estimate the model we ran a series of linear regressions with heteroscedasticity correction for the relevant maize production systems in each country using the open source Gretl software (Cottrell and Lucchetti, 2017). Administrative units of Mexico and USA were classified as 1) high-yield irrigated (> 2 ton/ha and > 75% of maize area under irrigation), 2) high-yield rainfed (> 2 ton/ha and > 95% of maize area rainfed), 3) mixed (>5% and <75% of maize area under irrigation irrespective of yield), and 4) low-yield rainfed (< 2 ton/ha and > 95% of maize area rainfed). In the case of Ecuador we grouped cantons according to their region: Amazonia, Andes and coastal region. We did not used the same grouping as in the case of the other countries for two reasons: 1) there was a specific interest of the TEEB committee in the mentioned geographical regions, and 2) the small number of observations (*i.e.* cantons) complicated the usage of the same grouping criteria used for the other countries.

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[79] https://water.usgs.gov/nawqa/pnsp/usage/maps/about.php

The objective of the multiple regression analysis was to estimate the parameters of the relationship and degree of association between ecosystem services, management factors and maize production—the quantitative relation between the independent variables (ecosystem services and inputs) and the dependent variable (maize production).

The production function provides an account of the quantity of product that we can expect to obtain when we combine inputs in a certain way. That is, through multiple regressions we determine the way in which maize production varies in relation to 1) ecosystem services/regulation and 2) inputs.

Mexico

The initial regression model for Mexico had the following specification:

$\ln(MP_i) = \beta0 + \beta1 (\ln SOC_i) + \beta2\ 2(\ln AP_i) + \beta3 (RS_i) + \beta4\ 2(\ln MxT_i) + \beta5 (SA_i) + \beta6 (IA_i) + \beta7 (\ln IS_i) + \beta8 (\ln H_i) + \beta9 (\ln F_i) + \beta10 (\ln MT_i) + \beta11 (Mid\text{-}A_i) + \beta12(High_i) + \varepsilon i$

where,

MP= maize production (tons); β0= intercept; SOC= soil organic carbon (g/kg of soil); AP= annual precipitation (mm); RS= coefficient of rainfall seasonality; MxT= maximum temperature (^{o}C); SA= sown area (ha); IA= irrigated area (% of sowed area)[80]; IS= area sowed with improved seeds (ha); H= area treated with herbicides (ha); F= area treated with fertilizers (ha); MT= sown area with exclusive use of mechanical traction (ha); Mid-A= mid-altitude[81]; High= highland.

A set of variables included in the initial models had to be excluded from the final models given the presence of collinearity between the predictor variables. These were identified using the *Variance Inflation Factor* (VIF) method. The *Variance Inflation Factor* "…measures the inflation of the variance of a slope estimate caused by the non-orthogonality of the predictors over and above what the variance would be with orthogonality" (Liao and Valliant, 2012: p.53). A commonly used rule of thumb is to consider VIF values above 10 to be a signal of the presence of multicollinearity between the independent factors (*ibid*.).

As none of the values of the VIF values for the high-yield rainfed, mixed and low-yield rainfed municipalities were above 10, the final models for these were the same as the initial models for all Mexican municipalities. In the case of high-yield irrigated municipalities the high VIF for management variables indicated a high correlation between the management variables pointing to the use of technological packages. In order to reduce the high

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[80] The variable of irrigated area was not included in the models of high-yield and low-yield rainfed municipalities in Mexico, Ecuador and USA because there are practically none irrigated areas as a result of the criteria used to define this category (*i.e.* at least 95% of area is rainfed).

[81] For Mexico we included two dummy variables to control for median altitude of municipalities. In Ecuador this variable was already controlled for by the grouping of cantons in the before mentioned regions. In USA only 84 counties were located above the 1200 m above sea level, we therefore did not include altitude as a dummy in this case.

multicollinearity between predictor variables, we excluded most of the management practices variables from the model, leaving the use of improved seeds as the main indicator for technological input.

The finally estimated regression model for high-yield irrigated municipalities was the following:

$$\ln (MP_i) = \beta 0 + \beta 1 (\ln SOC_i) + \beta 2\ 2(\ln AP_i) + \beta 3 (RS_i) + \beta 4\ 2(\ln MxT_i) + \beta 5 (SA_i) + \beta 6 (IA_i) + \beta 7 (\ln IS_i) + \varepsilon i$$

where,
MP= maize production (tons); β0= intercept; SOC= soil organic carbon (g/kg of soil); AP= annual precipitation (mm); RS= coefficient of rainfall seasonality; MxT= maximum temperature (^{o}C); SA= sown area (ha); IA= irrigated area (% of sown area); IS= area sowed with improved seeds (ha).

The final regression model for high-yield rainfed, mixed and low-yield rainfed was the same as the initial model specified above (note the exception for rainfed municipalities).

USA

The estimated regression models for USA had the following specification:

$$\ln (MP_i) = \beta 0 + \beta 1 (\ln SOC_i) + \beta 2 (\ln AP_i) + \beta 3 (RS_i) + \beta 4\ 2(\ln MxT_i) + \beta 5 (HA_i) + \beta 5 (IA_i) + \beta 6 (\ln H_i) + \beta 7 (\ln F_i) + \beta 8 (\ln I_i) + \varepsilon i$$

where,
MP= maize production (tons); β0= intercept; SOC= soil organic carbon (g/kg of soil); AP= annual precipitation (mm); RS= coefficient of rainfall seasonality; MxT= maximum temperature (^{o}C); HA= harvested area (ha); IA= irrigated area (% of harvested area); H= use of herbicides (kg); F= use of fungicides (kg), I= use of insecticides (kg).

Since the values of the VIF for all regression model remained below 10, we did not exclude any of the predictor variables from the models.

Ecuador

The estimated regression models for Ecuador had the following specification:

$$\ln (MP_i) = \beta 0 + \beta 1 (\ln SOC_i) + \beta 1\ 2(\ln AP_i) + \beta 2 (RS_i) + \beta 3\ 2(MxT_i) + \beta 4 (SA_i) + \beta 5 (IA_i) + \beta 6 (\ln IS_i) + \beta 7 (\ln W_i) + \beta 8 (\ln PPM_i) + \beta 9 (\ln AF_i) + \beta 10 (\ln AM_i) + \varepsilon_i$$

where,

MP= maize production (tons); β0= intercept; SOC= soil organic carbon (g/kg of soil); AP= annual precipitation (mm); RS= coefficient of rainfall seasonality; MxT= maximum temperature (^{o}C); SA= sown area (ha); IA= irrigated area (% of sown area); IS= sowed area with improved seeds (ha); W= workers hired (#); PPM= area with phytosanitary measures (ha); AF= area treated with fertilizers (ha); AM= agricultural machines (#).

The values of VIF for the costal regression model showed a similar pattern of technological use as high-yield irrigated factors in Mexico, were most of the management practices were highly correlated. For the same reason we only kept the use of improved seeds as the main indicator of agricultural intensity in the final regression model for this region.

6.1.1.5 Value of the marginal product of ecosystem services

Agricultural revenue is equal to output multiplied by the price of the product. The revenue function is the revenue obtained by a specific level and combination of inputs. The increase in revenue, when an additional unit of input is added, is known as the value of the marginal product (VMP). This is equal to the price of the product multiplied by the marginal physical product of the input (*e.g.* labor, capital, fertilizers, sown area, precipitation, etc.) which is the rate at which total output changes as a result of a change in the quantity of that input.

In the Cobb-Douglas production function the regression coefficients are output elasticities (*i.e.* a measurement the responsiveness of output to a change in levels of inputs) through which the value of the marginal product is calculated. The regression coefficients represent a measure of the percentage change in the output given the increase in 1% in the input (*i.e*. ecosystem services and management factors). These beta coefficients obtained through the regression were used to calculate the value of the marginal product of a production input as follows:

$$VMP_{ij} = PM_i \times b_{ij} \times \left(MP_i / X_{ij} \right), j = 1, \ldots, n$$

where,
PM_i= Price of maize per ton in USD in the production system[82]; β_{ij} = beta coefficients of significant independent variables in the regression equation for that system; MP_i= maize production in tons in the ith production system; X_{ij}= the jth independent variable in the ith production system in corresponding unit of measurement.

VMP was calculated for each observation, by agro-system classification by country.

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[82] The price per ton of maize we used was taken from FAOSTAT (2016) and represented producer prices for maize. FAO (http://www.fao.org/waicent/faostat/agricult/prodpric-e.htm) defines the variable of producer prices of a given commodity as: "the national average prices of individual commodities comprising all grades, kinds and varieties received by farmers when they participate in their capacity as sellers of their own products at the farm gate or first-point-of-sale." For Ecuador producer prices of maize in 2000 were of USD $380 per ton, in México USD $223.5 in 2007 and in USA, USD $271 in 2012. The use of producer prices from different years responded to the use of management data from those specific years for the regression models.

The impact of a discrete change in the jth input can then be calculated as:

$$PM_i \times \Delta MP_i = PM_i \times b_{ij} \times \left(MP_i / X_{ij} \right) \times \Delta X_{ij}$$

where ΔX_{ij} is discrete 1% increase in the physical value of the input.

Finally, to assess the value of the marginal product by ha and ton, we simply divided the result by the sown area and maize production of each canton, municipality and county.

Caveats

There are several caveats to take into account when interpreting the results of the present exercise. These limitations emerge as a result of the type of available data and the level of aggregation of the data.

Aggregation of data

Data is aggregated at the level of the administrative units, which without doubt obscures the variability of the state of ecosystem services provision for agriculture. This will be especially pronounced in the case of cantons/municipalities/counties with a large surface and/or administrative units characterized by a diversity of geo-climatic conditions. In addition to the spatial aggregation of the data, its temporal aggregation represents a source of uncertainty as well. Temperature and precipitation have a differential impact on maize production depending on the growth stage of the plant (e.g. Çakir, 2004). Our precipitation and precipitation variability data reflect annual values, while maximum temperature represents a data point.

Type of data

The second source of uncertainty is related to the source of our proxy variables of ecosystems services. Soil and climatic data do not represent primary data but modelled data (Hijmans et al., 2005; https://soilgrids.org/). The third source of uncertainty comes from available data with respect to agricultural management practices for Mexico and USA. Data about management practices directly used for maize production is only provided at the state level, that is, the data available at the municipality and county level represented general agricultural management practices. Our first attempt to control for this lack of maize-specific agricultural management data was to select those administrative units with more than 75% of agricultural surface dedicated to maize production. However, in the case of high-yield irrigated counties in USA close to 90% of all counties had maize areas that represented less than 50% of the total agricultural area which was also the case in 87% of the high-yield rainfed and mixed counties. In the case of USA data we intended to control for the lack of maize-specific herbicide and pesticide data by including only those pesticides listed in the 2012 and 2014 USDA Chemical Use Survey.

In spite of the previously mentioned shortcomings we consider that this exercise provides a useful starting point to value the ecosystems services underlying maize production.

6.1.2 Results

6.1.2.1 Ecuador

A total of 203 cantons were used for the three production functions developed for Ecuador. Ecuadorian regions were characterized by different environmental conditions. Cantons in the Amazonia were located at all ranges of altitudinal floors ranging from 230 to 3,162 msl (mean= 1,350 msl). Amazonian soils were characterized by relatively high levels of soil organic carbon associated to the warm climate, and high levels of precipitation homogeneously distributed along the year (Fig. 6.1 and 6.2). Andean cantons were located at mid and high altitudes from 150 to 3,672 (mean= 2,312 msl) in areas with relatively steep slopes (Fig. 6.1). Mean annual temperature in this region ranged from 6.8 to 24.7 °C with a mean of 15 °C. Cantons in the coastal region were located at a very low altitude were precipitation was highly seasonal and temperature was high (Figs. 6.1 and 6.2).

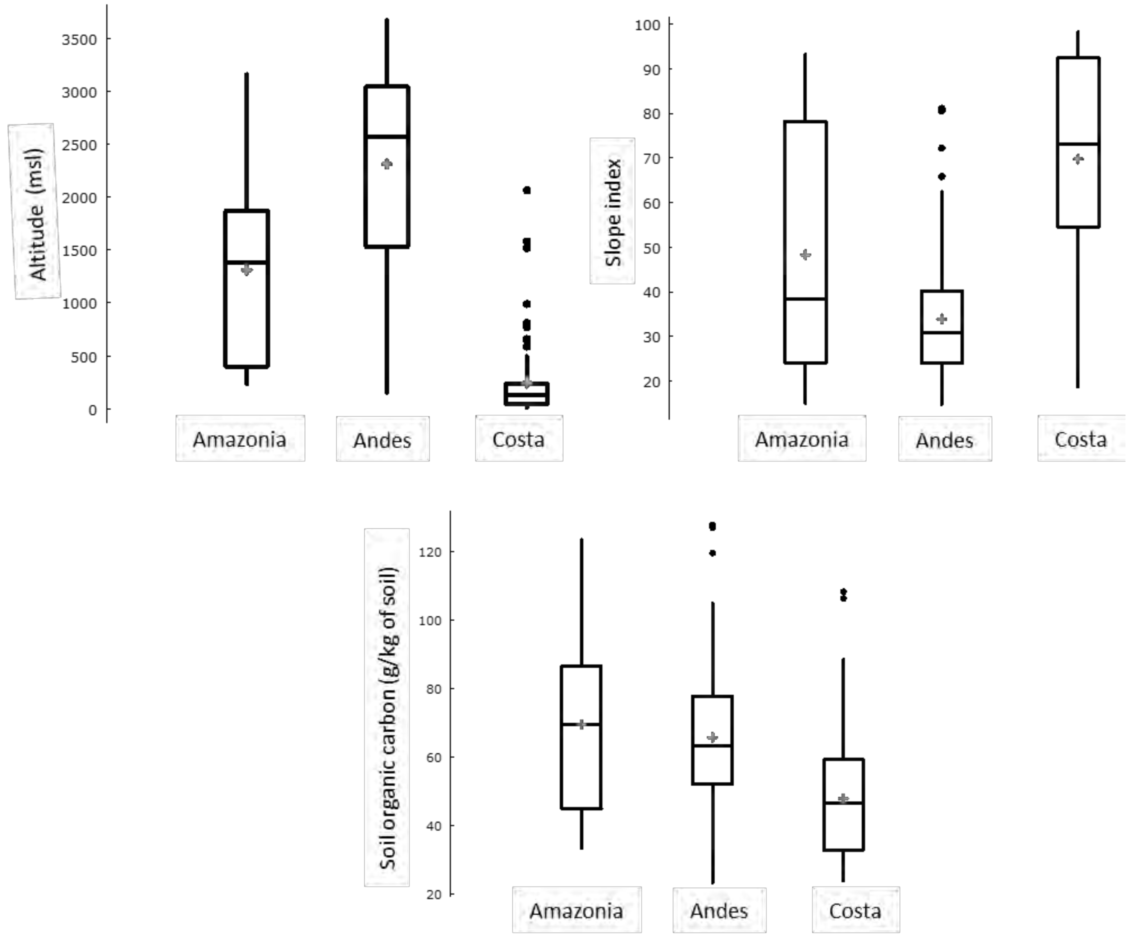

Figure 6.1 Boxplot for altitude, slope index and soil organic carbon conditions among maize producing regions in Ecuador. Note: High values of the slope index indicate less pronounced slopes.

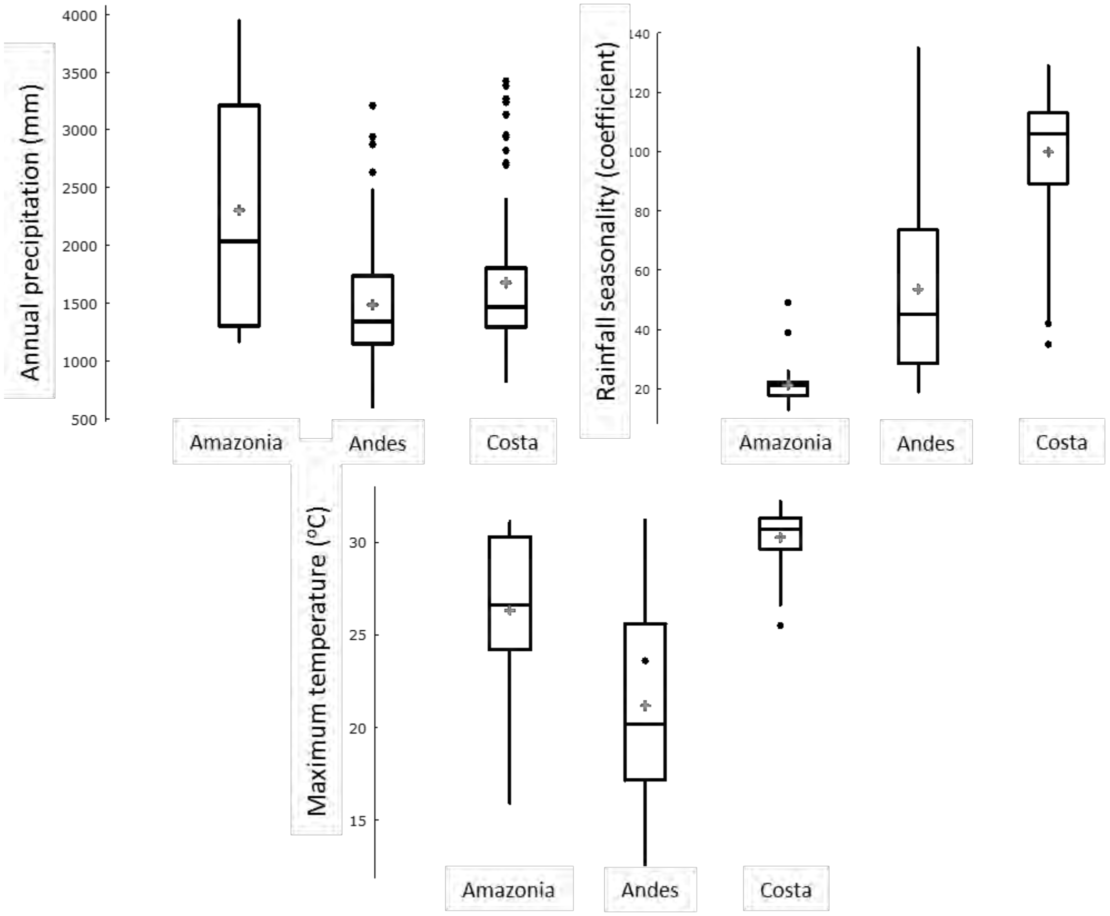

Figure 6.2 Boxplot for rainfall seasonality, maximum temperature and annual precipitation.

Coastal cantons produced 77% of dry maize in the country in 55% of the sown area of maize. These cantons were also the most input intensive: 95% of the dry maize was sown in monoculture, 74% of this area was object of phytosanitary management, 48% use certified seeds and 78% was grown with fertilizers (Tab. 6.1). Coastal cantons were followed by Andean cantons in intensity, while Amazonian cantons showed the lowest proportions of agricultural inputs, but also a very small area were maize is produced.

The Amazonia model explained 99% of the variance in maize production (Tab. 2 in annex 2.3). A positive relation of maize production with the variables of sown area and phytosanitary measures was found ($p< 0.05$). Tropical wet conditions are favorable to bugs and weeds; therefore, the use of any phytosanitary control has an effect on production. Annual precipitation, number of agricultural machines and area fertilized were negatively related with maize production. The negative relation of maize production and annual precipitation was somehow expected given the high levels of precipitation in the Amazonian region (Fig. 6.2), which can lead to waterlogging negatively affecting maize production.

The Andean model explained 97% of the variance in maize production (Tab. 2 in annex 2.3). A positive relation of maize production with maximum temperature, sown area, use of improved seeds, phytosanitary measures and agricultural machines was found. Even though average maize yields are similar to those in the Amazonia region, production conditions are different in the Andes region. The harvested area is seven times larger than in the Amazonia, and the higher production inputs reflected in the higher use of phytosanitary measures, improved seed and agricultural machines had certainly a positive effect on maize production in certain cantons. The relatively cool temperature found in the Andes poses a challenge for maize production in this region, as the average max temperature barely reaches 23 ^{o}C and the temperature at which maize shows its peak growth is at aprox. 27^{o}C (Hatfield and Prueger, 2015).However, this range and peak in maize growth in response to temperature will probably differ for different maize landraces (Perales et al., 2003; Mercer at al., 2008). The Andean model also showed a negative relation between maize production and rainfall seasonality.

Table 6.1 Comparative statistics of production factors in Ecuador

	Amazonia	**Andes**	**Costa**
Yield (ton/ha), mean (SD)	0.76 (0.2)	0.6 (0.4)	1.5 (0.8)
Maize production (ton), total	5,252	29,512	120,068
Sown area (ha), total	6,457	45,311	59,747
Irrigated area (ha), total (% of maize area)	26.4 (0.4)	7,076.2 (15.6)	5,158.02 (8.6)
Workers hired (#), total (#/ha)	1,166 (0.2)	14,890 (0.3)	20,926 (0.4)
Area sown with improved seeds (ha), total (% of maize area)	346.5 (5.4)	4,287.4 (9.5)	29,141.2 (48.8)
Area treated with phytosanitary measures (ha), total (% of maize area)	295.2 (4.6)	1,3711.1 (30.3)	44,744.7 (74.9)
Agricultural machines (#), total (#/ha)	1,835 (0.3)	11,694 (0.3)	13,561 (0.2)
Area treated with fertilizers (ha), total (% of maize area)	219.7 (3.4)	17,516.6 (38.7)	47,074.9 (78.8)
N	38	89	76

Finally, the coastal model explained 98% of the variance in maize production (Tab. 2 in annex 2.3). A positive relation of maize production with soil organic carbon, sown area and use of improved seeds was found. This region produces four times more maize than the Andean region and almost 20 times more than the Amazonian region, and the use of improved seed has a large effect in this production ($p < 0.001$). The use of improved seed was highly correlated with use of phytosanitary measures and agricultural machines; however, in spite of the input intensive methods of this region maize yields were only two times larger than in the Andes. As can be observed in figure 6.1., the coastal region of Ecuador showed the lowest levels of soil organic carbon content (SOC). Hence, SOC might only be a limiting production factor in this region, and not in the Andean region were soils are rich in this nutrient given their volcanic origin; or in the Amazonia were SOC is deposited as the results of the rapid decay of abundant organic matter in tropical humid rainforests. It should be noted however, that the SOC content of rainforest soils is quickly lost by the conversion of forests to agricultural lands (van Noordwijk et al., 1997; Guo and Gifford, 2002).

Value of the marginal product of ecosystem services in Amazonian, Andean and coastal cantons in Ecuador

The estimated production functions for maize production in the Amazonian, Andean and coastal cantons of Ecuador in 2000 were the following:

Amazonia maize production= -0.1338 (Annual precipitation) + 1.0988 (Maize production) + 0.0537 (Improved seeds) + 0.0542 (Phytosanitary measures) -0.0630 (Agricultural machines) -0.0704 (Fertilizers) + e

Andean maize production= -0.2266 (Rainfall seasonality) + 0.5722 (Max temperature) + 0.5010 (Sown area) - 0.1587 (Irrigated area) + 0.1092 (Improved seeds) + 0.1314 (Phytosanitary measures) + 0.2428 (Agricultural machines) + e

Coastal maize production= 0.3046 (Soil organic carbon) + 0.7560 (Sown area) + 0.4161 (Improved seeds) + e

As mentioned above, by using the elasticities and the value of maize at farmers' prices, we estimated the values of the contributions of ecosystem services and other inputs to maize production. Note that the sum of the values presented in table 6.2 corresponds to total VMP by maize system. In other words, when the input in physical terms fluctuates or increase in one percent (average reported) the production increases (or decrease) in that total value in currency in dollars for the whole maize agro system classification. The estimated marginal value of the products represents the contribution of the ecosystem services to the production of maize: an estimate or approximation to the value of ecosystem services with a quantitative basis, with other inputs ceteris paribus assumption.

a) Value of the marginal physical product of ecosystem services: land and soil

Results from the regression model for the three Ecuadorian regions show that land had one of the largest effects over maize production. Increasing in 1% the sown area increases maize production in 1.09% in the Amazonia, 0.50% in the Andean region, and 0.75% in the coastal region (Tab. 6.2). This increase in maize production cast a VMP of land of USD $21,928 in the Amazonia, USD $56,185 in the Andean region and USD $344,951 in the coastal region of Ecuador.

Soil organic carbon had a positive relation with maize production only in the coastal region of Ecuador were most of the maize is produced. In this region, increasing in 1% the organic carbon content of soil would increase maize production in 0.30% representing a gain of USD $138,988.

b) Value of the marginal physical product of ecosystem services: climate

Annual precipitation resulted in a negative elasticity for maize production in the Amazonian region of Ecuador. An increase of only 23.1 mm in the annual precipitation would represent a loss of the maize output equivalent to USD $2,672 in that region. In the Andean region, rainfall seasonality showed to have a significant negative effect on maize production. Therefore, if rainfall would become less homogeneously distributed the loss in maize production would amount to USD $25,413 (Tab. 6.2). In the Andean region, were heat and solar radiation represent a limited resource, maximum temperature positively affected maize production. Here, the marginal value of maximum temperature was of USD $61,793, given by an average increase in 0.2 ^{o}C.

Table 6.2 Value of the marginal product of production inputs (ecosystem services and management practices) for maize production in Ecuador. Maize Production function 2000, all values in current price 2000 USD.

Input Factor (physical units)	**Elasticities (β coeff)**	**ΔX_i (average) physic units**	**∑ (USD) j=1…j=N**	**Average (USD)**	**VMP/ ha (USD)**	**VMP/ ton (USD)**
			Ecuadorian Amazon N= 38 cantons; Harvested maize area = 6,457 (ha) Maize production = 5,252 (tons)			
Sown area (ha)	1.0988**	1.7	21,928	577	3.2	4.2
Annual precipitation (mm)	-0.1339**	23.1	-2,672	-70	-0.4	-0.5
			Ecuadorian Andes N= 89 cantons. Harvested maize area= 45,311 (ha). Maize production = 29,512 (tons)			
Maximum temperature (°C)	0.5722**	0.2	61,793	694	6.2	15.2
Sown area (ha)	0.5010**	5.1	56,185	631	1.1	1.9
Irrigated area (ha)	-0.1587**	0.2	-2,758	-31	-0.2	-0.4
Rainfall seasonality (coeff)	-0.2266*	0.5	-25,413	-286	-0.5	-0.9
			Coastal region of Ecuador N= 76 cantons. Harvested maize area= 59,747 (ha). Maize production= 120,068 (tons)			
Sown area (ha)	0.7560**	7.9	344,951	4,539	4.0	2.9
Soil organic carbon (g/kg of soil)	0.3046*	0.5	138,988	1,829	1.6	1.2

Source: Author's estimations. Notes: Maize farm price USD $380 in 2000; only significant environmental factors were included in the table.

