Exploration of agro-ecological options for improving maize-based farming systems in Costa Chica, Guerrero, Mexico

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To my dear wife Lupita
and my handsome son Diego André
To the memory of my parents

Abstract

In the Costa Chica, a region of Southwest Mexico, farming systems are organized in smallholder units. The dominant cropping systems are based on maize (*Zea mays* L.), either as monocrop or intercropped with roselle (*Hibiscus sabdariffa* L.). Continuous cropping, and unbalanced fertilizer management systems with an inadequate replenishment of organic matter stocks have caused depletion of soil fertility and low crop yields. This thesis aimed to evaluate alternative cropping systems in terms of their contribution to on-farm productivity and to regeneration of the soil resource base. A set of approaches including farm surveys, on-farm experiments and model-based calculations was applied to characterize farming systems, identify main livelihood constraints and evaluate alternative cropping and farming systems. Main constraints identified were low yields of the major crops maize and roselle, low levels of nitrogen, potassium and soil organic matter, low resource use efficiencies, high production costs, limited marketing opportunities and low prices of products. To address prevailing production constraints, farmer-managed experiments were established in two communities within the region. In on-farm experiments the legumes Canavalia (*Canavalia brasiliensis* Mart. Ex Benth) and Mucuna (*Mucuna pruriens* L.var. utilis (Wall ex Wight) Burk) were intercropped in (added to) maize monocrops and maize-roselle mixtures. Intercropping did not decrease maize and roselle yields, and resulted in major reductions of the weed biomass, as well as an increased N uptake by both the food crops and the cropping system as a whole. In nutrient management trials different sources of macro-nutrients were evaluated in maize monocrops and maize-roselle intercrops. The results showed that improvements at field scale are feasible in the short term. Partial replacement of mineral NPK by organic NPK in the form of vermicompost, leading to 10-20% lower total N and K inputs, did not result in lower maize yields or a reduced uptake of N and K. This suggests that the N and K from the vermicompost were utilized better by the maize crop than from the inorganic fertilizers due to lower leaching losses. An experiment on decomposition of and N release from aboveground biomass residues, crop root residues and vermicompost demonstrated that, although the pattern of decomposition