* Significant at 95% confidence level

** Significant at 99% level

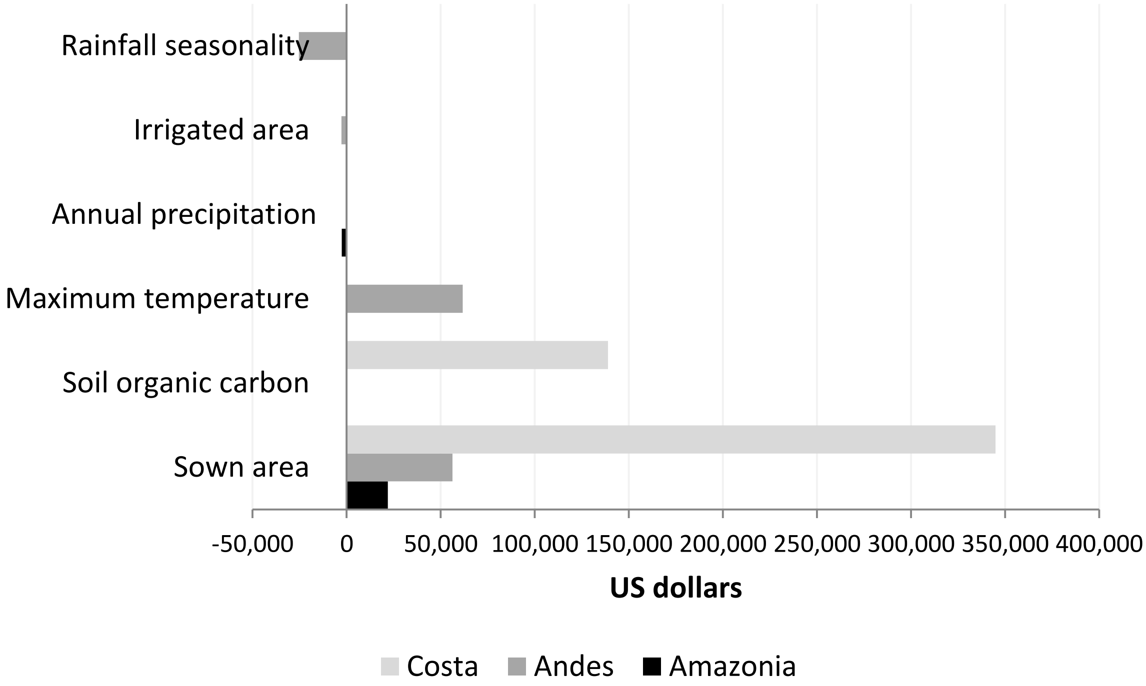

Figure 6.3 Value of the marginal product of ecosystems services for maize production in different maize-producing regions in Ecuador

As can be observed in figure 6.3, sown area and maximum temperature had a similar VMP for maize production in the Andean region pointing to the crucial role of solar radiation for maize production in this region. In the coastal region the largest VMP was for sown area followed by the area sowed with improved seeds and the content of SOC in soil. Soil organic carbon was only statistically relevant for maize production in the coastal region. This does not mean that soil organic carbon is irrelevant for maize production in other regions. The absence of a significant effect of soil organic carbon in the Andean or Amazonian region was SOC content in soil was higher may be due to a ceiling effect were adding more SOC does not necessarily increase maize production.

To get a sense of the relative importance of ecosystem services in the different Ecuadorian cantons, Figure 6.4 reports the sum of the VMP estimates for all services. The cantons in which ecosystem services have the greatest impact on maize production are some cantons in the coastal regions, and in the Pindal and Celica cantons of the Loja province in the in the Andes region.

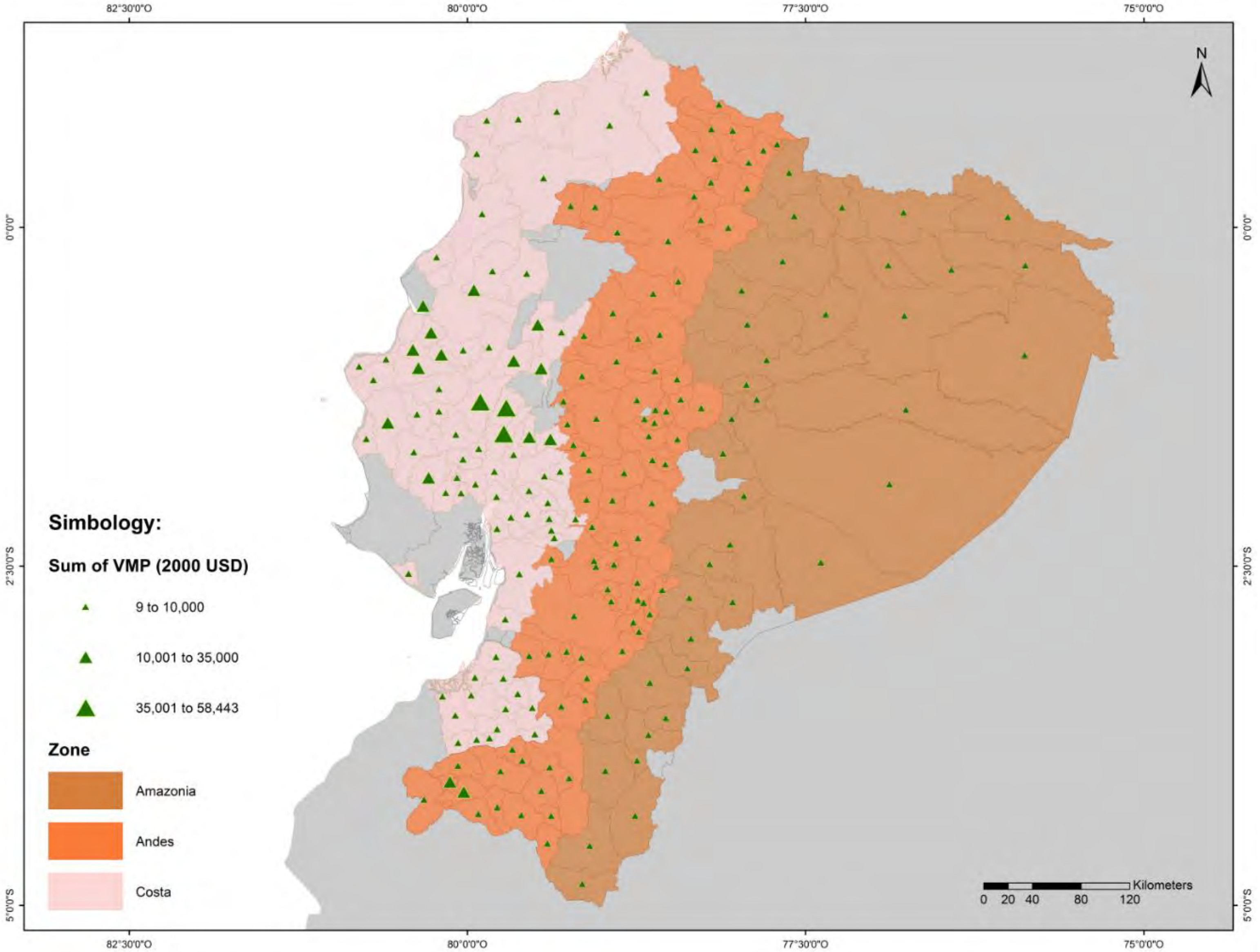

Figure 6.4 Sum of VMP of ecosystem services in different maize producing cantons in Ecuador. Note: The triangles represent the sum of all significant environmental factors that had a positive effect on maize production and for which VMP was estimated.

6.1.2.2 Mexico

A total of 2,287 municipalities were included in the regression analysis for Mexico. The large majority of municipalities consisted of low-yield rainfed (46.3%), followed by mixed (32.8%), intensive rainfed (16.4%) and intensive irrigated municipalities (4.5%). Mixed municipalities produced 36.3% of the total maize production, followed by intensive or high-yield rainfed (27.1%), intensive irrigated (25.5%) and low-yield rainfed (11%) municipalities (Tab. 6.3). High-yield irrigated municipalities were located at low to median altitude levels (mean (SD): 1008 (784) msl)) and in geographical areas that were relatively flat (mean (SD): 77.3 (17)), they also were characterized by having soils with low SOC content, low in annual precipitation and high in reference evapotranspiration, which are typical climate conditions of dry warm regions in the north of Mexico (Tab. 3.1 in annex 2). High-yield irrigated units were characterized by a high intensity of inputs as they had the greatest percent of maize area under irrigation, area treated with herbicides and insecticides, use of improved seeds and exclusive use of mechanical traction (Tab. 6.3).

High-yield rainfed and mixed municipalities showed a similar level of input intensity with respect to the area sown with improved seeds and the use of herbicides and insecticides (Tab. 6.3). However, mixed municipalities had a higher area with exclusive use of mechanical traction. Mixed municipalities were also found at higher altitudes but showed a better climatic and soil profile with 1.6 higher SOC levels and annual precipitation than in high-yield irrigated municipalities. In contrast, low-yield units showed the most favorable environmental conditions in terms of soil organic carbon, annual precipitation, lower reference evapotranspiration, in addition to the lowest use of inputs (Fig. 6.5, 6.6 and tab. 6.3). These municipalities were distributed at medium altitudes (mean (SD): 1260 (816) msl), and over relatively steep terrain (mean (SD): 50.7(26.7)).

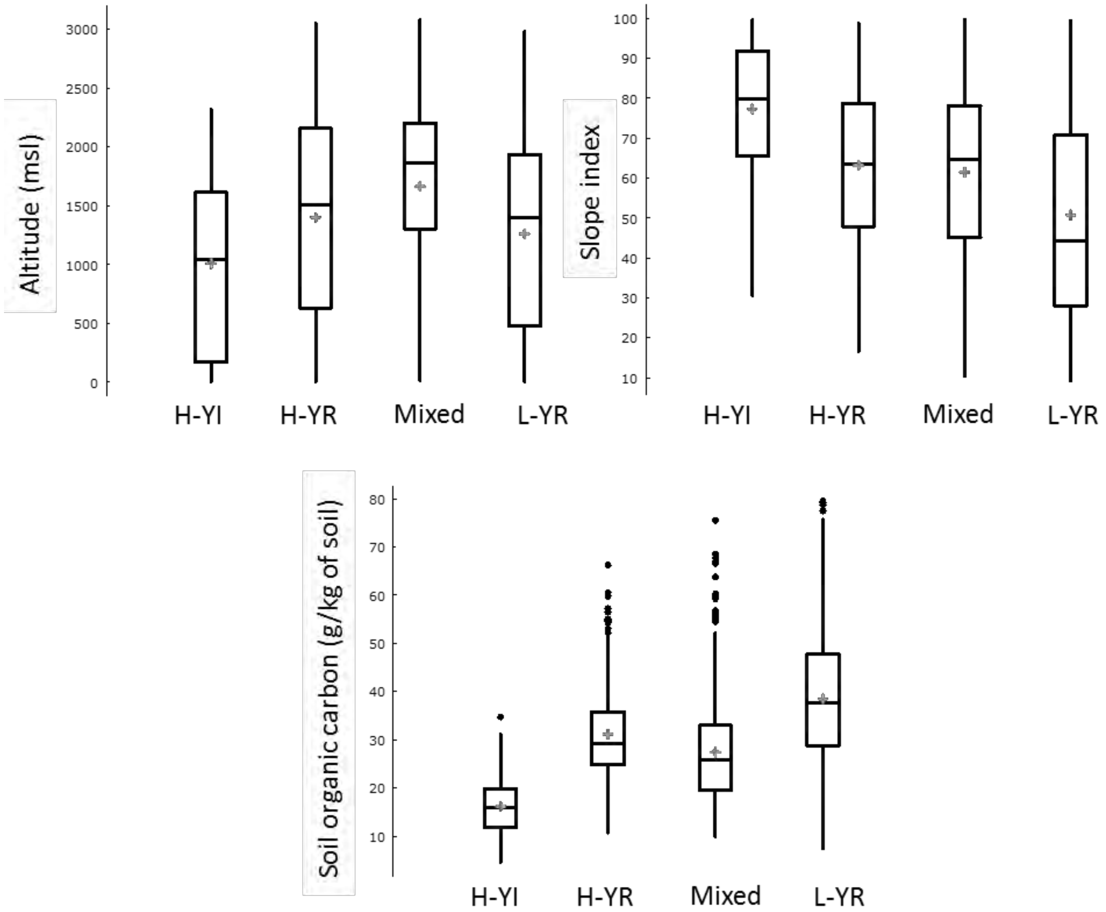

Figure 6.5 Boxplot for altitude, slope index and soil organic carbon conditions among maize producing municipalities in Mexico. Legend: H-YI= high-yield irrigated, H-YR=high-yield rainfed, L-YR=low yield rainfed. Note: High values of the slope index indicate less pronounced slopes.

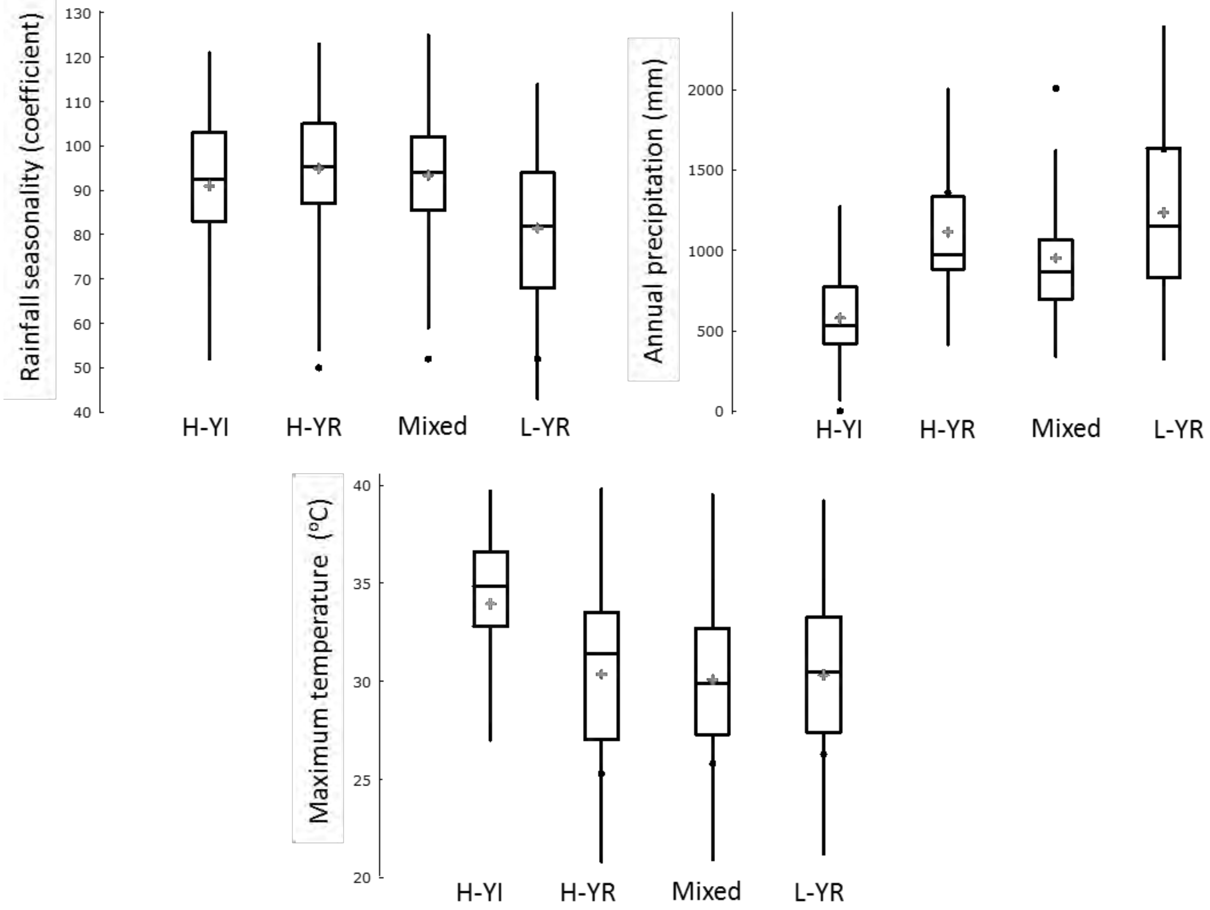

Figure 6.6 Boxplot for rainfall seasonality, maximum temperature and annual precipitation. Legend: Legend: H-YI= high-yield irrigated, H-YR=high-yield rainfed, L-YR=low yield rainfed.

The regression models for Mexico explained 99%, 93%, 95% and 88% of the variance of high-yield irrigated, high-yield rainfed, mixed and low-yield rainfed municipalities (Tab. 4 in annex 2.3). Soil organic carbon (SOC) was positively related to maize production in high-yield rainfed municipalities and negatively related to it in high-yield irrigated municipalities. We anticipated soil organic content to have a positive relation with maize production given its established relation with yield (Lal, 2006; Bergamaschi et al., 2007; Huang et al., 2015). Therefore, the negative relationship between maize production and SOC was unexpected; we believe that this might be the result of increased fertilizer use in places with lower SOC, which might be obscuring the relationship between SOC and maize production.

Annual precipitation was positively related to maize production in low-yield rainfed areas, while maximum temperature had a negative relation with maize production in mixed and low-yield rainfed units. Rainfall seasonality and sown area was positively related to maize production in all maize systems, while irrigated area was significant for maize production in high-yield irrigated and mixed units. The area sown with improved seeds was positively related to maize production in all municipalities with the exception of low-yield rainfed areas. Use of herbicides was important for mixed and low-yield rainfed municipalities, and use of exclusive mechanical traction was relevant in high-yield rainfed ones (Tab. 4 in annex 2.3).

As expected, maize production showed a negative relation to the dummy variable of highland and mid-altitude in the low-yield rainfed and mixed regressions. This means that in these cases more maize is produced at lower altitudes. In the case of high-yield irrigated municipalities, higher altitudes were related to an increase in maize production. A closer inspection of the database shows that most of the high-yield irrigated municipalities situated at high altitudes are located in the central plateau of Mexico were maize is intensively produced taking advantage of the favorable conditions of solar radiations and rainfall in this region.

Table 6.3 Descriptive statistics of maize production in Mexico

	High-yield irrigated	**High-yield rainfed**	**Mixed**	**Low-yield rainfed**
Yield (ton/ha), mean (SD)	5.2 (2.1)	3.4 (1.5)	2.4 (1.5)	1.1 (0.4)
Maize production (ton), total	5,975,182	6,352,507.2	8,502,924.1	2,582,729.1
Sown area (ha), total	722,906	1,755,062.7	2,936,591.0	2,641,462.3
Harvested area (ha), total	712,025	1,673,538.1	2,640,901.0	2,248,988.6
Irrigated area (ha), total (% of maize area)	683,524 (94.6)	19,876.1 (1.1)	719,490.4 (24.5)	22,140.5 (0.83)
Area sown with improved seeds (ha), (% of maize area)	440,073 (60.9)	300,952.6 (17.1)	530,498.6(18)	88,085.8 (3.3)
Area treated with herbicides (ha), (% of maize area)	340,842 (47.1)	498,627.2 (28.4)	851,343.1 (28.9)	163,662.9 (6.1)
Area treated with fertilizers (ha), (% of maize area)	488,805 (67.6)	723,664 (41.2)	1,339,143 (45.6)	389,759 (14.8)
Area with exclusive use of mechanical traction (ha), (% of maize area)	638,062 (88.3)	628060.1 (35.8)	1,452,700.4 (49.4)	530,307.6 (20)
N	102	376	749	1060

Value of the marginal product of ecosystem services in high-yield irrigated, high-yield rained, mixed and low-yield rainfed municipalities in Mexico

The estimated production functions for maize production in high-yield irrigated (HYI), high-yield rainfed (HYR) mixed (M) and low-yield rainfed municipalities in Mexico in 2007 were the following:

HYI maize production= -0.2234 (SOC) + 0.3979 (Rainfall seasonality) + 1.0235 (Sown area) + 0.9535 (Irrigated area) + 0.0915 (Improved seeds) + e

HYR maize production= 0.1616 (SOC) + 0.6361 (Rainfall seasonality) 0.9483 (Sown area) + 0.0463 (Improved seeds) + 0.0344 (Mechanical traction) + e

M maize production= 0.2209 (SOC) 1.2669 (Rainfall seasonality) -0.4919 (Max temperature) 0.8895 (Sown area) 0.3134 (Irrigated area) 0.0787 (Improved seeds) 0.1059 (Use of herbicides) -0.1283 (Mid-altitude) -0.2456 (Highland) + e

LYR maize production= 0.1931 (Annual precipitation) 0.3166 (Rainfall seasonality) + -0.2784 (Max temperature) 1.0167 (Panted area) 0.0348 (Use of herbicides) -0.1329 (Mid-altitude) -0.2659 (Highland) + e

a) Value of the marginal physical product of ecosystem services: land and soil

The importance of land and the characteristics of soils are reflected in the output elasticities of these variables. Our results show that when the sown area is increased in 1%, maize production increases in 1.024% in high-yield irrigated municipalities, 0.948% in high-yield rainfed, 0.890% in mixed, and 1.017% in low-yield rainfed systems. As can be noted, there are diminishing returns to land in high-yield rainfed and mixed counties. The marginal value of land for all municipalities amounted to USD $49,935,640.

Soil organic carbon was significantly related to maize production in mixed, high-yield irrigated and rainfed municipalities. The VMP for soil organic carbon amounted to USD $2,293,750 in high-yield rainfed units and USD $4,198,587 in mixed municipalities. In the case of high-yield irrigated maize production, the elasticity for soil organic carbon was negative (-0.223), however given the explanation given above about this unexpected negative relation, we will not consider the VMP for this factor.

Table 6.4 Value of the marginal product of production inputs in Mexico. Maize Production function 2007, all values in current price 2007 USD.

Input Factor (physical units)	Elasticities (β coeff)	ΔX_i (average) physic units	∑ (USD) j=1…j=N	Average (USD)	VMP/ ha (USD)	VMP/ metric ton (USD)
High yield irrigated N = 102. Sown maize area (000)=722,9 Maize production (tons) = 5,975,182						
Sown area (ha)	1.0235**	70.87	13,669,011	134.01	11.55	2.3
Irrigated area (ha)	0.9535*	0.93	12,734,053	124.8	17.76	2.1
Rainfall seasonality (coeff)	0.3979**	0.91	5,314,053	52.09	4.49	0.9
Soil organic carbon (g/kg of soil)	-0.2234*	0.16	-2,983,358	-29.2	-2.52	-0.5
High-yield rainfed N= 376. Sown maize area (000) =1,755 Maize production (tons) = 6,352,507						
Sown area (ha)	0.9483**	46.7	13,463,553	35,807	7.1	2.1
Rainfall seasonality (coeff)	0.6361**	0.9	9,031,403	24,020	4.8	1.4
Soil organic carbon (g/kg soil)	0.1616*	0.3	2,293,750	6,100	1.2	0.4
Mixed N= 749. Sown maize area (000) = 2,936 Maize production (tons) = 8,502,924						
Rainfall seasonality (coeff)	1.2669**	0.9	24,075,726	32,144	6.4	2.8
Sown area (ha)	0.8895**	39.2	16,904,408	22,569	4.5	2.0
Irrigated area (ha)	0.3134**	0.2	5,955,556	7,951	1.6	0.7
Soil organic carbon (g/kg of soil)	0.2209**	0.3	4,198,587	5,606	1.1	0.5
Maximum temperature (°C)	-0.4919**	0.3	-9,348,459	-12,481	-2.5	-1.1
Low-yield rainfed N = 1060. Sown maize area (000) =2,641 Maize production (tons) = 2,582,729						
Sown maize area (ha)	1.0167**	24.9	5,898,668	5,5565	2.2	2.3
Rainfall seasonality (coeff)	0.3166**	0.8	1,990,839	1,878	0.8	0.8
Annual Precipitation (mm)	0.1931**	12.3	1,039,456	981	0.4	0.4
Maximum temperature (°C)	-0.2784*	0.3	-2,108,467	-1,989	-0.80	-0.8

Source: Author's estimations. Notes: Maize farm price USD $223.5 in 2007; only significant environmental factors were included in the table.

* Significant at 95% confidence level

** Significant at 99% level

b) Value of the marginal physical product of ecosystem services: climate

The input of enough water in the right moment is crucial for maize production. Increasing the annual precipitation in 12.3 mm in average has the potential to increase 0.193% the production of maize in low-yield rainfed areas, implying a gain of USD $1,990,839 (tab. 6.4). In high-yield Irrigated and mixed areas, the lack of adequate precipitation involves the need of external irrigation. The water that is used to irrigate maize fields is obtained from rainfall stored in dams and deep wells, which is the reason why we consider it an ecosystem service. The elasticity of irrigated area in high-yield irrigated areas was highly significant: an increase in 1% of the irrigated area would increase maize production in 0.95% amounting to USD $12,734,053 (Tab. 6.4). In mixed systems, the VMP of this ecosystem input was valued in USD $5,955,556.

Rainfall seasonality was the climate factor with the greatest impact on maize production in all Mexican maize producing municipalities. An increase in 1% in the rainfall seasonality coefficient had the potential to increase maize production in 0.40% in high-yield irrigated areas, 0.64% in high-yield rainfed, 1.27% in mixed and 0.32% in low-yield rainfed areas, representing a total VMP of USD $40,412,021.

Maximum temperature had, as expected, a negative impact on maize production in mixed and low-yield rainfed areas. Results show that an increase of only 0.3 °C in the maximum temperature would imply a loss of 9,348,459 USD in maize production in mixed areas and of USD $2,108,467 in low-yield rainfed areas (Tab. 6.4).

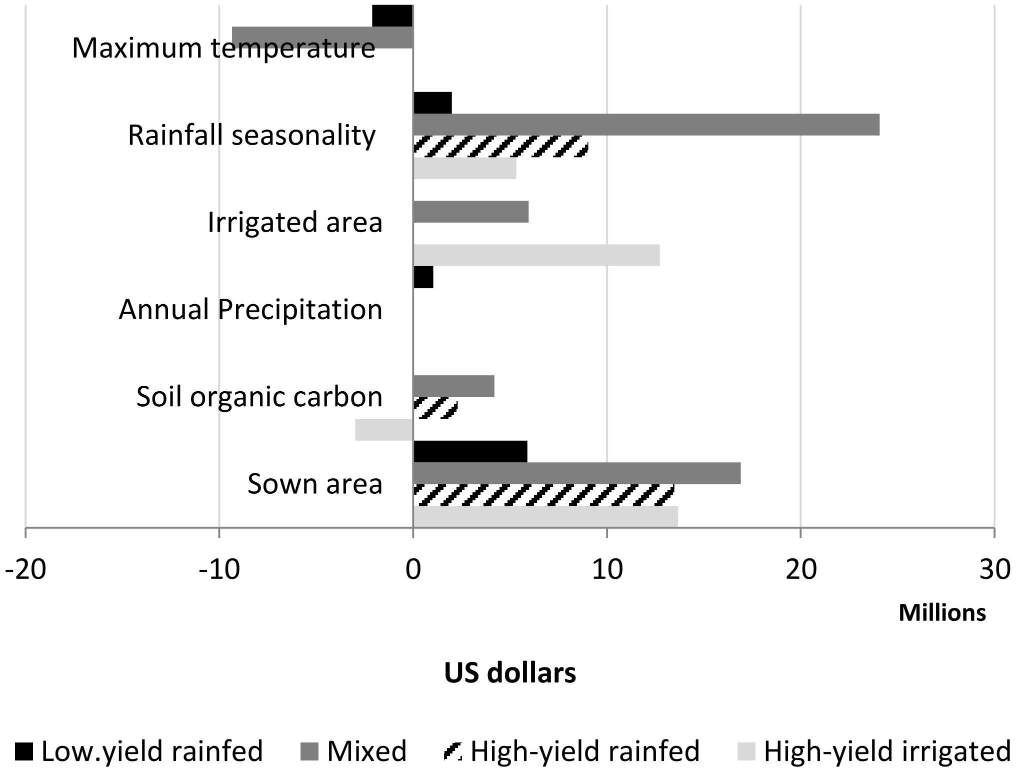

Figure 6.7 Value of the marginal product of ecosystems services for maize production in different maize-producing municipalities in Mexico

The crucial importance of irrigation for high-yield irrigated municipalities was reflected in a similar VMP of sown and irrigated area. It can be concluded that, among these municipalities, having land to plant is just as important as using external irrigation for maize production.

The positive impact of rainfall seasonality for maize production in all municipalities is striking. An increase in the rainfall seasonality coefficient indicates that the distribution of rainfall is more seasonal, that is, distributed over fewer months through the year (Walsh and Lawler, 1981). Our results indicate that in Mexico, having a well-defined rainfall period may facilitate agricultural production, as producers are able to better plan the sowing time to ensure that the maize plant gets water during the critical periods of maize growth and also to achieve a threshold of rainfall above which the water requirements of maize plants are met.

Maximum temperature had negative consequences for maize production in low-yield rainfed and mixed municipalities. Since maize production is lower in low-yield rainfed areas, the VMP of maximum temperature, which in this case has a negative value, has a lower economic value in terms of maize losses than in mixed areas (Fig. 6.8b). However, even though the value measured in USD may not be that relevant, maize losses have, without a doubt more negative consequences for these vulnerable municipalities were maize is mainly produced for self-consumption, greatly impacting food security of peasant families. In spite of the negative elasticities of maximum temperature, local producers still cultivate native maize landraces due to their economic and cultural significance (see sections 5.4 and 6.4). This, together with the important maize genetic diversity maintained and managed by them in a multiplicity of ecological conditions constantly adapting through time, is what constitutes the evolutionary service (see sections 5.1 and 5.2) that will become the main buffer against the negative impacts of climate change on the production of this vital crop worldwide.

The following map (Fig. 6.8a) depicts the sum of the VMP of the relevant ecosystem services in each type of maize producing municipality. As mentioned above, a high VMP results from a combination of high levels of maize production and high levels of provision of ecosystems services. The highest VMP were found in the state of Sinaloa, followed by high-yield rainfed municipalities in the states of Jalisco, Guanajuato, Estado de México, and some municipalities in the state of Guerrero, Chiapas, Veracruz, and Tamaulipas.

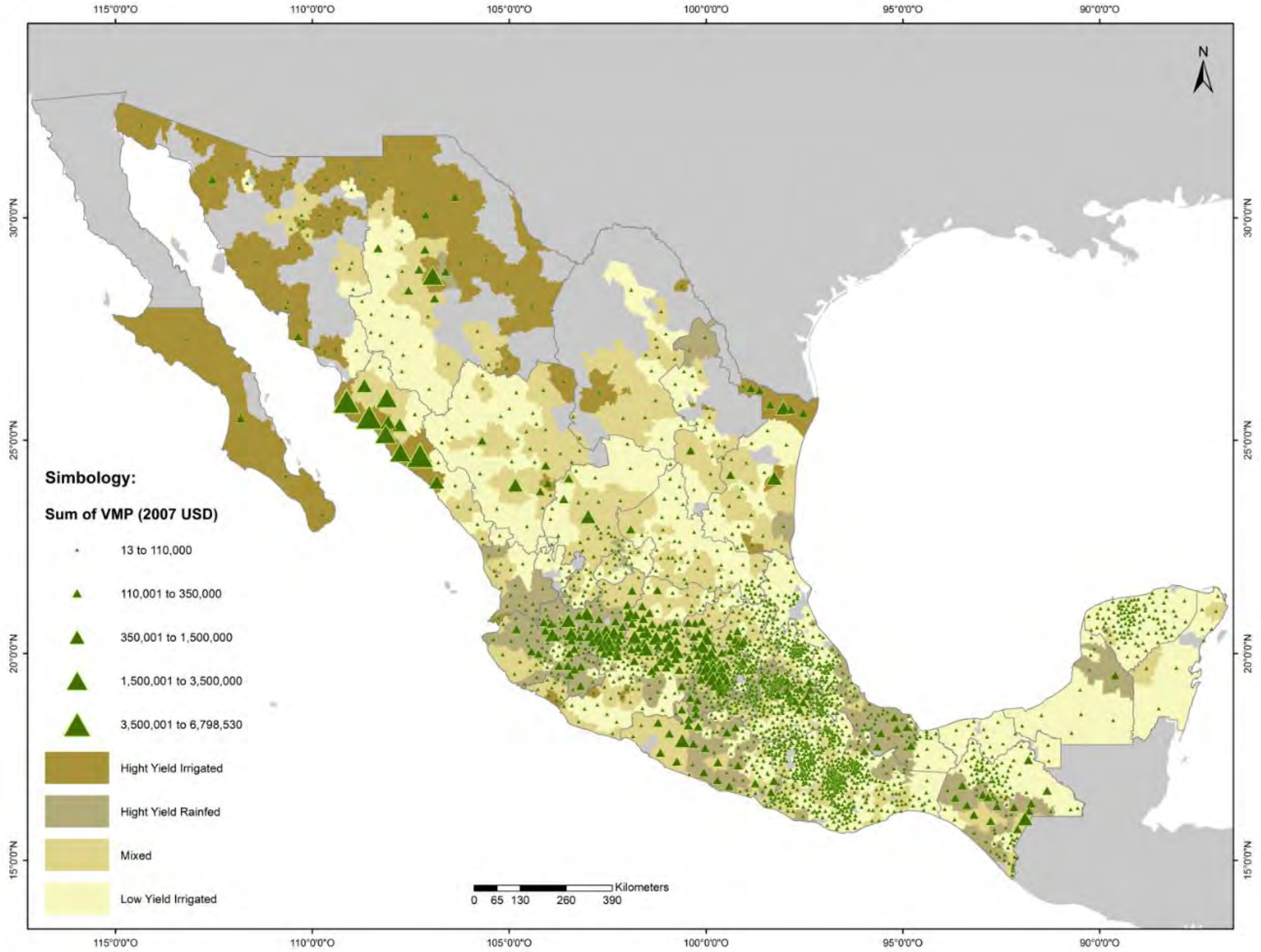

Figure 6.8a Sum of VMP of ecosystem services in different maize producing municipalities in Mexico. Note: The triangles represent the sum of all significant environmental factors that had a positive effect on maize production and for which VMP was estimated.

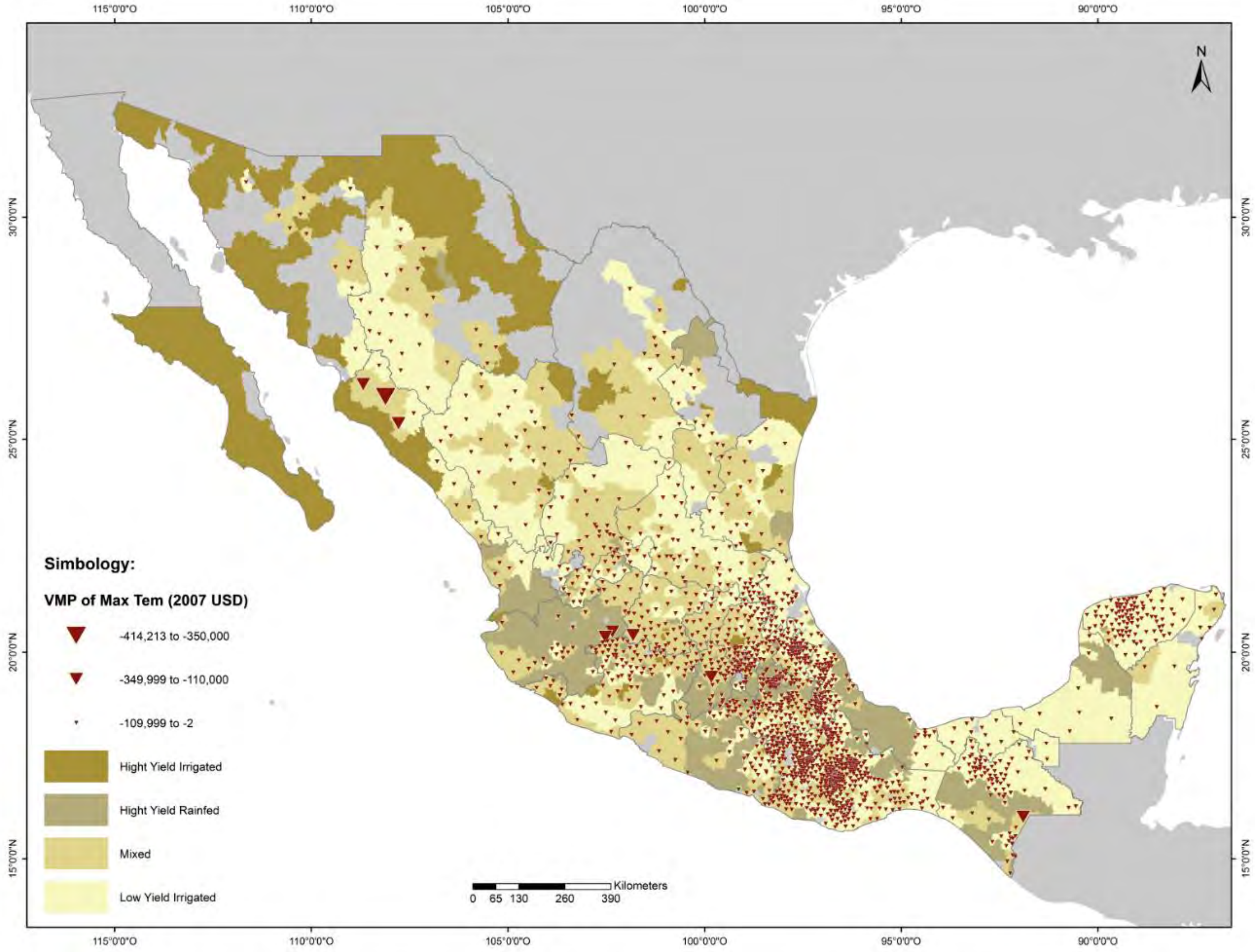

Figure 6.8b VMP of maximum temperature in different maize producing municipalities in Mexico

6.1.2.3 USA

A total of 2,231 counties were included in the regression analyses for USA of which 68.4% were high-yield rainfed, 21.3% were mixed and 10.3% were high-yield irrigated counties. As expected, irrigated counties were characterized by the lowest annual precipitation and the highest reference evapotranspiration along with the lowest soil organic carbon content in the soil. High-yield rainfed counties on the other hand had the best soil organic carbon profile in soil along with higher precipitation and lower evapotranspiration. Apart from irrigated surface and herbicide use, counties behaved in a similar manner with regards to management practices (Tab. 6.5).

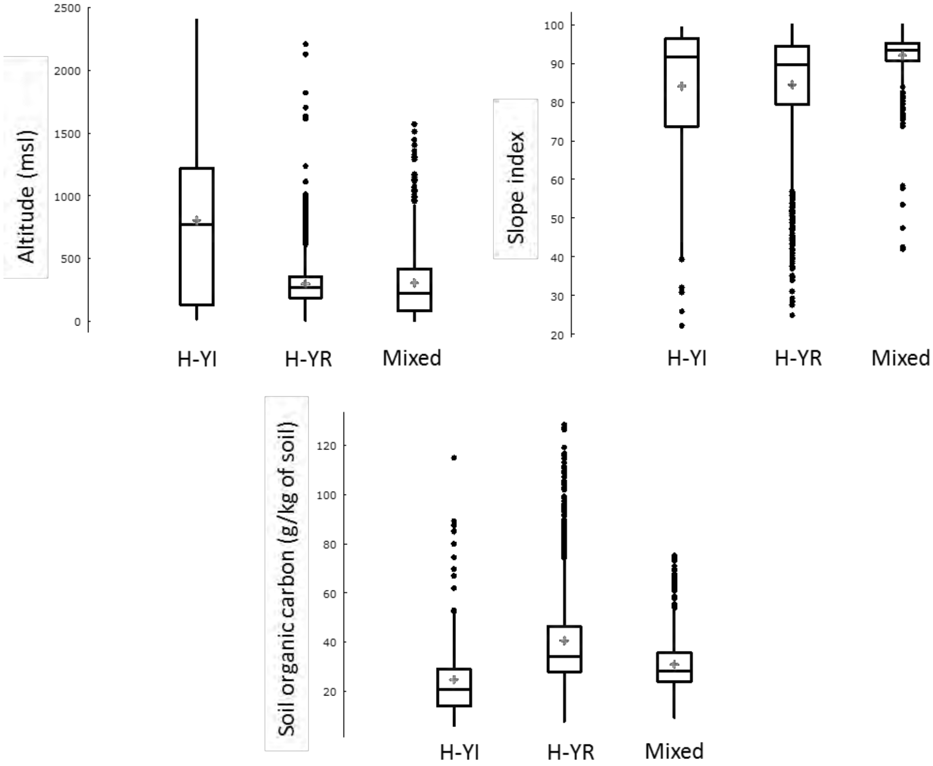

Figure 6.9 Boxplot for altitude, slope index and soil organic carbon conditions among maize producing counties in USA. Legend: H-YI= high-yield irrigated, H-YR=high-yield rainfed. Note: High values of the slope index indicate less pronounced slopes.

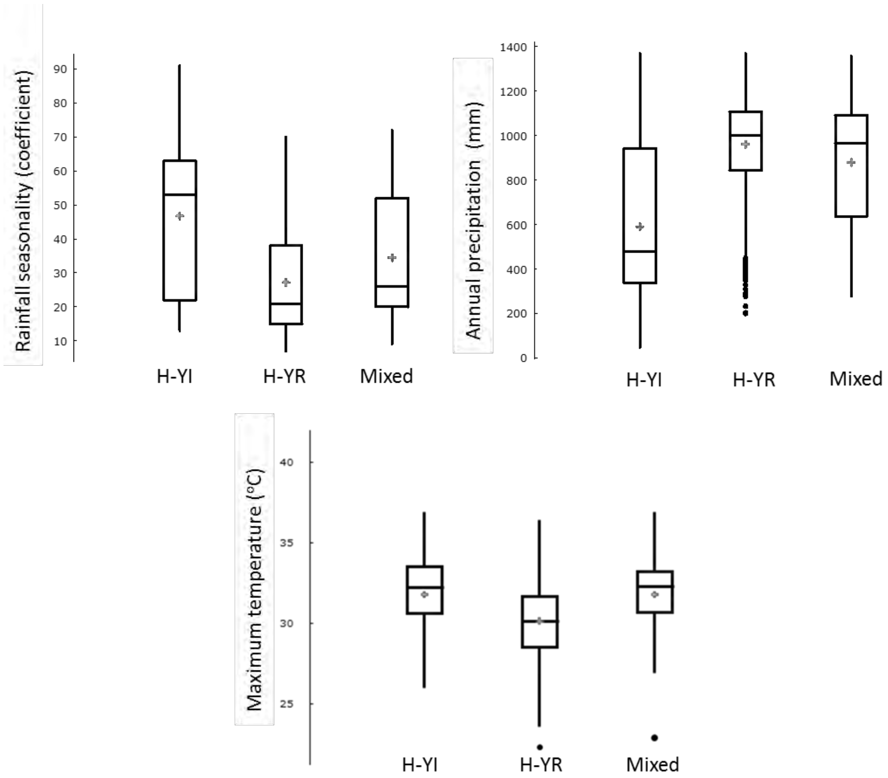

Figure 6.10 Boxplot for rainfall seasonality, maximum temperature and annual precipitation among maize producing counties in USA. Legend: H-YI= high-yield irrigated, H-YR=high-yield rainfed.

Table 6.5 Comparative table of production factors for maize production in USA

	High-yield irrigated	**High-yield rainfed**	**Mixed**
Yield (ton/ha), mean (SD)	10 (2.3)	6.3 (2.2)	6.9 (2.4)
Maize production (ton), total	32,123,608	170,289,888	55,959,999.7
Harvested area (ha), total	3,059,049	23,409,826	8,026,466
Irrigated area (ha), total (% of maize area)	2,642,960.1 (86.4)	187,243.6 (0.8)	2,161,457.1 (26.9)
Use of herbicides (kg), total (kg/ha)	31,521,524.3 (10.3)	121,839,851.7 (5.2)	54,365,256.4 (6.76)
Use of fungicides (kg), total (kg/ha)	488,762.6 (.16)	1,111,748.5 (.05)	641,996.6 (.08)
Use of insecticides (kg), total (kg/ha)	202,272.3 (.07)	330,905.3 (.01)	278,071.4 (.03)
N	230	1526	475

Regressions for the high-yield irrigated, high-yield rainfed and mixed models explained 99%, 98% and 97% of the variance respectively (Tab. 6 annex 2.3). Soil organic carbon showed a positive relationship with maize production in high-yield rainfed and mixed counties (Tab. 6 annex 2.3). Annual precipitation was positively related to maize production in mixed counties while maximum temperature was negatively related to maize production in all counties with the exception of high-yield irrigated ones. The exposition of maize plants to high temperature during the grain, fiber, or fruit production period experience lower productivity and reduced quality (Hatfield et al., 2014). High nighttime temperatures have already affected maize yield in 2010 and 2012 across the Corn Belt (*ibid*.). High temperatures have a negative impact in maize production because they affect energy accumulation in the maize plant. High temperatures cause the maize plant to grow faster and burn off much of the energy that it accumulates through photosynthesis, respiration exceeds photosynthesis (Dowswell et al., 1996). High-yield irrigated areas may be somehow protected from these high temperatures due to the addition of moisture in critical periods of plant growth through external irrigation. Harvested area was also found to have a positive relation to maize production in all maize producing counties as did the use of fungicides in high-yield irrigated and rainfed areas, and insecticides in high-yield rainfed and mixed areas (Tab. 6 annex 2.3). The negative relation between the use of herbicides and maize production in high-yield rainfed areas was unexpected, as was the negative relation with insecticide use in high-yield irrigated areas.

Maize production in USA has risen over time resulting from a series of advances in technology including the development of hybrids, fertilizers, pesticides, machinery, etc. We therefore expected the use of insecticides, herbicides, fungicides to have a positive relation with maize production. The negative betas obtained for insecticide use in high-yield irrigated counties may be related to the use of improved transgenic seeds, that is, counties producing larger quantities of maize might be planting Bt-corn, thereby requiring fewer insecticides. In USA 15% (range 8 to 20%) of all corn planted in 2012 corresponded to insecticide resistant (Bt) only varieties, followed by herbicide tolerant seeds (21%, range: 15-36%), and stacked gene varieties (52%, range: 41-64%) (https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx). Together, 88% of the planted area of maize is sowed with this GMO varieties (*ibid*.).

Value of the marginal product of ecosystem services in high-yield irrigated, high-yield rained and mixed counties in USA

The estimated production function for maize production in high-yield irrigated (HYI), high-yield rainfed (HYR) and mixed (M) counties in 2012 was the following:

HYI maize production= - 0.1158 (Rainfall seasonality) + 0.2672 (Max Temperature) + 1.0629 (Harvested area) + 0.7886 (Irrigated area) + 0.396 (Herbicides) - 0.0172 (Insecticides) + e

HYR maize production = 0.2453 (SOC) -0.5223 (Max Temperature) + 1.0265 (Harvested area) -0.0532 (Herbicides) + 0.0230 (Fungicides) + 0.0644 (Insecticides) + e

M maize Production = 0.1433 (SOC) + 0.2091 (Annual precipitation) -0.3067 (Max Temperature) + 1.0160 (Harvested area) + 0.2523 (Irrigated area) + 0.0763 (Insecticides) + e

Table 6.6 Value of the marginal product of production inputs in USA. Maize Production function 2012, all values in current price 2012 USD.

Input Factor (physical units)	**Elasticities (β coeff)**	**ΔX_i (average) physic units**	**∑ (USD) j=1…j=N**	**Average (USD)**	**VMP/ha (USD)**	**VMP/ton (USD)**
			High-yield irrigated N = 230. Harvested maize area = 3,059,049 (ha). Maize production = 32,123,608 (metric tons)			
Harvested area (ha)	1.0629**	133	92,527,308	402,293	28.9	2.9
Irrigated area (ha)	0.78856**	0.9	68,648,586	298,472	21.4	2.1
Maximum temperature (°C)	0.2672*	0.3	23,262,416	101,141	7.3	0.7
Rainfall seasonality (coeff)	-0.1158**	0.5	-10,081,510	-43,833	-3.1	-0.3
			High-yield rainfed N = 1526. Harvested maize area = 23,049,826 (ha). Maize Production = 170,289,888 (metric tons)			
Harvested area (ha)	1.0265**	153,4	473,708,217	310,425	17.5	2.8
Soil organic carbon (g/kg of soil)	0.2453**	0.4	113,184,361	74,171	4.2	0.7
Maximum temperature (°C)	-0.5223**	0.3	-241,044,512	-157,958	-8.9	-1.4
			Mixed N= 475. Harvested maize area = 8,026,466 (ha) Maize production = 55,959,999 (metric tons)			
Harvested area (ha)	1.0160**	169,3	154,080,097	324,379.2	19	2.7
Irrigated area (ha)	0.2523**	0.3	38,255,645	80,538.2	4.7	0.8
Annual precipitation (mm)	0.2091**	8.8	31,709,482	66,756.8	3.9	0.6
Soil organic carbon (g/kg of soil)	0.1433*	0.3	21,725,415	45,737.7	2.7	0.4
Maximum temperature (°C)	-0.3067*	0.3	-46,513,352	-97,922.8	-5.7	-0.8

Source: Author’s estimations. Notes: Maize farm price in USA, 271 USD in 2012; only significant environmental factors were included in the table.

* Significant at 95% confidence level

** Significant at 99% level

a) Value of the marginal physical product of ecosystem services: land and soil

As we have seen in Ecuador and Mexico, the sown area represents one of the principal contributions in magnitude to maize production. In USA when the harvested area is increased in 1% the value of the marginal physic product is USD $92.5 million in high-yield irrigated areas, USD $473.7 million in high-yield rainfed areas and USD $154 million in mixed areas.

Soil is one of the most important components of the land resource, soil is the natural medium for the growth of vegetation; also soil is the culmination product of the pooled influence of climate, geography, organisms (flora, fauna and human) on original rocks and minerals, above time. The VMP of soil organic carbon was valued in USD $113 million in high-yield rainfed and USD $21 million in mixed areas in the USA.

b) Value of the marginal physical product of ecosystem services: climate

The irrigated area in high-yield irrigated and mixed counties was valued in USD $68.6 and USD $38.2 million respectively, while the VMP of annual precipitation was of USD $31.7 million in mixed areas. With regards to the effect of temperature, our results indicate that an increase of only 0.3 ^{o}C in the maximum temperature would imply a loss of maize equivalent to USD $241 million in high-yield rainfed counties, and of USD $46.5 million in mixed maize producing areas. Our results are consistent with the National Climate Assessment (NCA) (2014) projections on the negative impact of high temperatures on the development of maize plants. In doing so, the recommendations/ adaptation issued by ERS USDA in the face of climate change are crucial. Rainfall seasonality, on the other hand, showed a negative relation to maize production, which implies that an increase of 1% in the seasonality of rainfall would represent a loss of USD $10 million in high-yield irrigated areas in the USA.

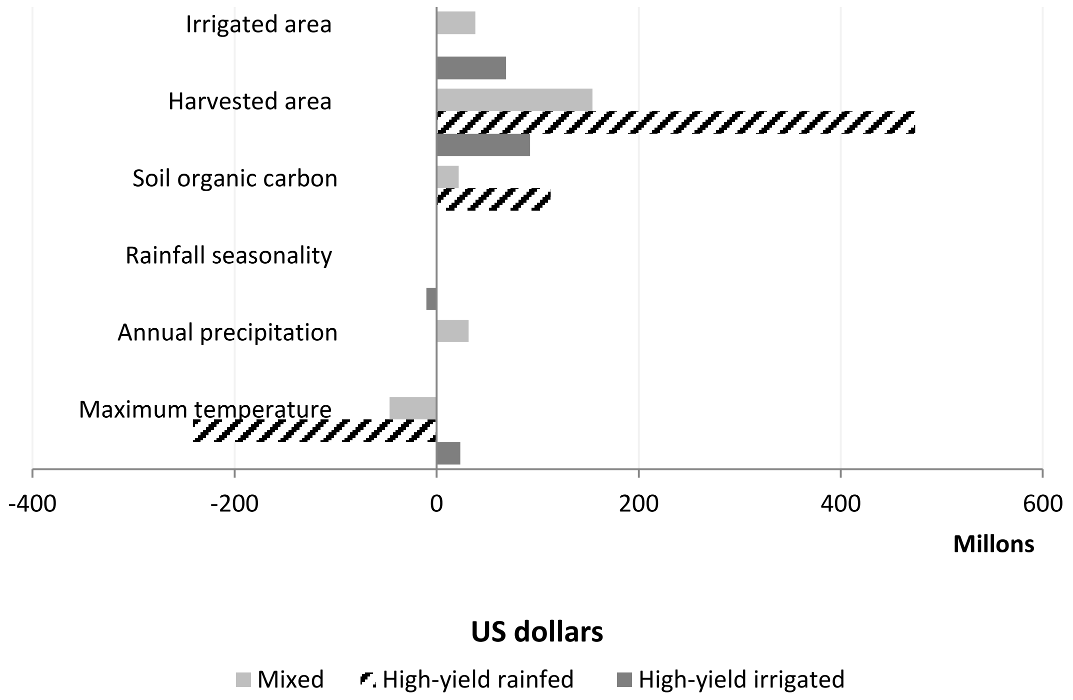

Figure 6.11 Value of the marginal product of ecosystems services for maize production in different maize-producing municipalities in USA

In USA, harvested area, followed by maximum temperature and soil organic carbon, yielded the highest VMP among high-yield rainfed counties (Fig. 6.11). Among high-yield irrigated counties harvested area and irrigated area yielded similar values, which, as in the case of high-yield irrigated municipalities in Mexico, implies almost the same marginal value for land and water (Fig. 6.11). Maximum temperature represented an ecosystem service asset only for high-yield irrigated counties which, through the use of external and planned irrigation, are able to shield maize plants from the negative effects of high temperatures and moisture deficiency. However, the value of the marginal product of maximum temperature in the case of high-yield rainfed and mixed counties was negative (Fig. 12b)

The map with the sum of VMP of ecosystem services for each type of maize producing county is depicted in figure 6.12a. Evidently, the highest VMP were found in the Corn Belt area, which included the states of Iowa, Illinois, Minnesota, Wisconsin, Michigan, Indiana, Kentucky, Nebraska, North and South Dakota, and Missouri. Other states like Mississippi, Indiana, North and South Carolina, Delaware and Maryland also showed high marginal values of ecosystem services.

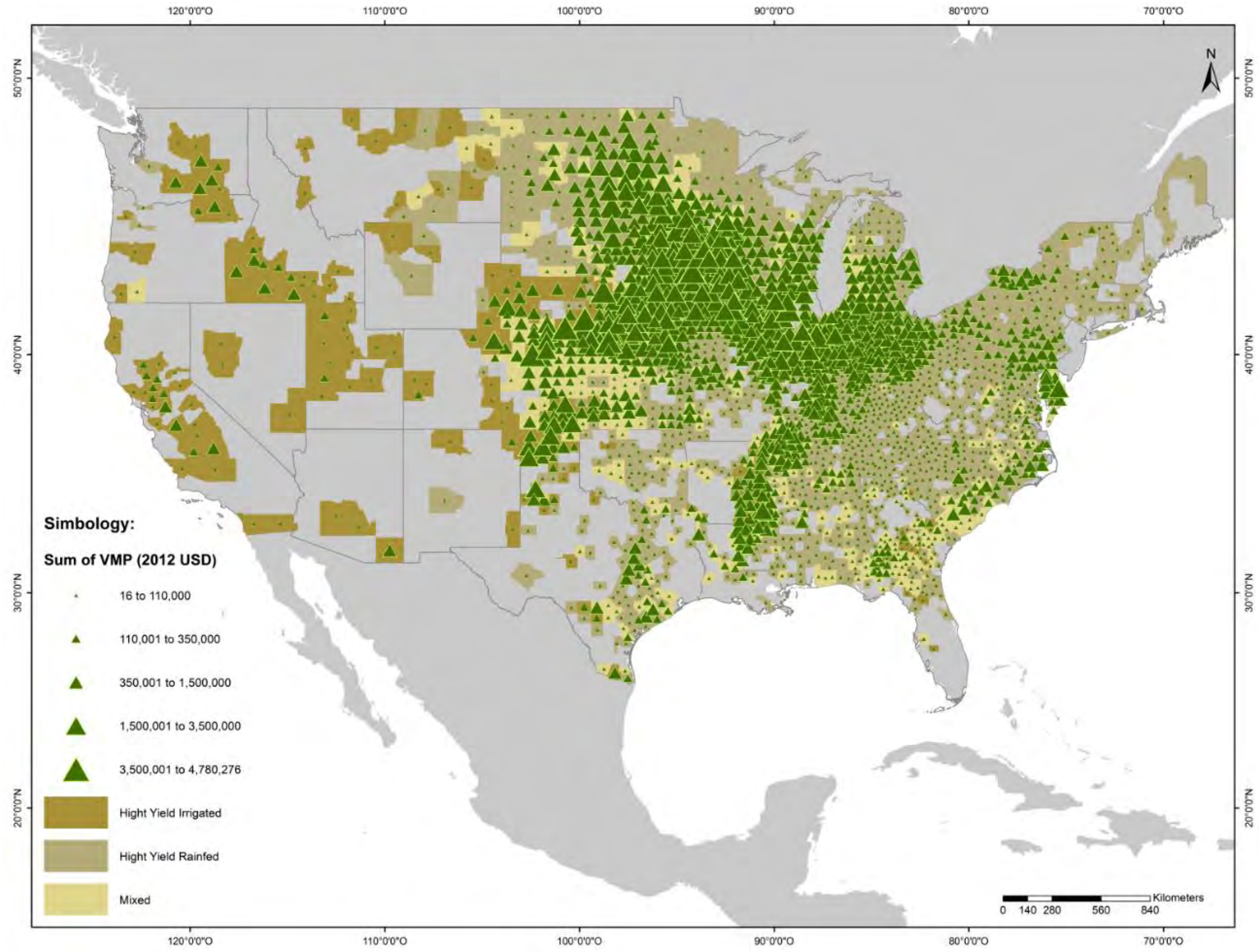

Figure 6.12a Sum of the VMP of ecosystems services for maize production in different maize-producing counties in USA. Note: The triangles represent the sum of all significant environmental factors that had a positive effect on maize production and for which VMP was estimated.

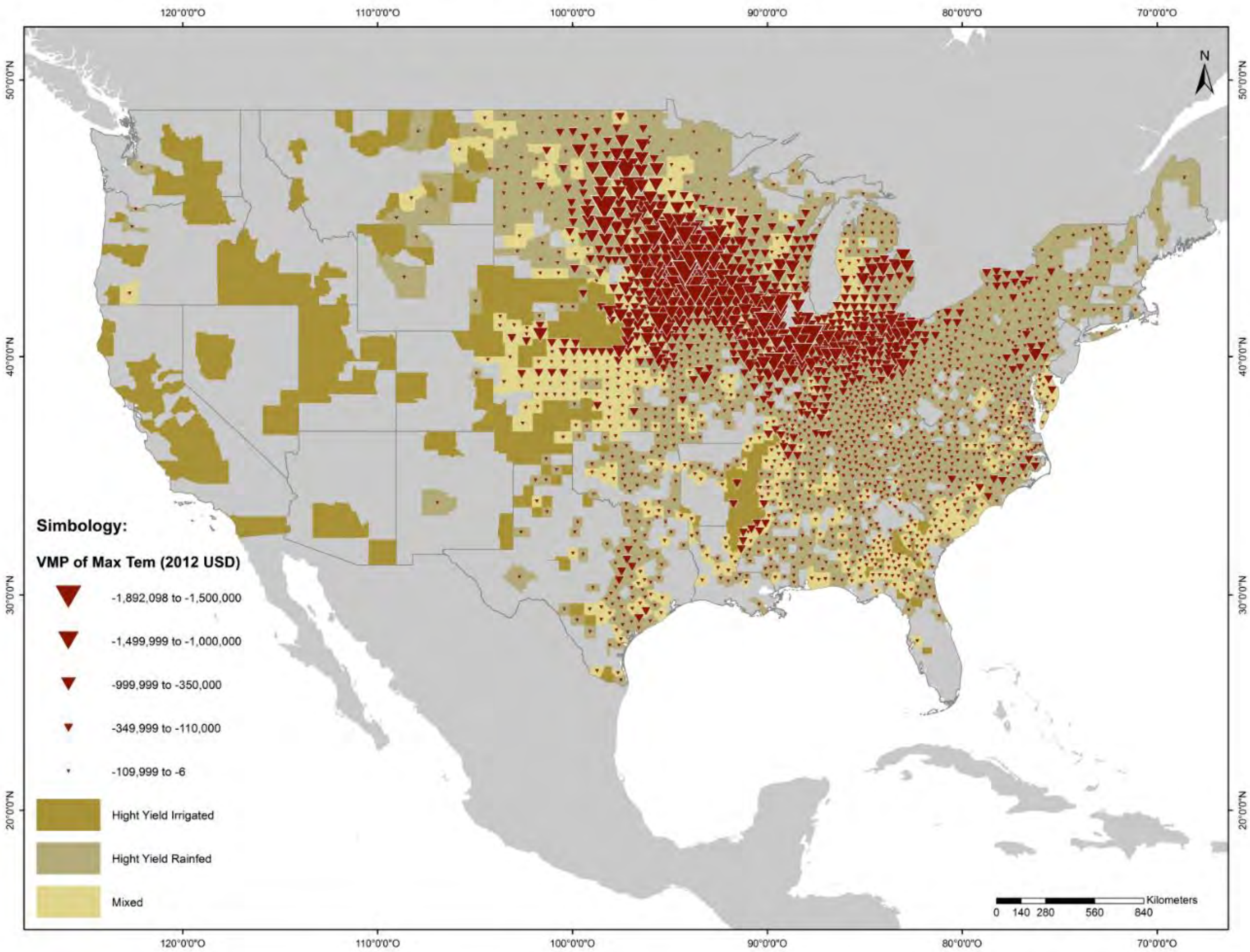

Figure 6.12b VMP of maximum temperature for maize production in different maize-producing counties in USA

6.1.3 Discussion and final thoughts

The valuation of ecosystem services can be approached from both supply and demand sides. In this case we take the demand for maize as given, and use it to derive the value of ecosystem services to agriculture. This supply is determined by the conditions, processes and trends of ecosystems. The aim of the present chapter was to estimate the value of the marginal physical product of ecosystem services as a partial measure of their importance for maize production in our three case study countries. The monetary valuation of this study can also be read as the cost when the damage to one of the valued elements occurs, this is, what would be the costs of the ecosystem services lost due to their deterioration (SOC) or change? How much would it fail to contribute to the production function for each marginal change in case of deterioration, scarcity or disappearance?

Land, a vital important national resource, supports all living organisms including plants as well as every primary production system and storage for surface and ground water. Land had the highest marginal value in all production systems assessed. The value of the land estimated here can be considered a gross underestimation because it only refers to maize production; however, land has many other economic uses. Moreover, as arable land becomes scarcer, its value increases even more, more so if we consider that arable land differs in terms of its biochemical and biophysical properties, as well as in relation to the socioeconomic infrastructure.

A key element of land is soil. Soil is important for its texture and structure, its content of organic and inorganic elements, and as a source of nutrients, moisture, aeration, temperature, microbial flora, etc., which contribute to provide the plant optimal soil conditions for vegetative development. Soil organic carbon (SOC) is related to the sustainability of agricultural systems since it affects soil properties linked to crop yield (Martínez et al., 2008). SOC affects the amount and availability of soil nutrients, contributing elements as N (nitrogen), which is usually deficient. In addition, SOC modifies the acidity and the alkalinity towards values near the neutrality, and then it increases the solubility to several nutrients. SOC associated to the soil organic matter provides colloids having high cation exchange capacity. Its effect on the physical properties of the soil is reflected in the soil structure and pore size distribution (Martínez et al., 2008). We found SOC to be relevant for maize production in the Coastal region of Ecuador, were its marginal value was estimated in USD $138,988. In México, the marginal value of SOC was valued in USD $2.3 million in high-yield rainfed areas and USD $4.2 million in mixed areas. In USA SOC was valued in USD $113.2 million and USD $21.7 million in high-yield rainfed and mixed counties respectively. The absence of a significant effect of SOC with maize production does not mean that SOC isn´t relevant for maize production in other areas or regions, but the absence of a significant relation may reflect a ceiling effect, were adding more SOC does not add more benefits in terms of yield once an optimal level is reached.

Climatic elasticities were relevant for maize production in all our study countries. In the Andean region of Ecuador maximum temperature had a marginal value that was even greater than the sown area of maize. Therefore, rising temperatures in the Andean region are expected to positively affect maize production. In contrast, warm regions in Mexico and USA, especially those deprived of external irrigation, might be especially vulnerable to the effects of high temperatures as shown by the negative elasticities for maximum temperature gotten for mixed and low-yield rainfed municipalities in México. In these municipalities, an increase in 1% in the maximum temperature would yield to potential losses worth USD $11.4 million. In USA, losses for an increase in 1% in the maximum temperature might amount up to USD $287.5 million among high-yield rainfed and mixed counties. It is important to consider that the increase in 1% calculated here, represents an increase in 0.3 ^{o}C in the maximum temperature. Climate change scenarios for Mexico forecast increases of 0.5 to 1 for October temperatures for a great portion of its territory by 2030 (Conde et al., 2011). By 2070-2099 the increase under a *rapid emissions reduction* scenario forecasts an increase of 0.55 to 1.65 ^{o}C, and under *a continued emission increase* scenario an increase in 2.75 to 3.85 ^{o}C (Walsh et al., 2014). For USA, the projected increase for the first scenario is of 2.75 a 3.85 ^{o}C, and for the second 4.95-6.05 (*ibid*.). These scenarios suggest that the value of losses will exceed our estimates by far. Moreover, Thomas et al. (2016) using climate change scenarios predict the loss of 46.7 million hectares in suitability areas for the cultivation of maize in Mesoamerica. Aside from the need of an urgent emissions reduction, adaptation strategies to the projected increase in temperature might include a number of agronomic and agro-ecological practices that buffer plants against this temperature increase, including: the conservation maize landraces and research on the plasticity and adaptability of these to climate change (Mercer and Perales, 2010), improvement of farmers' landraces (Hellin et al., 2014), use of high-temperature sensitive varieties (Tao and Zhang, 2010), development of climate change resilient germplasm (Cairns et al., 2013), implementation of conservation agriculture management strategies (see section 5.3), and the provision of supplementary irrigation (Magombeyi et al., 2008; Ndhleve et al., 2017), among others.

Even though annual precipitation represents an ecosystem services that is as crucial as land for any kind of agricultural production, it only resulted a significant factor for maize production in the Amazonian region of Ecuador, low-yield municipalities in Mexico, and mixed counties in USA. In the Amazonian region of Ecuador maize production would be negatively impacted by an increase in precipitation, while in Mexico and USA this increase would favor maize production. The absence of a significant effect of rainfall in the rest of the regressions may have different explanations: a) a reduced range or variation in rainfall, b) the presence of an effect of the temporal distribution of rainfall and c) the presence of external irrigation that buffers the negative effects of a lack of optimal precipitation. If rainfall in a region is distributed within an optimal range for maize production, variations within that range will have a minimum effect on plant growth. This might explain the lack of an effect of precipitation on maize production in Ecuador. The buffering effect of external irrigation, on the other hand, became evident in the regression results of Mexico and USA. We found that Irrigated area was relevant for high-yield irrigated and mixed areas in Mexico and USA. The marginal value of this service in Mexico was estimated in USD $12.7 and USD $5.9 million in high-yield irrigated and mixed areas respectively. In USA this marginal value amounted to USD $68.6 and USD $38.2 million for high-yield irrigated and mixed counties respectively. In high yield-irrigated areas in Mexico the value of land approached the value of irrigation.

The effect of the temporal distribution of rainfall showed to have important consequences for maize production in all countries, especially in Mexico. In Ecuador and USA rainfall seasonality had a negative relation to maize production in high-yield irrigated counties in USA and the Andean region of Ecuador. In Mexico the relation was positive and significant for all maize producing municipalities. The highest VMP of rainfall seasonality was estimated for mixed municipalities, summing a total of USD $24 million, which represented 7.1 million more than the VMP for sown area. For high-yield rainfed areas the estimated value was of USD $9 million, USD $5.3 for high-yield irrigated, and USD $1.9 million in low-yield rainfed municipalities. Rohr et al. (2013) modeled the relation of soil moisture, plant productivity, related C inputs through litterfall, and soil C dynamics in tropical dry ecosystems, and showed that for a given annual rainfall, there is a rainfall seasonality that maximizes plant productivity. They concluded that longer than optimal wet seasons reduce daily rainfall frequencies leading to inadequate soil moisture levels incapable of buffering water stress. Shorter wet seasons, on the other hand, result in water leakage and runoff, also affecting plant productivity (*ibid*.).

In sum, our results provide an estimate of the marginal value of a set of selected ecosystem services for maize production in different maize producing areas in Ecuador, Mexico and USA. Future attempts to will greatly benefit from longitudinal data, data at a lower level of aggregation (*e.g*. farm level), the use of primary instead of modelled data (*e.g.* data on soil and climate), and maize-specific management data (as available for Ecuador).

6.2 The hidden value of green water provision for maize production

Authors: Esmeralda Urquiza-Haas and Daniel Ortiz Santa María

Supply of water is a critical ecosystem service for agriculture. It is estimated that around 70% of the water extracted from aquifers, rivers and lakes is used in agricultural production (FAO, 2011b). About 86% of the water extracted in Africa (215 km^3/year) is used in agriculture, while this value is 49% in America (790 km^3/year), 82% in Asia (2451 km^3/year), 29% in Europe (374 km^3/year) and 70% (26 km^3/year) in Oceania (FAO, 2011b). Around 40% of crops worldwide are produced in areas with irrigation provision. These areas represent 20% of the total global agricultural area (UN Water, 2013; quoted in Garbach *et al*., 2014).

Water availability in agricultural ecosystems depends not only on irrigated water but more importantly on infiltrated water and moisture retained by the soil. Indeed, it is estimated that around 80% of the water used by agricultural crops comes from this latter source (Molden, 2007, quoted in Power, 2010). Soil moisture retention is regulated by factors such as organic matter content, vegetal coverage and composition of the community of macro- and microorganisms in the soil (*ibid*.). The infiltrated water from rainfall is known as green water. When considered as a process, green water is formed by water temporally stored in, on top of the ground and land vegetation, which eventually evaporates from the soil, from intercepted water, and plant transpiration (Schyns et al. 2015). According to Oki and Kanae (2006) approximately 3/5 of the precipitation over land is integrated into the green flow and 2/5 into the blue flow that ends in the ocean and superficial and underground water reservoirs on land. Falkenmark and Rockström (2006) consider two components as part of the green water flow, a productive part represented by plant transpiration which is involved in biomass production, and the unproductive part represented by water evaporation. For the present purposes we assume the definition of green water as the rainwater consumed (*i.e.* transpired) by plants, including crops (Rockström and Gordon, 2001; Mekonnen and Hoekstra, 2011: p. 1578).

The aim of the present exercise was to monetize the dependency of maize systems on green water. Rainfed systems receive this benefit for free, but mixed and irrigated systems receive only a fraction of it, for which reason they have to complement this service with irrigated water that comes at a specific cost. This dependency is normally taken for granted. However, the climate change scenarios developed by the Intergovernmental Panel on Climate Change forecast increased temperatures and reduced precipitation for several world regions, including Mexico. For North America, climate model predictions for precipitation remain highly uncertain, but most suggest higher rainfall distributed in a heterogeneous way (McCarthy et al., 2001). Climate change scenarios for Mexico show that the better suited areas for maize production will diminish from 6.2 to 3%, while the marginally apt will increase from 31.6 to 33.4% or 43.8% (Monterroso-Rivas et al., 2011). This means that maize systems in some regions of Mexico will have to adapt to less apt conditions characterized by increased temperatures and reduced rainfall through different means, such as selecting maize varieties with greater drought tolerance, implementing management practices that act to enhance soil water retention or supplement maize systems with blue water (*i.e*. irrigation water), among others. Clearly, under a scenario of decreased precipitation regimes and reduced rainwater availability, irrigation costs can be expected to increase, further increasing the calculated values.

Mekonnen and Hoekstra (2011) quantified, in a spatially explicit manner, the worldwide green, blue and grey water footprint of crop production for the period 1996–2005. These water footprints were calculated for 126 crops, including maize. The concept of the water footprint was developed initially by Hoekstra (2003) to assess the appropriation of the world´s freshwater by human societies. The water footprint of a product is defined as "the sum of the water footprints of the process steps taken to produce the product" (Mekonnen and Hoekstra, 2011: p. 1578). The green and blue water footprint of maize was calculated by the authors considering crop evapotranspiration and maize yield, following the method and assumptions provided by Allen *et al*. (1998, cited in Mekonnen and Hoekstra, 2011) for the case of crop growth under non-optimal conditions. The model, which is a dynamic grid-based daily water balance model, is applied at a global scale using a resolution of 5 by 5 ARC minute. The resulting water footprint map, available in a raster format, was used to calculate green and blue water consumption in Ecuador, Mexico and the USA, as well as for the different production systems identified in the present study.

6.2.1 Methodology

To analyze the data according to maize systems, we collected the spatially explicit data of green water (in millimeters) modeled for 1996-2005 by Mekonnen and Hoekstra (2011) available in a 5 by 5 ARC minute raster grid and spatially explicit data about maize production, modelled for 2005 by You *et al.* (2014), also available at the same resolution. We then classified each pixel as rainfed (<25% of the harvested area is irrigated), mixed (between 25 and 75% of the maize area is irrigated), and irrigated (> 75% of the maize area is irrigated) using the percentage of maize irrigated area in each pixel. We deleted all pixels that had absolute zeros for green water and maize production. For the USA, we had an initial count of 117,027 pixels and a final count of 16,163 after deleting those cases with absolute zeros. In Mexico, the initial pixel count was 24,932 and the final count was 9453. In Ecuador, the initial count was 2984 and the final count was 1819.

To obtain total green water in cubic meters, we multiplied the millimeters of green water by the area of each pixel in square meters and divided the resulting number by a 1000. To estimate the value of green water per maize system, we used the mean of the deflated cost of irrigation water in USA in 2005 (USD \$1.144/m^3), which was priced at USD \$1.53/m^3 (Agricultural Resources and Environmental Indicators, 2006). For Ecuador, we used the deflated market price of pumped irrigation water (2015: USD \$0.25/m^3, 2005: USD \$0.165/m^3) (Y. Cartagena Ayala, pers. comm., 2016), and for Mexico we used the shadow price of water (2015: USD \$0.274/m^3, 2005: USD \$0.184; C. Cabrera Cedillo, pers. comm., 2016). The justification for using irrigation water prices is clear since any reduction in the amount of natural precipitation will require external supplementation with irrigation water if yields are to be maintained.

The formula we used to deflate water prices to the current water price was the following:
WP= (CW)*(CPI_YI /CPI)
where**,**

WP= Water price in the year of interest; CW= cost of water; CPI_YI= consumer price index of the year of interest; CPI= current (2016) price index.

In order to put the calculated value into perspective, we compared the value of this dependency to the value of the maize production output. For this, we used the producer prices per ton of maize in the analyzed countries: USD $79 for USA, USD $345 for Ecuador and USD $144.9 for Mexico (FAOSTAT, 2016). These prices represent the earnings received by farmers for maize, paid at the farm-gate or at the first point of sale, and are therefore the value of output. This value was calculated by multiplying the production of maize in each system (in tons) by the producer prices reported by the FAO for each country. We therefore did not consider production costs or governmental subsidies.

6.2.2 Results

Ecuador

As can be observed in the following map, maize is cultivated throughout Ecuador but, in spite of the high precipitation levels found in that country, the use of green water is quite low, mainly reflecting the low maize production in the country (Fig. 6.13). However, in most of the Ecuadorian provinces there are a few areas that present a higher use of green water.

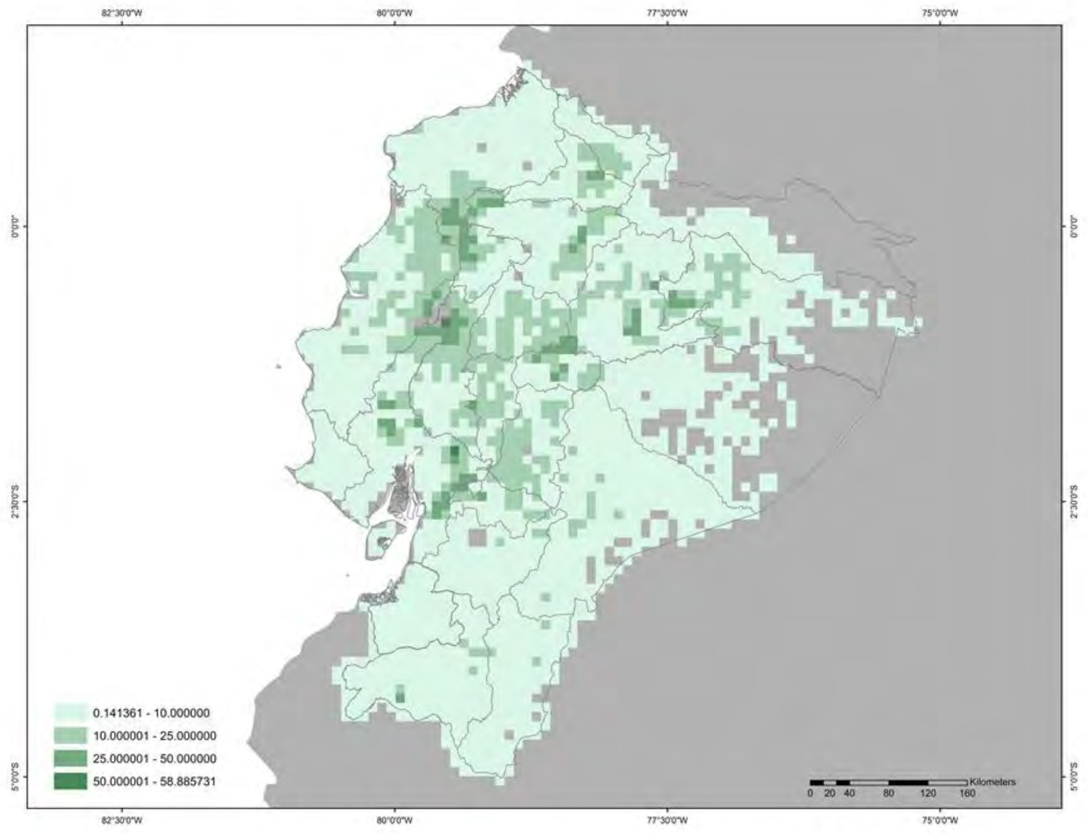

Figure 6.13 Map of green water use (in mm/year) by maize cultivars in Ecuador. Source: Own production with spatial data from Mekonnen and Hoekstra (2011).

For Ecuador, we had a total of 1819 pixels, of which 202 were irrigated, 101 were mixed and 1,516 were rainfed. Rainfed areas comprised 78.5% of the total harvested maize area and 68% of the national maize production and accounted for 79.7% of the total green water use (Tab. 6.7). As can be observed in table 6.7, rainfed areas used the greatest amount of green and blue water in absolute terms. Nevertheless, in relative terms (per ha), the irrigated areas presented the greatest use of green water per ha, while mixed areas presented the greatest use of blue water.

Table 6.7 Green and blue water use for maize production in Ecuador

	Rainfed	**Mixed**	**Irrigated**
Number of pixels	1,516	101	202
Harvested area, ha (total)	305,493	45,174	38,613
Irrigated area, ha (total)	6,917	19,430	37,772
Pixel area, ha (total)	15,371,697	1,024,339	2,094,251
Maize production, ton (total)	523,764	114,047	131,842
Maize yield, ton/ha (mean)	2	2.7	3.5
Green water, mm/year (mean)	5.5	6.4	7.2
Blue water, mm/year (mean)	1.1	2.4	1.2
Green water, m^3/year (total)	848,588,498	65,395,528	151,368,854
Blue water, m^3/year (total)	163,082,329	24,151,355	25,978,020
Green water, m^3/ha	55.2	63.8	72.3
Blue water, m^3/ha	10.6	23.6	12.4

Using irrigation prices for pumped water, we calculated the total value of green water use for maize production in irrigated, mixed and rainfed pixels (Tab. 6.8). The estimated cost of blue water was close to $26 million USD in rainfed areas, $3.9 million in mixed areas, and $4.2 in irrigated areas, while the green water value amounted to $140, $10.7 and $24.9 million USD, respectively.

Table 6.8 Value of green water use in rainfed, mixed and irrigated areas in Ecuador

	Rainfed		**Mixed**		**Irrigated**	
	Cubic meters	*USD*	*Cubic meters*	*USD*	*Cubic meters*	*USD*
GW, total	848,588,498	140,017,102	65,395,528	10,790,262	151,368,854	24,975,861
BW, total	163,082,329	26,908,584	24,151,355	3,984,974	25,978,020	4,286,373
GW, per ha	55.2	9.1	63.8	10.5	72.3	11.9
BW, per ha	10.6	1.8	23.6	3.9	12.4	2

In 2005, Ecuadorian farmers received an estimate of USD $345 for every ton of maize[83] they sold at the farm gate (FAOSTAT, 2016b). Thus, without taking any production costs into account, the estimated earnings for maize production was USD $180,698,476 in rainfed areas, USD $39,346,180 in mixed areas and USD $24,975,861 in irrigated areas. If the green water used for maize production were to be included as a production cost, this

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[83] The price listed for Ecuador is for maize used for human consumption.

would represent 77.5%, 27.4% and 54.9% of the output value of each system (Tab. 6.9). However, it must be noted that the output value from maize production in Ecuador may be much lower, given that the price listed in the FAO includes only maize for human consumption whereas the maize production data from You et al. (2014) includes the total amount of maize produced. This means that the relative value of green water may be much higher considering lower maize prices.

Table 6.9 Value of maize production[84] and green water used for maize production in Ecuador

	Rainfed		**Mixed**		**Irrigated**	
	Production	*Green water*	*Production*	*Green water*	*Production*	*Green water*
Total (USD)	180,698,476	140,017,102	39,346,180	10,790,262	45,485,593.4	24,975,861
% of production		77.5		27.4		54.9

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[84] Earnings from maize production are calculated by multiplying the total maize production by the producer prices obtained from FAOSTAT (2016). Production costs are not taken into account.

Mexico

Maize is cultivated throughout almost all of Mexico, possible due to the great variability in maize landraces selected by traditional farmers in order to adapt to the diverse range of ecological and climatic conditions that characterize this country. The use of green water in Mexico is significantly higher than in Ecuador, with the highest levels of green water use concentrated in the central and southern portion of the country (Fig. 6.14).

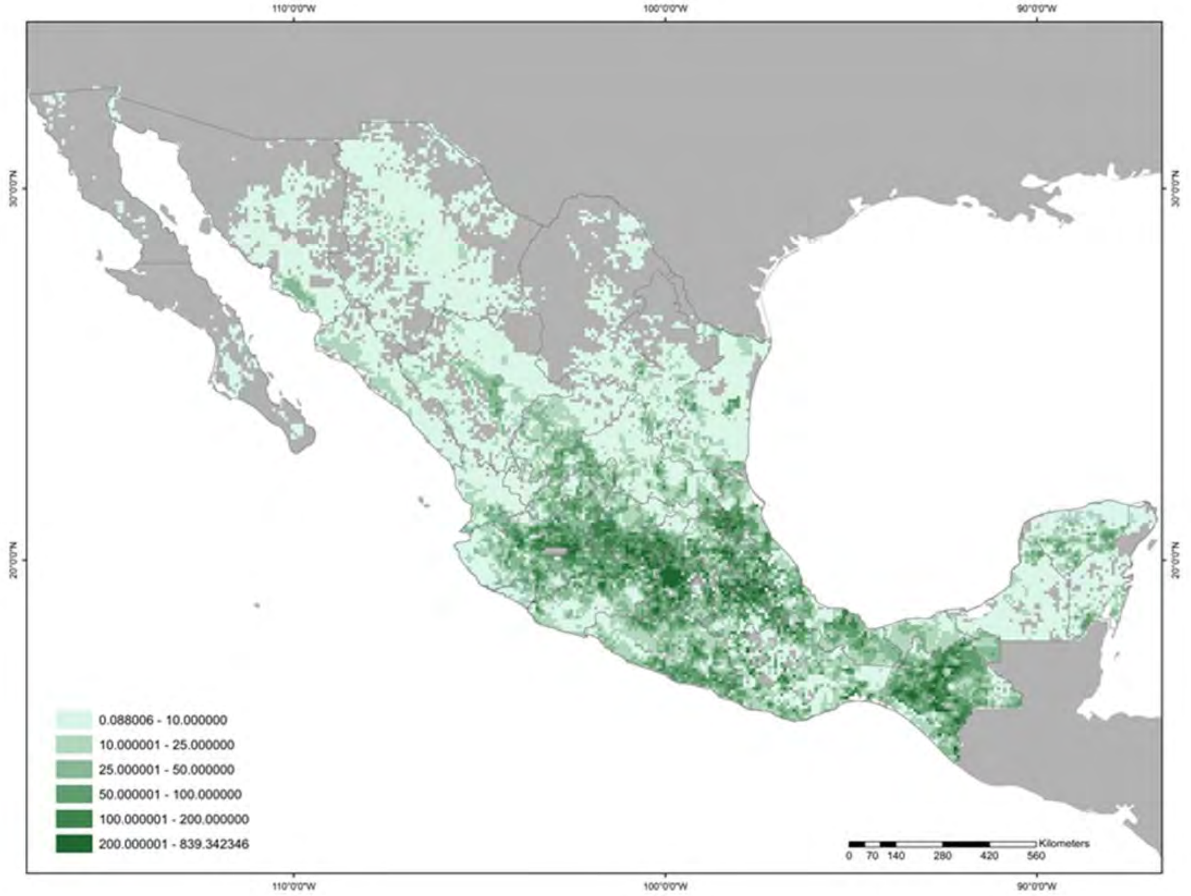


Figure 6.14 Map of green water use (in mm/year) by maize cultivars in Mexico. Source: Own production with spatial data from Mekonnen and Hoekstra (2011).

For Mexico, a total of 9453 pixels were used, of which 83.5% were rainfed, 8.7% mixed and 7.7% irrigated. The irrigated pixels had the smallest cultivated area (9.3%) but contributed 12.9% of the entire maize production. Rainfed areas accounted for 76.6% of the green water use and 72.5% of the blue water consumption (Tab. 6.10). Per hectare, the mixed units used the greatest amount of green water (581.5 m^3), followed by irrigated (487.1 m^3) and rainfed (347.5 m^3) units, whereas blue water use was greatest in the irrigated areas (9.1 m^3/ha) compared to the mixed (8.5 m^3/ha) and (4.5 m^3/ha) rainfed areas.

Table 6.10 Green and blue water use for maize production in Mexico

	Rainfed	**Mixed**	**Irrigated**
Number of pixels	7,831	824	721
Harvested area, ha (total)	4,218,378	762,060	505,143
Irrigated area (ha)	110,660	360,065	472,286
Pixel area (ha)	62,955,028	6,621,321	5,773,747
Maize production, ton (total)	9,580,672	2,956,981	1,837,301
Maize yield, ton/ha (mean)	1.7	3.0	3.5
Green water, mm/year (mean)	34.7	58.1	48.6
Blue water, mm/year (mean)	0.5	0.8	0.9
Green water, m^3/year (total)	21,874,719,577	3,850,432,498	2,812,627,946
Blue water, m^3/year (total)	285,643,748	56,160,575	52,254,880
Green water, m^3/ha	347.5	581.5	487.1
Blue water, m^3/ha	4.5	8.5	9.1

In Mexico, rainfed units used an estimated quantity of green water priced in $4 billion USD, while mixed and irrigated units used an equivalent of $708 and $517 million USD, respectively. With respect to the blue water, we estimated that rainfed units paid $52 million USD for irrigation water, while mixed areas paid just over $2 million USD and irrigated areas a total of $3.5 million USD.

Table 6.11 Value of green water use in rainfed, mixed and irrigated areas in Mexico

	Rainfed		**Mixed**		**Irrigated**	
	Cubic meters	USD	Cubic meters	USD	Cubic meters	USD
GW, total	21,874,719,577	4,024,948,402	3,850,432,498	708,479,580	2,812,627,946	517,523,542
BW, total	285,643,748	52,558,450	56,160,575	10,333,546	52,254,880	9,614,898
GW, per ha	347.5	63.9	581.5	107	487.1	89.6
BW, per ha	4.5	0.8	8.5	1.6	9.1	1.7

Given that the cost of irrigation water is higher in Mexico than in Ecuador and that the income gained from maize production is lower than in Ecuador (USD $144.9 per ton: FAOSTAT, 2016), the value of this service would represent 290% of the value of maize production of rainfed units, 165.3% of mixed units and 193% of the production of irrigated ones (Tab. 6.12).

Table 6.12 Value of maize production and green water used for maize production in Mexico

	Rainfed		**Mixed**		**Irrigated**	
	Production	*Green water*	*Production*	*Green water*	*Production*	*Green water*
Total (USD)	1,388,239,415	4,024,948,402	428,466,590	708,479,580	266,224,886	517,523,542
% of production		290		165.4		194.4

USA

As can be appreciated in figure 6.15 the greatest use of green water is distributed over the so-called Corn Belt, comprising the states of Iowa, Illinois, Nebraska, Minnesota, North and South Dakota, Missouri, Indiana, Kentucky, Ohio and Michigan.

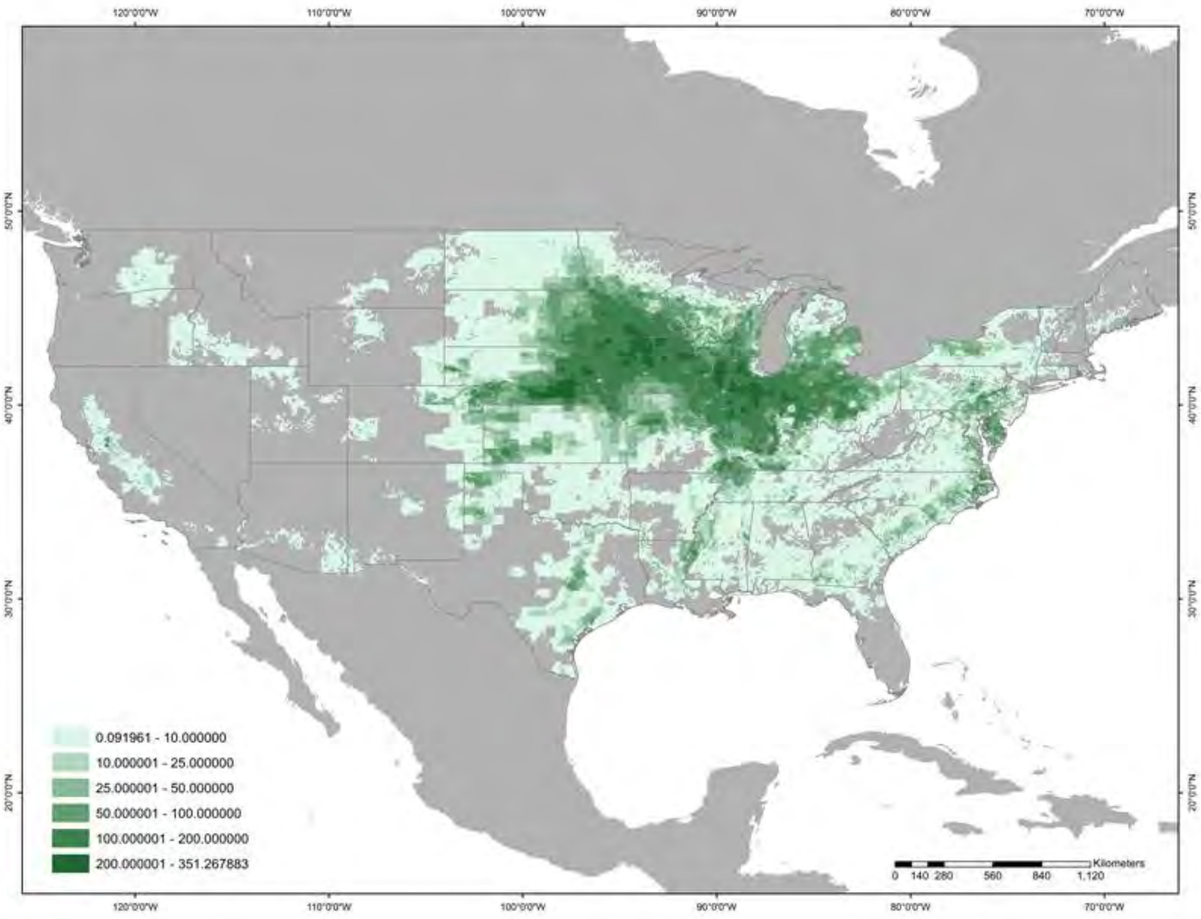


Figure 6.15 Map of green water use by maize cultivars in the USA. Source: own production with spatial data from Mekonnen and Hoekstra (2011).

In the USA, data from 15,843 pixels were used. Rainfed maize production comprised the great majority of maize production units in the USA (51%); this production type had the greatest cultivation area (78.6%), produced 78.5% of the total maize production and used up 74.5% of the total green water and 9.4% of the blue water used in maize production (Tab. 6.13). In contrast, irrigated areas used 13.2 % of the green water and 56% of the blue water.

Table 6.13 Green and blue water use in maize production in the USA

	Rainfed	**Mixed**	**Irrigated**
Number of pixels	8,084	1,967	5,792
Harvested area, ha (total)	9,175,927	1,406,654	1,098,442
Irrigated area (ha)	243,576	725,332	998,291
Pixel area (ha)	57,884,296	14,254,339	42,025,232
Maize production, tons (total)	91,679,060	13,239,136	11,883,406
Maize yield, ton/ha (mean)	8.3	8.4	8.2
Green water, mm/year (mean)	75.0	50.5	18.5
Blue water, mm/year (mean)	1.2	17.6	9.7
Green water, m^3/year (total)	42,977,520,227	7,061,935,808	7,649,766,038
Blue water, m^3/year (total)	672,648,776	2,455,443,630	3,995,685,257
Green water, m^3/ha	742.5	495.4	182.0
Blue water, m^3/ha	11.6	172.3	95.1

Using the deflated price for irrigated water in the USA, we estimate that the total value of green water use in rainfed, mixed and irrigated areas would amount to $49.1, $8.0 and $8.7 billion USD, respectively. For rainfed areas, this amount is approximately 63.8 times higher than that paid for irrigation water, but only 2.8 and 1.9 times higher than the estimated cost of irrigation water in mixed and irrigated areas.

As expected, rainfed areas in the USA used the greatest quantity of green water per hectare, followed by mixed and irrigated areas, while the use of blue water was higher among mixed areas compared to irrigated areas (Tab. 6.14).

Table 6.14 Value of green water use in rainfed, mixed and irrigated areas in the USA

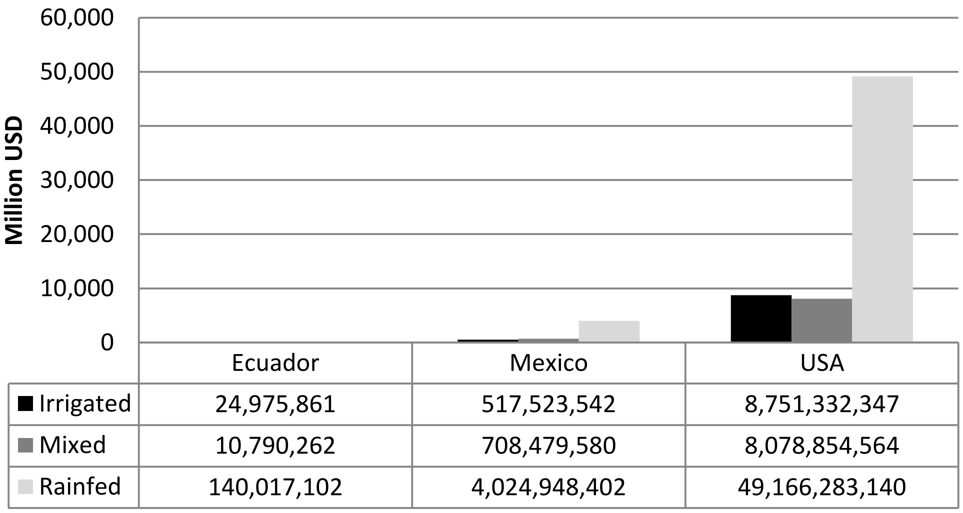
	Rainfed		**Mixed**		**Irrigation**	
	Cubic meters	*USD*	*Cubic meters*	*USD*	*Cubic meters*	*USD*
GW, total	42,977,520,227	49,166,283,140	7,061,935,808	8,078,854,564	7,649,766,038	8,751,332,347
BW, total	672,648,776	769,510,200	2,455,443,630	2,809,027,513	3,995,685,257	4,571,063,934
GW, per ha	742.5	849.4	495.4	566.8	182	208.2
BW, per ha	11.6	13.3	172.3	197.1	95.1	108.8

To determine how the estimated value of green water compares to the earnings obtained from maize production, we calculated the value of maize production (USD $79 per ton: FAOSTAT, 2016) at $7.2 and $1 billion USD in rainfed and mixed areas, respectively, and at $938 million USD in irrigated areas. If one compares the earnings from maize production to the value of green water, this would represent 678% (in rainfed areas), 772% (mixed) and 932% (irrigated) compared to the earnings from maize production (Tab. 6.15). Clearly, these are higher amounts, compared to those of Mexico and Ecuador, and this can be explained by the higher costs of irrigation water in the USA and the lower price paid per ton of maize produced.

Table 6.15 Value of maize production and green water used for maize production in the USA

	Rainfed		**Mixed**		**Irrigation**	
	Production	*Green water*	*Production*	*Green water*	*Production*	*Green water*
Total (USD)	7,242,645,715	49,166,283,140	1,045,891,760	8,078,854,564	938,789,074	8,751,332,347
% of production		678.8		772.4		932.2

The results presented here highlight that the potential value of green water for all maize production systems is very significant, yet it remains broadly unaccounted for both in maize markets and policies. Here, the hidden value of green water provision to maize production systems is shown by representing it as the dependency on or contribution of green water in maize production. The areas producing maize in the USA are those that "save" most if green water were considered an asset with economic value (Fig. 6.16) or, put another way, they would be those that "lost" the most if green water suddenly became unavailable and had to be replaced by irrigation. In order to better manage this service, policy should be developed in an integral fashion as recommended by Falkenmark and Rockströom (2006).



	Ecuador	Mexico	USA
■ Irrigated	24,975,861	517,523,542	8,751,332,347
■ Mixed	10,790,262	708,479,580	8,078,854,564
■ Rainfed	140,017,102	4,024,948,402	49,166,283,140

Figure 6.16 Value of green water in irrigated, mixed and rainfed maize areas in Ecuador, Mexico and the USA

Finally, a word of caution regarding our estimates presented here: we merged data from two different sources; those pertaining to maize areas and maize production came from You et al. (2014) while those pertaining to the green and blue water came from Mekonnen and Hoekstra (2011). While both of these sources used spatially explicit data about maize production generated by the FAO (2006) as their base, You et al. (2014) added subnational data from a network of data resources from various local subnational offices. This means that the data may not necessarily be compatible, which may produce estimates that are not entirely accurate. For example, it is expected that pixels with absolute zeros for green water use should also show absolute zeros for maize production; however, we found in Mexico that 7,696 pixels show absolute zeros for green water while almost half of these (3,405) present positive numbers for maize production. While we did not include pixels showing absolute zeros for green data or maize production, this finding shows that there is a potential mismatch that may to some extent affect our estimates of green and blue water use for areas classified as rainfed, mixed and irrigated in all case study countries.

The quantities of blue water use in Mexico and Ecuador have also probably been underestimated in our calculations. For example, in Ecuador we found that one hundred pixels out of two hundred and two, classified as irrigated, showed absolute zeros for blue water use. In Mexico, this was the case for 553 out of 721 pixels classified as irrigated, and in the USA, in 18 out of 5,792 pixels classified as irrigated.

Notwithstanding these potential limitations, we consider our estimates to be useful and they clearly show the economic importance of the dependency of maize systems on green water provision, which might be in jeopardy in some areas as a result of global climate change.

6.3 The cost of grey water in maize production systems

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Among the most widely acknowledged impacts of agricultural production on ecosystem services is the contamination of water by agrochemicals and nutrient loads (Conley et al., 2009b). It has been estimated that 50% of the nitrogen used in agricultural systems is used by the plants, 2 to 5% remains in the soil, 25% is released as N_2O emissions and 20% is leached into aquatic ecosystems (Galloway et al., 2004). Moreover, 20 to 40% of nitrogen inputs in estuarine and coastal waters are estimated to be of atmospheric origin (Duce, 1986; Fisher and Oppenheimer, 1991; Paerl, 1995; Coale et al., 1996, cited in Kahn and Mohammad, 2014).

The main consequence of leaching nitrogen-based fertilizers into water sources is that the excess of nutrients favors the growth of algae. On decomposition, these algae then promote reproduction of microbial communities. Such communities use up the available oxygen, provoking a significant decrease in the levels of dissolved oxygen in the water. One of the results of the hypoxia and anoxia generated by the boom of algae and aquatic plants is the presence of ‘death zones’ in lakes, estuaries and coasts; in other words, zones that are temporarily devoid of marine fauna (Diaz and Rosenberg, 2008). Globally, more than 400 ‘death zones’ have been identified (*ibid*.). Some of these zones present periodical hypoxia or stationary hypoxia; however, in other cases, such hypoxia is sustained, causing low secondary productivity, as well as the absence of benthic fauna (Seitz et al., 2009). Sustained hypoxia has been recorded in the Gulf of Mexico, the Chesapeake Bay and on the coasts of Denmark (Kemp et al., 2005; Conley et al., 2009a). The ‘death zone’ of the Gulf of Mexico is largely the result of maize and soybean production in the so-called *Corn Belt* of the USA, located in the states of Iowa, Illinois, Indiana, Nebraska, Kansas Minnesota and Missouri (Goolsby et al., 1999, quoted in McLellan et al., 2015) (Fig. 6.17). The area of the hypoxic zone of the Gulf of Mexico has varied from 40 km^2 in 1988 to 20,000 km^2 in 2001 and 2008 (Rabotyagov et al., 2012).

The impacts of hypoxic conditions on individual species and ecosystems have been extensively reviewed and involve diverse impacts on the behavior and physiology of organisms, causing a reduction in their fitness or even mortality in the organisms (Tab. 6.16) (Diaz and Rosenberg, 2008; Levin et al., 2009; Rabalais et al., 2010). However, the impacts of nutrient leaching on aquatic ecosystems are far from straightforward and are therefore difficult to evaluate given the multiplicity of factors that influence the health of this ecosystem (fishing techniques and intensity, altered hydrology, etc.) (Rabotyagov et al., 2012).

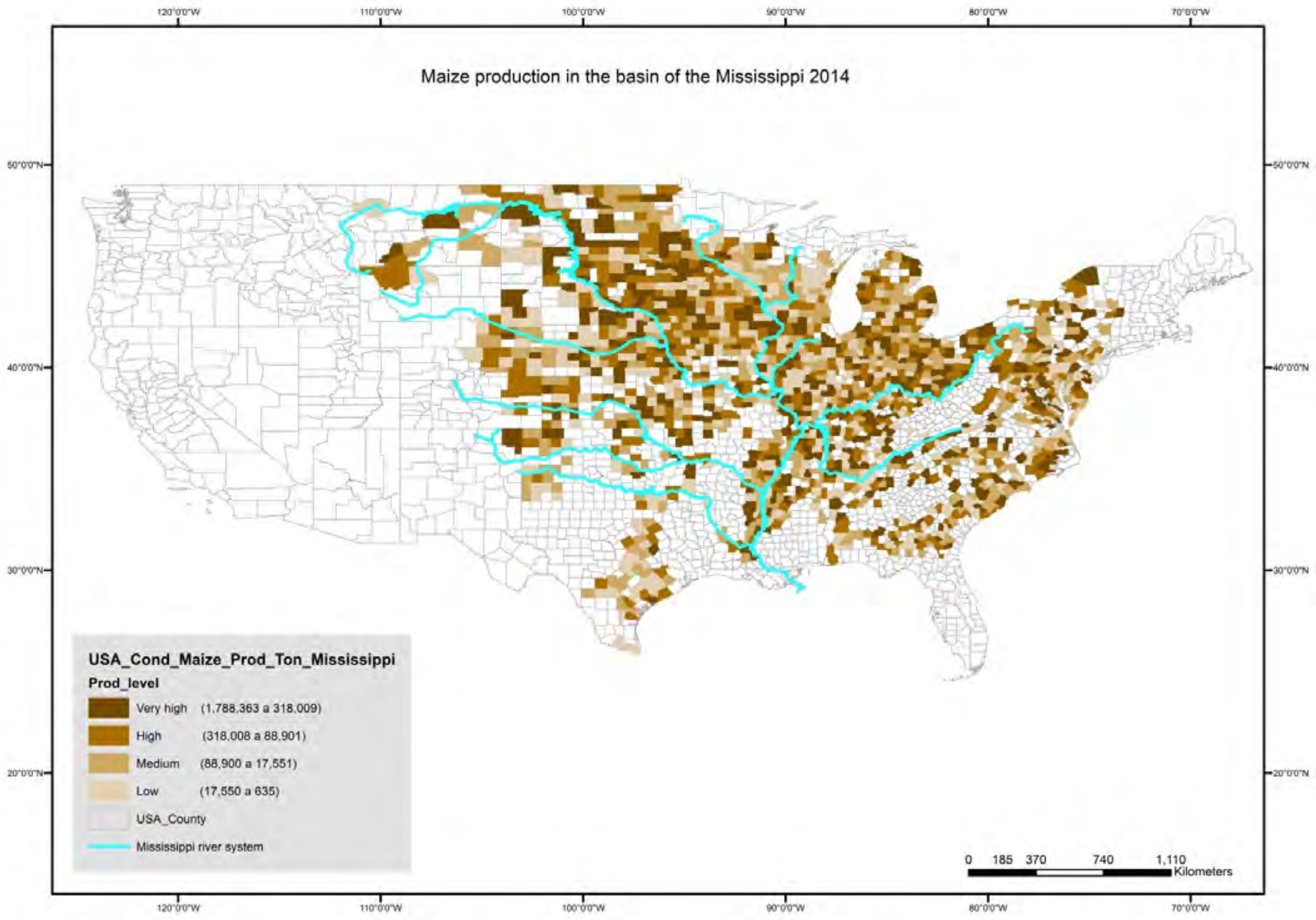

Figure 6.17 Maize production (tons/year) in the Mississippi Basin in 2014. Source: own production using data from USDA.

Table 6.16 Effects of eutrophication on aquatic ecosystems

Ecosystems	Impacts on seagrass, shellfish beds and finfish nursery areas	Kennish, 2007; Kennish, 2009
	Loss of submerged aquatic vegetation, altered benthic faunal communities and harvestable fisheries	Valiela, 2006
Phytoplankton	Change in the speciation of phytoplankton	Crosbie and Furnas, 2001; Ismael and Dorgham, 2003
	Shifts of phytoplankton species towards larger forms of diatoms and dinoflagellates	Furnas et al., 2005
Zooplankton	Changes in species diversity indices	Kozuharov et al., 2007
	Decline in species richness and abundance	Sendacz et al., 2006
	Changes in zooplankton size Increase of large-sized phytoplankton forms	Breitburg et al., 1999; Matsumura-Tundisi, 1999
	Change in species composition and species replacement	Straile and Geller, 1998; Hart and Wragg, 2009; Hsieh et al., 2011
Benthic fauna	Change in the populations of benthic invertebrates	Diaz and Rosenberg, 1995
	Changes in species composition of macrozoobenthos	Rosenberg et al., 1987
	Decrease in the macrozoobenthic biomass	Wang, 2006
	Escape of sensitive demersal (cod, whiting) and benthic fishes (dabs, flounder) Extreme loss of benthic diversity Mortality of bivalves, echinoderms and crustaceans	Gray, 1992
	Replacement of herbivores by detritivores	Cardoso et al., 2004
	Disappearance of benthic fishes Immobilization and/or death of lobsters Emergence of benthic infaunal species	Baden et al., 1990
	Growth inhibition of benthic animals (e.g. polychaeta *Nereis diversicolor*, bivalve *Abra alba* and the brittle star *Amphiura filiformis)*	Hylland et al., 1996
	Defaunation during summer hypoxia	Lim et al., 2006
Trophic Linkage	Changes in the feeding habits of higher consumers, zoobenthos, fishes and crabs	Chandra et al., 2005; Powers et al., 2005; Pihl, 2011
Seagrasses	Worldwide decline of seagrass ecosystems	Richardson, 2006
	Inhibition of photosynthetic processes in benthic plants and seagrass habitats	Walker et al., 1999
	Disturbance of the nitrogen and phosphorus metabolism of seagrass	Touchette and Burkholder, 2000
	Mortality of eutrophication-sensitive species such as *Acropora palmata*	Bell and Tomascik, 1993
Coral Reefs	Reduced survivorship of scleractinian corals	Birkeland, 1977
	Reduced diversity of hard coral species	DeVantier et al., 2006
	Collapse of coral reef community	Smith et al., 1981
	Reduced recruitment and modified trophic structures	Fabricius, 2005

	Coral mortality	Smith, 2006
	Inhibition of coral reef calcification by more than 50%	Kinsey and Davies, 1979
	Overgrowth and replacement of corals	Lapointe, 1997
Fish	Mortality-associated changes in fish community structure	Bauman et al., 2010; Guzman et al., 1990; Landsberg, 2002; Richlen et al., 2010; Smith, 1975

Source: taken from the review of Dorgham (2014).

6.3.1 Methodology

We decided to use the grey water estimates calculated by Mekonnen and Hoekstra (2011) to generate a partial estimate of the externalities of chemical nitrogen fertilizer used in maize production. Grey water refers to the "volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards" (p.1578). This means that the externalities calculated here capture only the cost of meeting one water quality standard. Mekonnen and Hoekstra (2011) calculated the grey water footprint relating to nitrogen use only. Data is modeled for 126 individual crops, including maize. The data is available at a global scale with a 5 by 5 ARC minute resolution (approximately 9 x 9 kilometers) (see Mekonnen and Hoekstra, 2011 for a detailed explanation of the method used to estimate grey water for crop production). The formula used by Mekonnen and Hoekstra (2011) to calculate the grey water footprint of a crop is as follows:

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{max} - c_{nat})}{Y} \left[\text{Volume/mass} \right]$$

The formula is described in Hoekstra *et al.* (2011: p. 41) as: "The grey component in the water footprint of growing a crop or tree (WF proc, grey, m^3/ton) is calculated as the chemical application rate to the field per hectare (AR, kg/ha) times the leaching-run-off fraction (α) divided by the maximum acceptable concentration (cmax, kg/m^3) minus the natural concentration for the pollutant considered (cnat, kg/m^3) and then divided by the crop yield (Y, ton/ha)."

To analyze the data according to maize systems, we collected the spatially explicit data of grey water (in millimeters) modeled for 1996-2005 by Mekonnen and Hoekstra (2011) available in a 5 by 5 ARC minute raster grid and spatially explicit data pertaining to maize production modelled for 2005 by You *et al.* (2014), also available at the same resolution. We then classified each pixel, also referred to here as production units, as smallholder (<2 ton/ha), intermediate (2 -6 ton/ha) and intensive (> 6 ton/ha), using the data on maize yield for each pixel. In all instances, we deleted cases with absolute zeros for green water and maize production. For the USA, we had an initial count of 117,027 pixels and an end count of 16,163 after deleting the cases with absolute zeros. In Mexico the initial pixel count was of 24,932 with an end count of 9,453. In Ecuador, the initial count was 2,984 and the end count was 1,819.

To obtain total grey water in cubic meters, we multiplied the millimeters of grey water by the area of each pixel in square meters and divided the resulting number by 1000. To estimate the cost of grey water per maize system, we used the mean of the deflated cost (USD \$1.144/m^3) of irrigation water in the USA in 2005, which was priced at USD \$1.53/m^3 (Agricultural Resources and Environmental Indicators, 2006). For Ecuador, we used the deflated market price of pumped irrigation water (2015: USD \$0.25/m^3, 2005: USD \$0.165/m^3) (Y. Cartagena Ayala, personal communication, 2016) and for Mexico, we used the shadow price of water (2015: USD 0.274/m^3, 2005: USD 0.184; C. Cabrera Cedillo, personal communication, 2016). In order to put the calculated remediation costs in perspective, we compared the value of externalities to the value of maize production. For this, we used the producer prices of maize in the analyzed countries; USD 79 for the USA, USD 345 for Ecuador and USD 144.9 for Mexico (FAOSTAT, 2016b). These prices represent the income received by farmers for maize as earned at the farm-gate or at the first point of sale. As such, they accurately represent the output value.

6.3.2 Results

Ecuador

The grey water footprint of Ecuador was the smallest among our case study countries, as is clearly reflected in the map below (Fig. 6.18). Practically none of the provinces would require more than 10mm/year to reduce the pollution caused by nitrogen leaching in Ecuador, according to the estimation developed by Mekonnen and Hoekstra (2011). This lies in stark contrast to the situation in the USA and Mexico (see figures below).

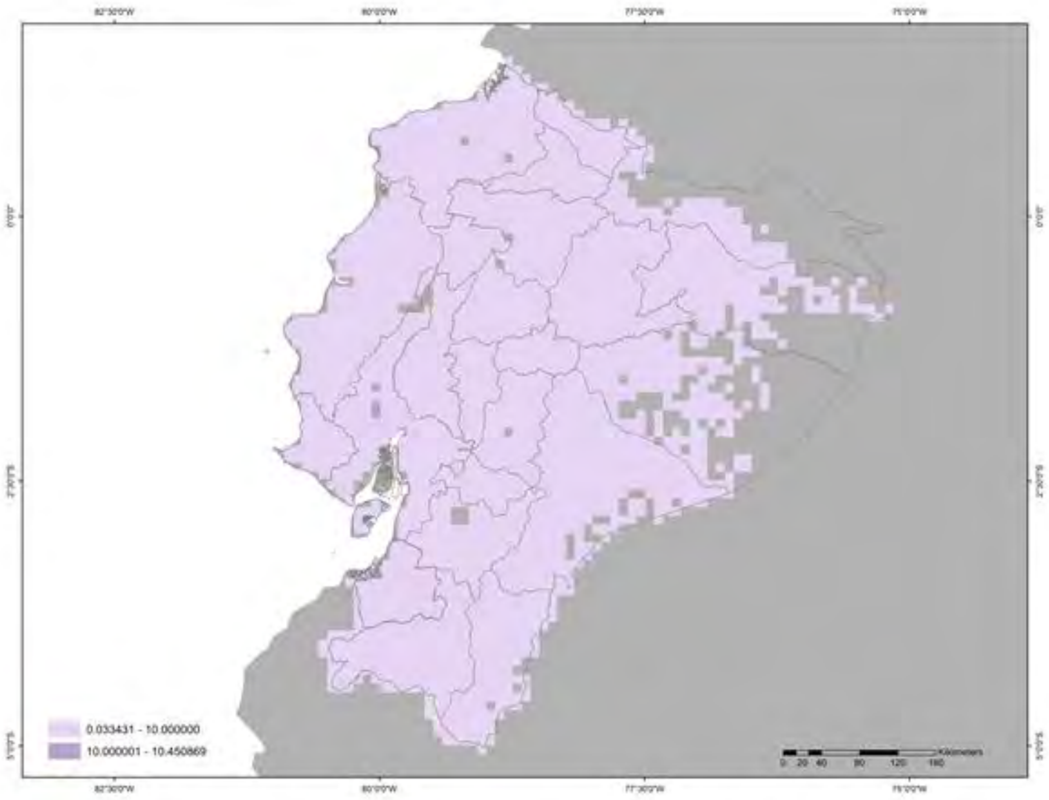

Figure 6.18 Grey water footprint (in mm/year) of maize production in Ecuador. Source: own production with spatial data from Mekonnen and Hoekstra (2011).

A total of 1,819 pixels were used to calculate the cost of grey water in Ecuador. Of these, almost half (45.8%) corresponded to smallholder production units (maize yield < 2 ton/ha) and the rest (54.2%) to mixed production units (maize yield between 2 and 6 ton/ha). Only 6 pixels had yields of over 6 ton/ha and these were included in the intermediate production category. Smallholder pixels represented 57.4% of the harvested area, 37.2% of the total production and 42% of the total grey water footprint (Tab. 6.17). As expected, the total and per hectare grey water footprint of smallholder units was lower than that of intermediate producers (Tab. 6.18).

Table 6.17 Maize production and grey water in Ecuador

	Smallholder (<2 t/ha)	**Intermediate (2-6 t/ha)**
Number of pixels	833	986
Harvested area, ha (total)	223,345	165,936
Pixel area (ha)	8,463,902	10,026,385
Maize production, ton (total)	286,055	483,598
Maize yield, ton/ha (mean)	1.2	3
Grey water, mm/year (mean)	0.8	1
Grey water, m^3/year (total)	69,661,194	96,111,690
Grey water, m^3/ha	8.2	9.6

The total and relative costs of grey water in Ecuador are much lower than those of the USA (see below), not only because their absolute quantity is smaller but also due to the lower costs of irrigation water in Ecuador (Tab. 6.17).

Table 6.18 Total and relative costs of the grey water footprint of intermediate and stallholder maize production units in Ecuador

	Smallholder		**Intermediate**	
	Cubic meters	*USD*	*Cubic meters*	*USD*
Total	69,661,194	11,494,097	96,111,690	15,858,429
Per ha	8.2	1.4	9.6	1.6

Due to the high prices commanded by producers for maize and the low prices for irrigation water in Ecuador, the partial remediation costs associated with nitrogen leaching represented 11.6% of the maize production revenues in low-yield units and 9.5% in the intermediate units (Tab. 6.19).

Table 6.19 Value of maize production and grey water footprint costs in maize production units in Ecuador

	Smallholder		**Intermediate**	
	Production	*Grey water*	*Production*	*Grey water*
Total (USD)	98,688,975	11,494,097	166,841,275	15,858,429
% of production		11.6		9.5

Mexico

The highest values of the grey water footprint in Mexico were distributed along the length of the central highlands, mainly across the states of Jalisco, Guanajuato, Querétaro, Estado de Mexico, Puebla and Tlaxcala and, in its southern portion, through the states of Chiapas and Guerrero and towards the east mainly in Veracruz (Fig. 6.19).

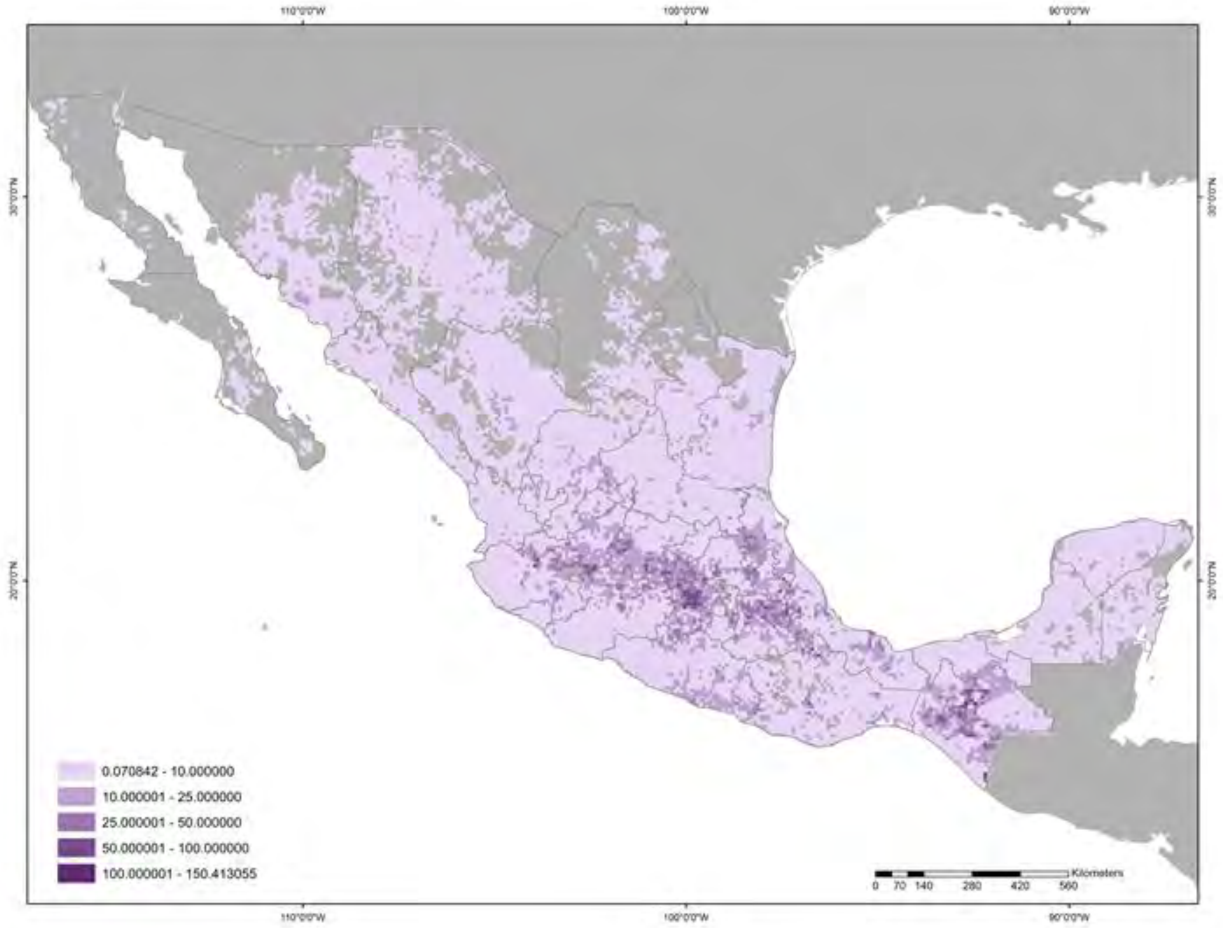

Figure 6.19 Grey water footprint (in mm/year) of maize production in Mexico. Source: own production with spatial data from Mekonnen and Hoekstra (2011).

Intensive maize production units (*i.e.* pixels) were rather scant in Mexico compared to the USA. They represented only 3.1% of the total maize production units (9,376) included in the present analysis, shared 5.9% of the total maize area and accounted for 17% of the total maize production (Tab. 6.20). Intermediate and low-yield producers shared a similar percentage of the harvested area of maize (47.5 and 46.7%).

Table 6.20 Maize production and grey water in Mexico

	Smallholder (<2 t/ha)	**Intermediate (2-6 t/ha)**	**Intensive (>6 t/ha)**
Number of pixels	5,821	3,261	294
Harvested area, ha (total)	2,559,203	2,603,471	322,908
Pixel area (ha)	46,798,806	26,209,356	2,341,934
Maize production, ton (total)	3,222,304	8,700,100	2,452,551
Maize yield, ton/ha (mean)	1	3.1	7.8
Grey water, mm/year (mean)	5.4	9.4	14.5
Grey water, m^3/year (total)	2,531,530,818	2,466,275,405	338,955,782
Grey water, m^3/ha	54.1	94.1	144.7

As expected, the grey water footprint was highest among high-yielding units, followed by intermediate and then low-yielding units in both average and per hectare terms. However, given the larger maize production areas of both the intermediate and low-yield units, these ultimately present a greater absolute grey water footprint than the intensive units (Tab. 6.21).

Table 6.21 Total and relative costs of the grey water footprint of intensive, intermediate and low-yield maize production units in Mexico

	Smallholder		**Intermediate**		**Intensive**	
	Cubic meters	*USD*	*Cubic meters*	*USD*	*Cubic meters*	*USD*
Total	2,531,530,818	465,801,671	2,466,275,405	453,794,675	338,955,782	62,367,864
Per ha	54.1	10	94.1	17.3	144.7	26.6

The higher revenues obtained from maize production in intensive pixels resulted in a lower share of grey water costs relative to that of the intermediate and low-yielding units, making these costs potentially higher for smallholders if these producers were to assume this expense (Tab. 6.22).

Table 6.22 Value of maize production and grey water footprint costs in maize production units in Mexico

	Smallholder		**Intermediate**		**Intensive**	
	Production	*Grey water*	*Production*	*Grey water*	*Production*	*Grey*
Total (USD)	466,911,835	465,801,671	1,260,644,433	453,794,675	355,374,625	62,367,864
% of production		99.7		35.9		17.5

USA

Figure 6.20 shows that the highest grey water footprint in the USA is distributed along the *Corn Belt* region, corresponding to the states of Iowa, Illinois, Minnesota, South Dakota, Nebraska, Kansas, Missouri, Indiana and Ohio, as well as to small portions of Idaho, Washington and Texas.

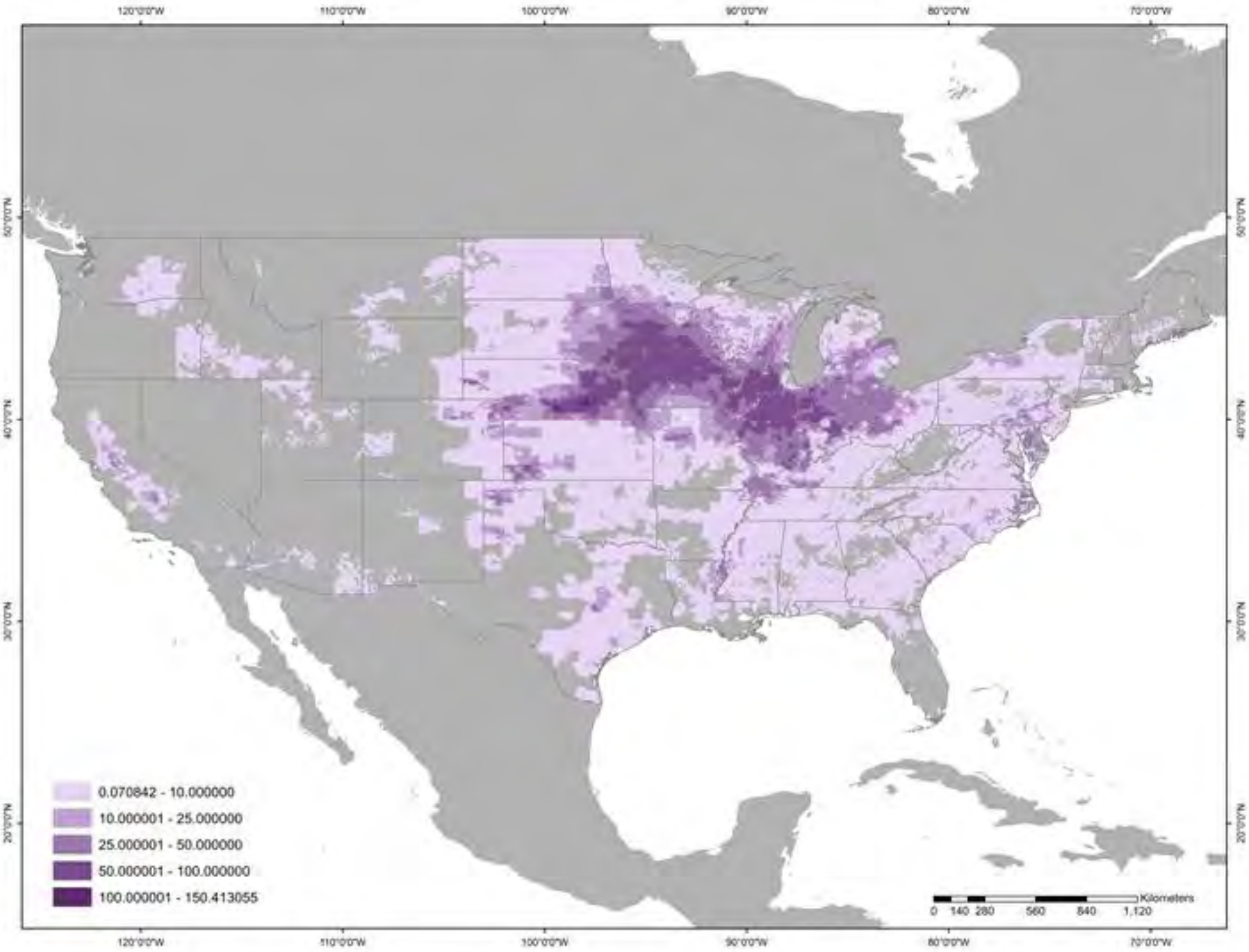

Figure 6.20 Grey water footprint of maize production in the USA. Source: own production with spatial data Mekonnen and Hoekstra (2011).

A total of 15,845 units were included in the analysis, of which 0.3% represented smallholder units, 19.6% were intermediate and 80.1% were intensive units. Intensive units accounted for 95.6% of the total harvested area of maize and 98% of the entire maize production (Tab. 6.23). On average, intensive maize producers had a higher grey water footprint (20.6 mm) than the intermediate units (3.1 mm) in both total (18,484,160,113 *vs.* 709,811,663 m^3) and relative (203.2 *vs.* 31 m^3/ha) terms (Tab. 6.23).

Table 6.23 Maize production and grey water in the USA

	Smallholder (<2 t/ha)	Intermediate (2-6 t/ha)	Intensive (>6 ton/ha)
Number of pixels	44	3,113	12,686
Harvested area, ha (total)	2,479	509,109	11,169,455
Pixel area (ha)	323,094	22,894,453	90,946,320
Maize production, ton (total)	3,915	2,387,562	114,410,125
Maize yield, ton/ha (mean)	1,4	4.8	9.1
Grey water, mm/year (mean)	2.2	3.1	20.6
Grey water, m^3/year (total)	7,110,060	709,811,663	18,484,160,113
Grey water, m^3/ha	22	31	203.2

Intensive counties generate total grey water costs that far exceed those of the intermediate and small production units (Tab. 6.24). The costs also exceed those of these latter producers on a per hectare basis.

Table 6.24 Total and relative costs of the grey water footprint of intermediate and intensive maize production units in the USA

	Smallholder		**Intermediate**		**Intensive**	
	Cubic meters	*USD*	*Cubic meters*	*USD*	*Cubic meters*	*USD*
Total	7,110,060	8,133,909	709,811,663	812,024,542	18,484,160,113	21,145,879,169
Per ha	22	25.2	31	35.5	203.2	232.5

The cost of grey water in smallholder units represented 2,630% of the total income (value of output) from maize production, 430% of the income from maize production in intermediate units, and 234% of that of the intensive units (Tab. 6.25); *i.e.*, if producers were to bear the external costs of nitrogen leaching from maize production, all of their earnings would be lost due to the remediation costs involved.

Table 6.25 Value of maize production and grey water footprint costs in maize production units in the USA

	Smallholder		**Intermediate**		**Intensive**	
	Production	*Grey water*	*Production*	*Grey water*	*Production*	*Grey water*
Total (USD)	309,293	8,133,909	188,617,390	812,024,542	9,038,399,865	21,145,879,169
% of production		2,629.8		430.5		233.9

Grey water footprint in USA, Mexico and Ecuador

The three countries generated grey water footprints that differed enormously. The total grey water generated by the three countries was 24,703 million cubic meters per year, valued at $22,975 million USD, of which 77.7% was produced by the USA, 21.6% by Mexico and 0.7% by Ecuador (Fig. 6.21). In the USA, intensive units were responsible for almost the entire grey water footprint of the country, while in Mexico, smallholders and intermediate producers were responsible for this mainly because they represent the predominant maize producers. In all countries, the intensive pixels presented a higher grey water footprint on average as well as a higher amount of grey water per hectare of maize produced. This is to be expected given that Mekonnen and Hoekstra (2011) originally used data on yield to calculate the grey water use.

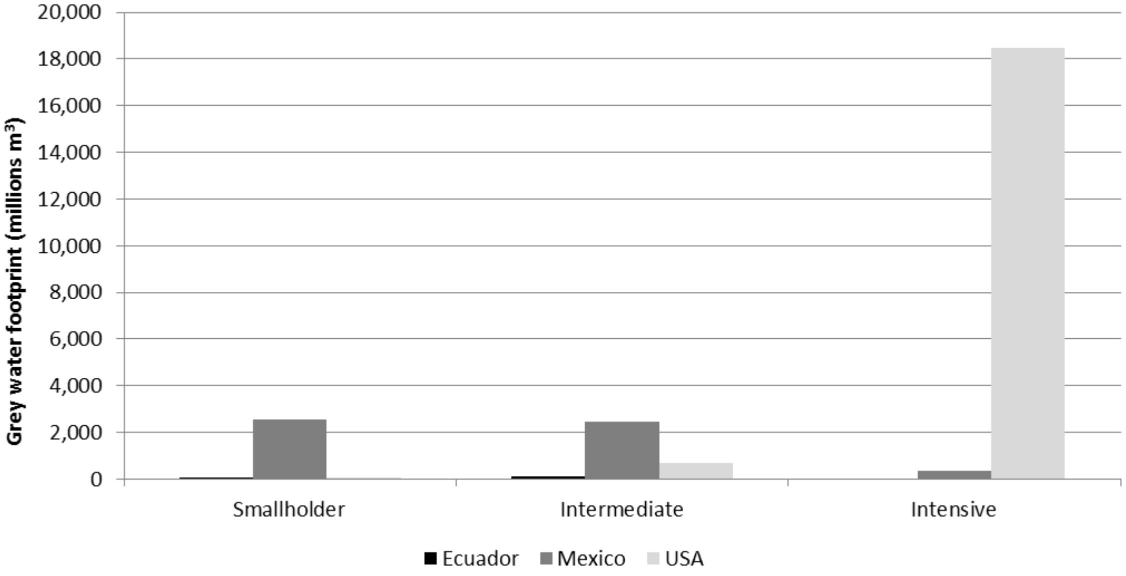

Figure 6.21 Total grey water footprints of intensive, intermediate and smallholder maize production units in Ecuador, Mexico and USA

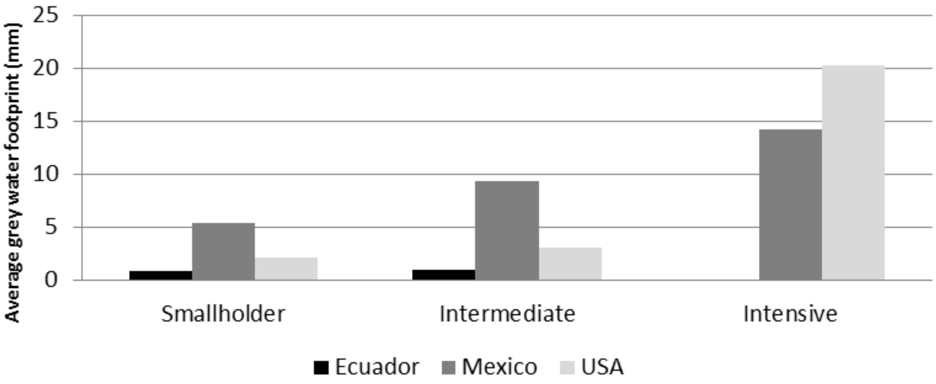

Figure 6.22 Average grey water footprint of maize production in Ecuador, Mexico and USA

The average grey water footprint of maize production also shows important differences among maize production systems (Fig. 6.22). On average, smallholder and intermediate production units in Mexico generate a larger grey water footprint than the equivalent units in Ecuador and USA, while intensive units in USA generate a larger footprint than their counterparts in Mexico. Average maize yields are similar among the smallholder units of the three countries, which means that a higher amount of nitrogen fertilizers is used in Mexico in order to achieve the same productivity. Intermediate units in Mexico and Ecuador have a similar average yield, but the quantity of the average grey water footprint in millimeters is much higher in Mexico than in Ecuador. Higher amounts of nitrogen fertilizers may be needed to produce crops in less fertile soils, but it may also be the case that fertilizers are inefficiently used by producers, especially where their use is subsidized by governmental authorities (Barbier and Bishop, 2010).

Using the cost of the quantity of water required to dilute nitrate levels in water to value the impact of eutrophication represents, without doubt, only a small part of the total economic cost that must be accounted for, given the negative impacts of nitrogen leaching on aquatic ecosystems and biodiversity. The total economic value of water eutrophication driven by maize production in particular and agriculture in general will certainly exceed by far the remediation costs of diluting nitrate levels in water.

Turner *et al.* (1999, quoted in Rabotyagov et al., 2012), using data from a contingent valuation in Sweden and Poland, estimated the economic benefits of restoring eutrophication levels in the Baltic to a sustainable level at $10 billion USD. Smith (2007a, quoted in Rabotyagov et al., 2012) estimated the total benefits from reducing hypoxic conditions in a blue crab fishery in North Carolina at $1 to $7 million USD per year. Massey, Newbold, and Gentner (2006), also quoted in Rabotyagov et al. 2012, estimated that a 25% increase in dissolved oxygen levels in the Chesapeake Bay would increase catch rates by 20%, producing economic benefits of over $80 million USD per year. Davenport and Drake (2011) estimated losses for the recreation business profiting from Grand Lake Saint Marys in Ohio, USA, at $35 to $45 million due to nutrient-related algae blooms. Moreover, the health costs of nitrates in drinking water in the European Union, which have been linked to colon cancer, has been calculated at an population-averaged health loss of 2.9 euro per capita or 0.7 euro per kg of nitrate-N leached from fertilizer (Van Grinsven et al., 2010).

Evidently, identification of populations affected by water eutrophication as well as inclusion of diverse valuation approaches will help to provide a more inclusive and extensive perspective of the implied costs.

6.4 The value of maize landraces: a shadow price analysis to support decision making related to the protection of the centers of origin and genetic diversity of maize in Mexico in 2011

Authors: Laura Saad Alvarado and Alejandra Barrios

The cultural value of Maize in Mexico is tightly linked to a biological, geographical and historical context, since the country is located in a region where agriculture originated, and is considered the center of origin and a center of diversity of this crop. Centers of origin and genetic diversity have been recognized as being of "crucial importance to humankind" (Cartagena Protocol on Biosafety to the Convention on Biological Diversity) and measures for their protection have been fostered by some countries. The Mexican Biosafety Law (DOF, 2005) considers that the areas within Mexico where the centers of origin and genetic diversity of native crops are located should be officially established in order to facilitate their protection (see Box 6.1).

In this context, in order to comply with the cost-benefit obligations previously required in order to decree these areas for maize, in 2011, the Mexican Ministry of Environment (SEMARNAT by its Spanish acronym) developed an economic study in which it applied the methodology of shadow prices to make other values of maize landraces visible (such as characteristics related to physiochemical aspects, cropping, culture, diet and cuisine) in order to demonstrate the benefits implicit in preserving the areas where these are grown (SEMARNAT, 2011). Economists devoted to the study of agricultural production units have analyzed these as a business, assuming that the decision-making of farmers regarding inputs and outputs will be linked to market prices and potential monetary benefits. Other academic economists have focused their attention on shadow price evaluation to explain the decision-making of small-scale producers, where these may or may not be linked to markets through sale of the crop, if a surplus beyond self-consumption is obtained: These do not necessarily take the form of corporate production units guided by monetary gain.

Arslan and Taylor (2009) produced an assessment of the cultural values underlying the production of maize landraces by traditional maize farmers in Mexico, through shadow prices using ENHRUM[85] as its basis (See Box 6.2 to learn about the methodology used). In the full ENHRUM sample, 74% of households did not sell any maize in the market, while this number increased to 80% for households that grew only traditional varieties (TVs). In the south-southeast region of Mexico, which encompasses states with a high proportion of indigenous people, 92% of the plots were cultivated with TVs. Traditional varieties are produced in smaller plots, with more labor but less fertilizer and investment, and 69% of the traditional maize plots are cultivated with saved seed, as opposed to 13% of modern maize plots. The key findings of the econometric model estimated by Arslan and Taylor (2009) were: 1) there is a substantial difference between shadow and market prices of traditional maize varieties in Mexico; 2) the characteristics of maize valued by farmers and their households are not reflected in market prices; these include color, palatability, smoothness of dough and suitability for certain dishes, ease of shelling and treating, as well as other social values, for example, the expertise of each farmer to grow maize

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[85] The National Survey to Rural Households in Mexico (ENHRUM) was a project launched by Study of Economic Change and Sustainability of Mexican Agriculture (PRECESAM) (lead by COLMEX) and the *Rural Economies of the Americas and Pacific Rim* (REAP) (lead by UC-Davies) to obtain representative nationwide information about the economy of rural households in Mexico (http://das-ac.mx/comunidad-enhrum/enhrum-i-2002/).

recognized by the community; 3) high shadow prices of TVs create incentives to grow subsistence crops with non-market values; 4) shadow prices are better at estimating the value of biodiversity in crops in their center of origin than market prices because it captures the farmers subjective valuation of these crops; 5) the estimated shadow prices of improved maize varieties are not significantly higher than market prices.

Box 6.1 Center of Origin and Centers of Genetic Diversity of Maize Legal Agreement

Authors: Laura Saad Alvarado, Patricia Tovar and Alejandra Barrios

Through the Mexican Biosafety Law[1] the legislative power recognized the relevance of Mexico being the center of origin of diverse species, several of them with a recognized global importance. This is reflected in the introduction of novel regulatory mechanisms in order to determine the "centers of origin and genetic diversity of species" (COCGD), as well as the establishment of restrictive rules to undertaking activities with genetically modified organisms (GMO) in such centers through a legal Agreement.

The national legal framework includes at least 13 dispositions directly applicable to the determination of COCGD[2], consolidating a national legal framework seeking to provide certainty to civil society as well as to the authorities involved in the determination of the COCGD in Mexico. It is in this manner that the protection of the species and the areas where they are present is addressed, and the precautionary principle towards possible risks that could affect biological diversity is attended.

The Agreement that determines the maize COCGD[3] is the first that has been published for the northern states of the country, and seeks to safeguard the conservation of the species for which Mexico is custodian, constituting a natural patrimony of common benefits not only for Mexicans, but for the world. Even though its emission might imply costs in its compliance, the Mexican State must act responsibly, putting the common welfare above individual profits.

The most important expected benefits are:

- Mexican small-scale farmer protection, who through their agricultural practices, seed selection and active and evolving seed exchange contribute, together with the environmental conditions (biotic and abiotic), to maize diversity. The small-scale farmers and their families, through holding, selecting and sowing maize seeds from the previous cycle provide an environmental service.
- *In situ* conservation. Protection of the genetic and morphological diversity of maize represented by 59 landraces, including a wide range of local varieties, and its wild relatives.
- Consideration of the rights of the indigenous, the national, and international scientific communities in instrumenting the precautionary approach towards the utilization of GM maize[4].
- Try diminishing the risk of the gradual substitution of the local varieties, which could accordingly increase the dependency of the farmers on a technology that will transfer resources to the seed companies that own the plant variety patents. If the small-scale farmers had to buy hybrid or GM seed each year they would depend on the market forces (supply and demand), which could contribute to a situation of food dependency contrary to the rights of Article 4 of the Constitution

...Box 6.1 continued

- Compliance with International Conventions and Agreements, as well as with the National Biosafety Law and its regulation.
- Avoid jeopardizing the diversity of native maize varieties, given the way gene flow occurs in maize through both pollen and seed exchange among Mexican farmers.
- Prevent the loss of the agrobiodiversity associated with maize, which constitutes a fundamental element towards the future when confronted with the menaces and unpredictable changes driven by climate change. The selection of seeds by the Mexican farmers is dynamic, as seeds co-evolve and adapt to the processes of climate change, making traditional farming systems resilient.

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[1] http://www.diputados.gob.mx/LeyesBiblio/pdf/LBOGM.pdf

[2] Ministry of Environment and Natural Resources (SEMARNAT) 2011. "Manifestación de Impacto Regulatorio del Proyecto de Acuerdo por el que se Determinan los Centros de Origen y Diversidad Genética Del Maíz En Territorio Nacional. Contrato DGSPYRNR-No-002/2011". Editor: Saad Alvarado Laura. México, 2011. Published in:
http://cofemersimir.gob.mx/expedientes/10404;
http://cofemersimir.gob.mx/archivo/expediente/10404/mir/35909
http://cofemersimir.gob.mx/expediente/10404/recibido/46622/B001104104

[3] http://dof.gob.mx/nota_detalle.php?codigo=5276453&fecha=02/11/2012

[4] Diverse stakeholders expressed their opinion while the legal agreement on COCGD and its regulatory impact assessment was under public consultation.

Box 6.2 Farmers' Subjective Valuation of Subsistence Crops: The Case of Traditional Maize in Mexico.

Authors: Laura Saad Alvarado and Alejandra Barrios

In the present box we provide a recount of the methodology followed by Arslan and Taylor (2009) to calculate the shadow price of maize landraces among small subsistence farmers in Mexico. The authors refer to shadow prices as the value of goods and benefits that cannot be merchandized in the market (the air or the rain, for example). The main aim of the study of Arslan and Taylor (2009) was to test if the decision prices for subsistence farmers in rural Mexico were the same as the prices of maize in the market. They reasoned that if shadow prices were higher than market prices this would play a fundamental role, like a *de facto* incentive, for farmers to maintain the cultivation of native maize landraces.

Arslan and Taylor established a conceptual framework to delimit and specify the object of study: they described the basic aspects of the agricultural systems of small subsistence farmers. They also highlighted the importance of clearly differentiating within crops (*i.e.* different maize landraces) and how these, in an asymmetric market, can be conceptualized as an object with multiple characteristics. They included information regarding the ceremonial (religious), cultural and consumption values of subsistence crops, the importance of possessing seeds in an imperfect seed market, the access of surplus production to the market (even if it implies monetary losses for produces due to the low market prices for maize), and finally they also valued the fact that Mexico is a center of domestication and diversity of several crops including maize.

The theoretical basis that the authors used for the calculation of the shadow price is based on a simple model for agricultural households subject to market restrictions for subsistence maize harvests; these restrictions are said to be asymmetrical given that producers can sell their crops but cannot buy crops of identical quality in the market. This reflects the non-market values associated to the production of maize within the households, rendering maize bought in the market an imperfect substitute for its consumption. Therefore, the production of maize within the households enters in a utility function as separated consumer goods.

All these theoretical considerations are developed in several equations and measured in a final econometric equation resulting from the comparison of prices to estimate the shadow price: for a farmer that produces the subsistence crop (that is $\mu 4 = 0$), the condition of first order for the work performance (L):

$$\mu 1 MPLs = \lambda w \quad (8)$$

The left side of the equation represents the marginal benefit that the farmer receives (in terms of utility) from the designation of an additional unit of labor for the production of the subsistence crop. The right side represents the marginal costs of the last unit of work in terms of utility. Even though $\mu 1$ *and* λ are not observable we can define an estimable expression for ρ in the following manner:

$$\boldsymbol{\rho \equiv \mu \frac{\mu 1}{\lambda} = \frac{\omega}{MPLs}}$$

…Box 6.2 continued

With this mathematical approach, a series of hypothesis were designed by using the following information:

The data used for the present study came from the ENHRUM[1] poll of 2003. It was sought that the variables and data included in the data base used for this study reflected the agronomical and socio-economical characteristics of farmers that possess/use native maize landraces, as well as the farmers that do not.

The hypothesis tested here was that shadow prices of maize for small subsistence farmers are different than the market prices for this crop. The authors of this study managed to calculate how different they are and to explain why market prices of maize are not related to production decisions of farmers cultivating landraces. They conclude that the many characteristics (culinary, cultural, resistance to pests, etc.) of native maize landraces differ from improved varieties, and define its shadow price.

Table 6.26 Summary Statistics for Estimated Shadow Prices and Observed Market Prices*

Variable	TV	MV
Shadow price for full sample	48.34	13.77
Shadow price for sellers	20.50	5.19
Shadow price for non-sellers	58.18	25.53
Observed market price/kg.	1.98	1.57

Are Estimated Shadow Prices Equal to Observed Market Prices?

	Modern variety (improved/ hybrid))		Traditional variety (criollo)	
	Alfa	Beta	Alfa	Beta
Seller	-1.94	5.22	21.08	0.70
F-test	(0.17)		(0.0)	
t-tests	(0.83)	(0.44)	(0.38)	(0.97)
Non- Seller	-15.03	40.10	**52.95**	**2.62**
F-test	(0.17)		(0.00)	
t-tests	(0.77)	(0.41)	(0.06)	(0.89)

*Taken from Arslan, A. and Taylor, E.© Farmers' Subjective Valuation of Subsistence Crops: The Case of Traditional Maize in Mexico. 2008. ARE. UC DAVIS. Working Paper No.08-002. Note: p-values in parentheses.

Estimating the value of landraces in Mexico

Parameters found in the econometric estimation of Arslan and Taylor (2009) were used to estimate the value of subsistence rainfed maize in Mexico in order to demonstrate the benefits of a decree of center of origin and diversification of maize based on the results of the research on maize landraces coordinated by CONABIO, the Global Maize Project (http://www.biodiversidad.gob.mx/genes/proyectoMaices.html) in Mexico.

Table 6.27 Estimation of the self-consumption of maize grain

	Year 2009	Self consumed	Estimated maize grain self consumed, 2009
	(a)	(b)	c= (a)*(b)
Rainfed maize grain			
Production (metric tons)	9,923,598	57.3%	5,686,221
Production value (thousands Mexican pesos Mx $)	$29,238,598	57.3%	$16,753,717
Rural average maize price	$2.94637		

57.3% self consumed maize. Source: Lazos, E. & Chauvet, M. Proyecto Análisis del Contexto Social y Biocultural de las Colectas de Maíces nativos en México. UNAM. UAM-A

*Taken from Ministry of Environment and Natural Resources (SEMARNAT) 2011. “Manifestación de Impacto Regulatorio del Proyecto de Acuerdo por el que se Determinan los Centros de Origen y Diversidad Genética Del Maíz En Territorio Nacional. Contrato DGSPYRNR-No-002/2011”. Editor: Saad Alvarado Laura. México, 2011. Published in: http://207.248.177.30/expediente/v99/_B001104104.pdf y http://207.248.177.30/regulaciones/scd_expediente_3.asp?ID=04/0851/171111 .

Table 6.28 Estimated production value (shadow price) of self-consumed rainfed maize in 2009, calculated for 2011**

Shadow regression (equation 11)*	$\boldsymbol{\rho=\alpha+\beta p+u}$
Value from regression, data 2003, shadow price*	$P =52.95+(2.62)(1.8)+u$
Price 2009	$2.95
Substituting prices $/kg, 2009	$p =52.95+(0)(2.94637)+u$
Shadow Price 2009 (ceteris paribus)	$52.95
Production	5,686,221
Estimation shadow price, maize production 2009 rainfed self- consumed (thousands Mx $)	$301,085,402
Inflation 2009-11	1.076355625
Value 2011 price	$324,074,965.99
Unit Price Mx $/kg 2011	$56.99

*Arslan, A. and Taylor, E.© Farmers' Subjective Valuation of Subsistence Crops: The Case of Traditional Maize in Mexico. 2008. ARE. UC-DAVIS. Working Paper No.08-002.
**Taken from Ministry of Environment and Natural Resources (SEMARNAT) 2011. "Manifestación de Impacto Regulatorio del Proyecto de Acuerdo por el que se Determinan los Centros de Origen y Diversidad Genética Del Maíz En Territorio Nacional. Contrato DGSPYRNR-No-002/2011". Editor: Saad Alvarado Laura. México, 2011. Published in: http://207.248.177.30/expediente/v99/_B001104104.pdf and http://207.248.177.30/regulaciones/scd_expediente_3.asp?ID=04/0851/171111

Like Arslan and Taylor (2009), we found that the shadow price of rainfed maize for self-consumption in 2011 is around nineteen times higher than the market price for white maize grain, assuming the existence of native maize seed supply. The difference in evaluation between the price dictated by the mainstream market and the traditional rainfed maize market can be explained by several factors, including the advantages of landraces when farming in a variety of environments, coping with production risks, managing pests and pathogens, avoiding or minimizing labor bottlenecks, coping with budget constraints, providing variety to monotonous diets, generating prestige and forging social ties, folklore values (handcrafting, among others); as well as the cultural, spiritual, religious, culinary specificities, driven by the differentiated tastes, colors and rheology of the *masa* doughs of the great variety of maize landraces. The many positive characteristics of maize landraces that are appreciated by the small-holder farmers in Chiapas include: sweeter *elotes* (corn-on-the-cob), more palatable *tortillas*, more palatable *posol*, better consistency for *tortillas* and fried corn dishes, less fuel and time needed to cook, dough that has a longer storage period and produces more *tortillas* per kilo of grain.

Studies using other economic approaches also conclude that the cultural values related to maize landraces promote the management of the crop and its conservation in traditional maize production systems. Escobar (2006), for example, concludes that native maize is highly appreciated among traditional communities; some farmers believe their maize is worth a higher price (at least double) when compared to commercial maize. He also concludes that maize diversity is also supported by a diversity of economic, social, environment and cultural values assigned by the farmers. The present results show that the use of shadow price methods is more appropriate for explaining small-scale production and these are becoming very important for the evaluation of biodiversity and achievement of international goals such as the Aichi targets and the Strategic Plan for Biodiversity 2011-2020 of the CBD. The strong link between the production and consumption of maize and the local cultures of traditional farmers in Mexico and Mesoamerica is expressed to a great extent in shadow prices of maize landraces that are nineteen (2011 prices) times higher than the prices of this crop in mainstream markets, highlighting the importance of designing ecosystem-friendly strategies and technological packages that will help smallholders to improve their production in a culturally meaningful way.

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7. PUBLIC POLICIES RECOMENDATIONS ON THE PRODUCTION OF MAIZE

7. Public Policy Recommendations on the Production of Maize

Authors: Francisca Acevedo, Caroline Burgeff, Alicia Mastretta-Yanes, Elleli Huerta, Pedro Álvarez Icaza and José Sarukhán

7.1. All policies related to the production of maize should acknowledge that there are different types of production systems, each with different dependencies and impacts on ecosystem services

Different maize production systems need different policies

The different maize production systems represent the historical response to a diverse set of needs through a variety of agricultural approaches, ranging from the recently (last seven decades) very large and intensive technified production systems with higher yields, to the traditional small scale maize production systems generally with lower yields (see section 3). The technified systems depend on different external inputs such as fertilizers and pesticides, uniformity of biophysical conditions, low agrobiodiversity (monocultures) and a generally narrow genetic base of the used crops. Their harvest is principally directed to global food and industrial markets both as grain and feed, diverse industrialized processed food products, and very recently targeting the generation of biofuels. These systems have important negative impacts on diverse human processes and ecosystem services. Traditional systems, on the other hand, are generally much less dependent on inputs such as fertilizers and pesticides; they are located in places with an considerable diversity of biophysical conditions, tend to produce biodiverse agroecosystems (polycultures) and possess a very rich genetic base (evolving and adapting on a regularly yearly basis because seeds are typically saved, selected and sown for a following cycle). Grain produced by these systems is principally used for food and directed for local consumption, including self-consumption.

Both production systems respond to different circumstances and needs, and dependent on and impact ecosystem systems differently (see sections 5.1, 5.2, 5.4 and 6.1, 6.2, 6.3, 6.4). Therefore, to ensure that the particularities, functions and necessities of each system are taken into account, policy formulation should be designed according to each system. For this, policies should avoid the uniformity of maize production systems as a unique production model, which would make vulnerable their different roles, objectives and outcomes. For example, in Mexico for small-scale farmers, the system of maize production is a "multi-functional" crop with great cultural importance (Bellon 1996), and hence its multiple dimensions must be taken into account as programs are designed and implemented.

Markets must differentiate, value and acknowledge the diverse sources and attributes of maize production systems and their resulting products.

Smallholder maize production systems hold, maintain and support the world’s richest and most diverse genetic stocks of crops and provide high quality diverse maize products (see sections 5.1., 5.2 and 5.4). In contrast, uniform global maize markets account for maize mainly as a cash crop and do not recognize the functions that maize genetic diversity holds nor the quality of its maize products.

In order to recognize and reconcile these two systems, differentiation mechanisms could be developed to help and reaffirm small-scale maize farming. This would create a positive feedback loop in relation to its production, with differentiated values related to other relevant and recognized quality properties for food. For instance, native maize produced by traditional smallholders is preferred for direct human consumption and is of interest for specialty markets, while maize produced by technified systems is preferred for industrial processes that do not demand the same quality. A recent workshop held jointly by CIMMYT and CONABIO started discussing this issue considering the recent culinary and gastronomical demands for high quality and diverse production of native maize landraces and products. This discussion still needs to be extended to other actors and consider a broader scale.

7.2. There is a need to invest more in publicly funded scientific research and specific data generation regarding maize production systems

Reconsidering agricultural research and development as a national state strategy

Public expenditure in agricultural research was seriously reduced globally between 1970 and 2000, picking up after that period but not homogeneously by all countries. At the same time, the private sector investment on agricultural research has been on the rise accounting at least for 40% of all agriculture research expenditure (FAO, 2014b). Between 1950 and 1980 Mexico was a net exporter of maize, based on strong public investment for research and development in agriculture and forestry. The abandonment of this effort in the last 30 years resulted in Mexico importing basic cereals. It is essential that food sovereignty be recovered by revert the low public investment in research and development efforts. Countries that have maintained a reasonable public investment in relation to their GDP in agricultural research have, in general, been less vulnerable to global food economic turmoil, in contrast to those that have depended on external supplies of key staple crops. It is only sensible and sound to strengthen internal research and development of agricultural institutions nationally.

There is a need for financial investment in global maize generation of knowledge, research and development.

A robust corpus of knowledge has been accumulated for maize, but we are still far from understanding many of the outlying basic components that drive and comprise maize production systems in the world. Specifically, if we account for all maize production systems we still do not fully comprehend the driving forces involved in its production, diversification and development through time and space. For instance, why a number of farmers prefer growing maize landraces over hybrid maize? What are the ecological consequences of growing large extensions of genetically homogeneous maize? (see section 5.2) How can maize wild relatives improve maize production? To answer this type of questions further research is needed in maize taxonomy, genetics, agronomy, agricultural practices, uses and the relationship with the ecosystem services (both dependencies and impacts), as well as socioeconomic and cultural factors.

Even in the areas of knowledge considered to be more advanced in maize research, important gaps remain to be filled. For instance, in the field of genetics several maize genomes have been sequenced and there is an important amount of data available from maize through the world, but we still need to better comprehend the basis of the centers of origin of maize, its wild relatives, the relationships between human groups and the ecological areas where maize and its wild relatives are present, as well as the processes by which they have evolved during the agricultural era (last 7-9 thousand years). It is also urgent to make breeding programs more efficient by making better use of the extant genetic diversity of the crop (see below) (Sanchez, 2011).

Maize diversity is a public good, and as such, additional to the current private sector efforts in research and development, knowledge generation must be triggered by public financial investment with a research agenda constructed and promoted by public interests. This should include the generated knowledge to remain in the public domain.

All maize farmers worldwide should be able to benefit more directly from research and breeding efforts

Breeding efforts have been very useful to increase yield on an annual basis and contribute towards productivity (see Box 5.2: A brief history of modern maize breeding and hybrid maize). However, these efforts have not been equally focused towards the different maize production systems nor have these production systems benefited people equally. For instance, most research has focused on maize production under systems and management methods (e.g. using expensive equipment and requiring large areas) different from what can be realistically done by smallholders. A second nonobvious but very important example is that the environmental conditions present where the vast majority of small scale farmers are located are poorly represented by the public research stations where improved maize lines and hybrids have been developed and tested. This means that those improved lines would perform poorly in the lands of the small scale farmers. Nevertheless, the native maize landraces from these smallholders have undoubtedly contributed with genetic material to the maize collections and genebanks worldwide, and to a large extent, have been incorporated to many maize breeding programs (both public and private).

The unbalanced benefit from maize breeding and research on agronomical and sustainable practices is a threat to the food security and development of rural areas and beyond. Therefore, it is necessary to formulate innovative approaches towards developing and fulfilling the needs of small scale farmers. One way of accomplishing this could be participatory plant breeding of local germplasm, as described below.

Breeding and agronomical efforts should incorporate a focus on local landraces

Since the 1950’s maize breeding has focused mostly on developing better hybrids based on already improved lines (see Box 5.2: A brief history of modern maize breeding and hybrid maize) to which landraces (mostly from Latin America) have served as “donors” to incorporate specific traits. This is desirable and would likely continue to happen without new public policies promoting it. In contrast, maize breeding using maize landraces as base material (instead of donors) has been lacking, especially for countries of Latin America. Motives for this include historical reasons, funding deficiencies and the effort needed at the early stages. However, the local adaptation of native landraces provides the necessary genetic background to produce a yield even under marginal environments. In those particular growing contexts, landraces commonly are equally or more productive than commercial hybrids, but they require much less inputs (see section 5.2).

The impact of improving landraces growing in marginal environments would be huge for food security and the rural economy of developing countries that consume maize. For example, in Mexico smallholders producing 0.7-3 ton/ha (mean 1.3 ton/ha) occupied 78% of the total area planted in 2010, and produced ~6 million ton (Box 4.1 Contribution of smallholder farmers to Mexico´s maize supply). With relatively little help from additional genetics and basic (but determined case-by-base) agronomical improvements these smallholders could increase their production to an average of 2.3 ton/ha, which would mean a production of 10.7 million ton. That would be enough to meet the daily maize consumption of ~ 88.5 million people in one year (Mexico current population is around 120 million, of which around 20% live in rural areas) [86].

For the previous reasons, besides being considered donor material for elite material, landraces should also be incorporated as the base material for new pre-breeding programs and for participatory breeding planned at local and regional scales. For this to happen, projects on participatory maize breeding should be promoted and supported in a relevant time-frame.

7.3. There is a need to support the valuation and conservation of on-farm crop genetic resources

We must make efforts to understand, value and strengthen the processes by which genetic diversity is continuously evolving.

The genetic variability present in the maize genomes and that of its wild relatives (*teocintles*) is a source of partially unknown, unaccounted, and undiscovered genetic richness that has the potential capacity of adapting to future challenges we are now starting to face (for example, climate change) (see section 5.2 and 6.1). It is a prevailing need to preserve such genetic variability and foster its continuing evolution. To do so, we must: (1) make every effort to assure the conservation of the habitats of the wild relatives of maize in its center of origin and genetic diversity, (2) recognize the role that the millions of smallholder farmers worldwide play in fostering an invaluable collection of diversity through their traditional agricultural practices and, (3) insure the necessary prevailing conditions for this diversification mechanism to subsist through time and space. In the case of maize in Mexico for example, the millions of small scale farmers are the stewards of Mexico's existing maize diversity and their efforts must be recognized, valued and incentivized.

The intellectual property rights derived from legally protected genetic materials developed and provided by the seed companies to the maize world production systems are of concern due to the legal effects and fate that the individually owned materials of the smallholder farmers may have. It has recently been argued that “natural and

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[86] 2.3 ton/ha * 4,687,008 (planted area with yields 0.7-3 ton/ha), and considering the mean maize consumption per capita per year as in Box 4.1

cultural heritage, biological resources, and intellectual property are legal concepts that should be grounded deeply in a human rights perspective, in particular on economic, social and cultural rights" (Larson et al, 2016). In this sense, Intellectual Property Rights Laws tend to favor and attend corporate private economic interests, which may hamper the collective purpose of protection of genetic resources of interest to humanity (*ibid.*) as well as the very process by which genetic diversity continuously evolves. This issue should be considered seriously to avoid any possible negative biological consequences of limiting the agricultural practices that promote the diversification of the maize resources, traditionally owned and managed by smallholder farmers. The current and even the new legal conditions in the actual conglomeration of seed, grain commodities and related food industries need to be monitored, analyzed and regulated adequately, so as to avoid hampering the continuous evolutionary processes in the hands of smallholder farmers around the world.

A worldwide driven decisive effort is needed to strengthening in situ conservation efforts to complement ex situ conservation in the public domain.

Given that maize diversity is a public global good, *in situ* conservation, must be an unquestionable common world target. This is particularly important in centers of origin and centers of genetic diversity of maize because they have a large biological, cultural, social and economic significance. Relying only on *ex situ* conservation efforts, even though valuable in itself, is an erroneous safeguard strategy because it leaves out the impressive and effective year to year evolutionary and selective processes driven by millions of smallholder maize farmers worldwide (see section 5.3: Genetic externalities of maize production in intensive and smallholders systems). Specific policies must be developed to target the *in situ* conservation of maize landraces, its wild relatives when present and related species in the existing diverse agroecosystems worldwide. Maize production chains and processing industries alike, but in relative proportions, should contribute substantially both monetarily and materially to this effort. *In situ* conservation of this kind must not be only restricted to maize, but to all potentially important crops, which are those that can contribute significantly to healthy and culturally adequate diverse diets and to sustainable food production systems.

Family agriculture and traditional small scale agriculture should be revalued

Maize production for human consumption is based on family agriculture holdings that are on average less than 5 ha in extension, and which represent at least 70% of all farmers (De Janvry et al., 1994). FAO (2014a) has calculated that family agriculture provides 80% of world food production. The contribution that these millions of farmers provide towards food security and dietary needs must be recognized, quantified, valued and revalued where necessary (see Box 4.1). Also, it should be considered that maize production in these traditional farms is regularly accompanied by other crops growing together with maize, such a beans, squashes, diverse green tender leaves, among others (a system that in Mexico is known as milpa). These farming systems also possess a thoughtful risk management strategy. For example, two or more varieties of maize can be planted differently (spatially and temporally) to increase the probabilities of obtaining the necessary harvest for the household depending on the rain patterns of the agricultural cycle.

The private benefit of these small-scale farmers is obtaining food, feed and fuel, and being mostly independent of the global market's ups and downs. However, the effort made by these small-scale farmers transcends this, because they additionally provide benefits to others. For instance, their maize is a source of useful alleles and allele combinations that are continuously under evolution. Also, when maize is combined with other crops and plant materials growing together it can be source to a healthy diet, so that people living on a nutritious diet causes less public health problems. Finally, a cultural sense of identity surrounded by what maize means is also important in Latin America on the whole, and particularly in Mexico (see section 5.4).

The practices followed by these small scale farmers are generally *de facto* favorable towards the environment, not only by having less impact on the ecosystem services than other types of maize production systems, but also providing an evolutionary service, which is fundamental for the future of food production.

7.4. A transition leading to sustainable practices in the production of maize should be promoted

All maize production systems must aim at being sustainable in their agricultural production approach. We here present a set of criteria that we think need to be taken into account.

"Sustainable use" is defined by the Convention of Biological Diversity (CBD) as "the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations". Agricultural sustainability is multidimensional, including the economic, social and cultural dimensions. To aim towards becoming sustainable, all maize production systems should follow a basic set of criteria including, but not restricted to:

- Preserving (not endangering) the *in situ* genetic reserve (with special emphasis in such geographic areas which hold particularly high diversity levels) and the human processes involved in its conservation and continuous use;
- Insuring the availability of genetic variability amongst the different productive options;
- Recognizing the existing interrelationships and dependencies amongst the different agricultural systems and each ecosystem with the aim of elaborating integral production and protection long term strategies;
- Maintaining ecosystem´s functionality to insure the services they provide (see section 5.3);
- Achieving profitability without the need of external financial aid and subsidies;
- Involving in decision making all actors in the agricultural production chain;
- Respecting human rights, including gender, and aspiring to contribute towards culturally and nutritionally adequate diets;
- Promoting the existence of informed societies, which translates into responsible consumers of the products derived from agriculture;
- Creating incentives that reward the incorporation of sustainable practices in the different agricultural productive systems;

- Promoting and encouraging the development of value chains that seek fair benefits to all those involved;
- Measuring and monitoring the positive and negative impacts to create a self-regulated feedback mechanism.

Financial support is necessary for the different maize production systems to aim towards sustainability

It is time -and it is urgent- to incorporate environmental criteria in agriculture activities that aim for sustainable ways of food production, in our case maize. This includes from policy making, research and development, to strategies of implementation and monitoring.

Maize production systems respond to different circumstances and needs, and are dependent of, and impact, ecosystems differently. In our opinion, the small traditional maize production systems are specially relevant and in need of attention, because they are the least cared for in financial and technical terms, and those that have the most positive impact on human well-being by: a) securing food and feed supply to a very important number of the world population, b) supplying plant genetic diversity (both maize related and from other plant species) to the world community at large, and c) lowering risk scenarios through diversification. Nevertheless, large intensive maize production systems also need our attention, since they also impact human well-being greatly, both in positive and negative ways (see sections 5.2 and 6.3), and this should be attended with care.

All maize production systems need to evolve to more sustainable ways of production. Financial aid and interdisciplinary knowledge should be developed and provided to achieve such an objective; as Tilman and collaborators (2002) have suggested already, incentives and policies must be reoriented in order to promote sustainable practices where the reward structures should be sufficiently creative and attractive for the producers to consider the value of ecosystem services in their practices (see also Box 7.1: Subsidies need to be reconsidered).

A pathway to sustainable maize farming production systems must be developed and pursued

New indicators must be developed that go beyond measuring yield and focus on the sustainability of the maize production systems. As can be seen from this report, even though maize is a very important crop comprising numerous research and development efforts, much data is still needed to account for other factors which are today absent in a formal valuation. These are: human well-being, resilience, ecosystem and evolutionary services, resource use efficiency, nutritional content by hectare, health impacts, calories disposition, local nutrients and total local production (as opposed to only yield).

New legal and financial instruments must be fostered through public policy development guided by the data generated through these new indicators measuring sustainability. Political concern, understanding and will are needed to transit to practices that are more sustainable at large.

Box 7.1 Subsidies need to be reconsidered

Author: Vicente Arriaga

Devised as compensational purposes, subsidies may have pernicious side effects, as they may encourage unsustainable practices leading to unwanted situations. It is then essential to assess and correct the impacts and externalities of subsidies.

Subsidies are designed to offset the adverse effects of price competition and promote the “modernization” of “inefficient” agricultural production systems. They also have a potential to induce better practices, once the unwanted effects of a production system (soil and water pollution, loss of cultivars diversity) have been identified. This is why subsidies must be redesigned to address each particular circumstance, so that their objectives can be directed to ensure sustainability and promote the conservation of biodiversity, including the diversity of cultivars.

The best way to use subsidies is to make them contingent on the fulfillment of a set of rules and standards that lead to better practices. For example, in the case of traditional agriculture with native landraces -if the positive impacts on global human well-being described above are to be maintained-, it is important to ensure that subsidies will not lead to “modernization” of farming practices by introducing improved seeds or fertilizer/pesticide use, as the induction of such technological changes may pose a threat to the use of the native landraces and therefore their conservation and evolution. Quite to the contrary, subsidies in such cases must be directed towards the protection and promotion of this type of agriculture, one on which the conservation of an important gene pool depends, tightly linked to mankind’s ability to respond to possible environmental changes. At the other side of the spectrum, where intensive agriculture with high fossil energy use takes place, subsidies should be conditional on the abatement of its polluting effects and the eventual substitution of unsustainable practices by sustainable ones.

Maize is grown in a wide variety of regions under the most diverse social, cultural, economic and political conditions, and the redesign of subsidies should take into account the specificities of each production system. Undoubtedly, the main obstacles to the redesign of subsidies are the vested interests of the modern agricultural sector and its political clout. Overcoming them is not an easy task. For making any change possible in the right direction, all the will power of governments is needed in order not to remove subsidies altogether, but to give them a better use while still pursuing the compensatory policy for which they were created.

Matías Domínguez Laso/CONABIO

8. CONCLUSIONS

8. Conclusions

Maize has become one of the most important crops for humanity because of its multiple uses and capacity for adaptation to a wide range of environmental conditions. Early after domestication, maize disseminated all over the world because of its great adaptability. The basis of this adaptability is the genetic diversity of the species, as well as the traditional agronomic human practices that have molded it over the last 9000 years. Today, maize is grown from sea level to more than 3500 meters above sea level, and from the tropics of America, Africa and Asia to the temperate regions of Europe and North America. This wide adaptability to different environments is matched by the spectrum of uses to which humans have put the crop. At present, maize has hundreds of uses that can be divided into two main groups: those for direct human consumption and all other uses. In the former, it is consumed directly as a food and in the latter it is used as feed for the poultry and meat industries, manufactured as an ingredient for processed food and used as a raw material for the production of bioethanol. For historical reasons, these two types of uses are, in turn, related to the type of agricultural system in which the maize is produced. Although both systems cultivate the same species, their dependencies and externalities differ and therefore the public policies and interventions that are necessary to make them more sustainable also differ.

Maize produced for direct human consumption as food is grown in a diversity of agricultural systems, ranging from traditional diverse agroecosystems with abundant inter-specific and intra-specific variability, to relatively input-intensive and genetically homogeneous agricultural systems. Small maize systems are extensively distributed around the world, but are concentrated throughout Sub-Saharan Africa, Mexico, Central America, Brazil and India and scattered throughout southern and northern Asia. Maize that is not intended for direct human consumption is generally produced in intensive agricultural systems. These systems are typically large in size, completely mechanized and with a high requirement for energetic and agricultural inputs. The most intensive of these systems are predominantly located in Western Europe, and the northern regions of the American, European and Asian continents.

How and why intensive agriculture emerged during the last century was dictated, to a certain extent, by changes in agronomic science and public policies. The development of maize hybrids in the United States during the 1950s increased the productivity of maize per acre. This encouraged the enlargement of intensive farms and the migration of smallholder maize producers towards more intensive forms of maize production. This new type of farming was promoted and subsidized because of the promise of higher yields; however, this increase in yield relied not only on genetic improvements, but also on modifying the environment with a high use of inputs. High input agriculture thus began to be promoted and subsidized. At the same time, for biological reasons, the offspring of these hybrids lacked most of the desired traits of their parents, thus creating a system that was dependent on an external provision of seeds every growing cycle and giving rise to the current seed industry. Exporting this type of system to other parts of world during the Green Revolution then required further agrochemical inputs. The increase in yield that this system provided in such a short time would have been a flawless advance in human history, were it not for the important negative externalities produced by this form of agricultural production.

The geographical and environmental contexts of each system define, to some extent, a particular set of dependencies and limiting conditions: Intensive rainfed systems have flourished in regions with fertile soils, sufficient rainfall, relatively low evapotranspiration and even topography. High investment in technology and inputs is less risky and more cost effective under these environmental conditions. On the other hand, smallholders had to adapt to harsher conditions (*i.e.* soils with nutrient limitations, areas with higher or lower temperatures, higher altitudes, steeper slopes, etc.), and the use of a wider degree of agrobiodiversity, from species to genes, was the key to successful adaptation. For traditional systems, diversity represents both risk insurance (because growing different varieties provides a yield even if some fail) and the basis of local adaptation that permits agriculture under such conditions. As a consequence, the genetic diversity preserved in the more traditional agricultural plots is key for the continuous adaptation of maize to changing environments and threats, thus making the intensive maize production systems dependent on traditional systems. This diversity is not only expressed in the genetic and phenotypic diversity of the cultivated crops, but also in the multiple ecosystems services they provide and on which they depend.

Agricultural management practices can have both positive and negative impacts on ecosystem services. The traditional practices of smallholder farmers tend to preserve multiple ecosystem services. Prominent among these are the maintenance of maize genetic diversity (*i.e*. evolutionary services) and provision of cultural services. Maize landraces are cultivated not only in Mexico but also in other parts of the world, despite intense pressure from the public agricultural sector and agroindustry to produce commercial lines. The permanence of these varieties can be attributed to a cluster of intrinsic characteristics that render them desirable for farmers, such as their adaptation to non-optimal environments, better yields in the face of diverse types of stress, or particular organoleptic properties required for the preparation of traditional dishes, among others. The cultural services associated with the cultivation of native maize landraces have a shadow price that is at least nineteen times the value of a ton of maize in the international market.

Intensive systems produce a far greater quantity of maize, but do so at a high cost to the environment. The genetic homogeneity of commercial crops has a profound impact on regulation services, such as disease and pest control. The large inputs of agrochemicals to control weeds, pests and diseases have negative impacts on a diversity of terrestrial and aquatic species, some of which are crucial to the provision of ecosystem services upon which other crops depend. The most extensively recognized externality is the leaching of nitrogen into aquatic ecosystems, causing the eutrophication of water bodies and provoking a cascade of negative consequences. Here, we provide only a partial estimate of the cost of meeting a certain water quality standard.

We believe that transition towards more sustainable, but also highly productive, agriculture is possible. Organic systems do produce lower maize yields; however, organic systems retain more carbon and nitrogen in the soil, thus increasing the value of ecosystem services provided. We also found that, compared to conventional practices, adoption of Conservation Agriculture (CA) enhances ecosystem services and reduces negative externalities. In the case of irrigated systems, given its ability to store soil water, CA required two fewer irrigations over the course of the maize growing season.

Finally, there is a type of externality that has seldom been considered but one that should be urgently addressed: the effect of different production systems on genetic diversity. Hybrid maize cultivars grown in intensive production systems are composed of genetically similar or even identical individuals and thus form large areas of monoculture. The most visible externality is that such genetic uniformity makes the crops susceptible to the rapid spread of pests and diseases. However, there are also other less-common externalities related to each production system; modern breeding and high-input agriculture have unintentionally narrowed the opportunity for further development due to breeding from a limited original source material, genetic bottlenecks and loss of local adaptation. Fortunately, however, the on-farm cultivation of maize landraces facilitates the generation of new diversity and promotes local adaptation.

The breeding strategy associated with intensive systems was implemented in order to pursue higher yields by controlling the environment through the use of diverse inputs. Unfortunately, high-input agriculture has turned out to have diverse negative consequences for the environment, and the diversity, particularly that presented by marginal environments, turned out to be beyond the range of adaptation of even the most widely-adapted lines. While there has been incorporation of new variation, it has basically been as donor material for very specific traits and represents only a small proportion of the genome. The problem with the failure to breed new base material is that it implies the omission of a wide range of the potentially useful diversity that was discarded early or never used at all. The first consequence of this is that the diversity absent from the breeding panels could be responsible for traits that were not important at the time of selection, but that may now be important here or in other parts of the world. The second consequence is that this lack of initial variation is eventually translated into a lack of divergence for inbred parental lines, thus limiting the results of further breeding for yield increases or adaptation to new conditions, such as those imposed through climate change and new abiotic stress.

With respect to traditional agriculture systems, evolution continues and actively shapes genetic diversity due to the characteristics and cultural preferences that smallholders continue to use: saving their own seed, growing several varieties and tolerating the sympatric growth of teosinte subspecies. These management characteristics create diverse opportunities for gene flow, and promote adaptation by subjecting crops to *in situ* natural selection. In contrast to the intensive production systems that promote genetic uniformity, this process involves billions of genetically different individual plants that reproduce through open-pollination with neighboring plants. This acts to increase diversity through recombination but also facilitates the occurrence of new mutations and local adaptation. The former occurs because of local and regional differences regarding which ear types are desired and which individual plants will survive to produce seed. The geographic scale at which this process takes place is huge; in Mexico alone, native maize is grown under these conditions over approximately 4.6 million ha, covering a range of environments. In this way, the strength and importance of native maize is in its numbers. Large populations grown in several different environments for millennia are of irreplaceable evolutionary value because they constitute a rich genetic pool that is locally adapted to conditions where commercial maize cannot be grown. Since these conditions are subject to constant change, this pool cannot be fully preserved in seed banks (*ex situ* conservation), but rather needs to keep evolving in the same system (*in situ* conservation), i.e., in large differentiated populations and different environments. We should change our mentality in order to take advantage of this evolutionary process to aid all production systems.

We therefore suggest that public policies should recognize the different types of maize production systems. In order to tailor adequate agricultural public policies, it is vital that the particularities, functions and necessities of each system are taken into account. In order to more clearly identify these particularities, there is a need to produce scientific research and generate specific data regarding maize production systems. This will allow a broader knowledge regarding the genetic, ecological, agronomic and social elements that interact in complex ways within these systems. Particular attention should be given to supporting the valuation and conservation of on-farm maize genetic diversity, and of crop genetic resources in general. A decisive globally-driven effort is required to: 1) strengthen *in situ* (*i.e*., on-farm) conservation efforts in order to complement *ex situ* conservation in the public domain and 2) move back to local adaptation of native landraces, and use these as base material for local breeding. This implies a re-evaluation of family and traditional small-scale agriculture. The focus on large-scale systems should be to assist their transition towards sustainable agriculture. Subsidies should be reconsidered in order to correct the historical tendency of promoting negative externalities. We believe that the best way to use subsidies is to make them contingent on the compliance with a set of rules and standards that lead to better practices, such as more efficient use of irrigated water and agrochemicals. At the same time, subsidies should abandon the currently prevailing goal of introducing commercial maize varieties into small-scale systems that manage landraces, and should in fact be used to encourage the ecological and social processes that can guarantee the reproduction of native landraces.

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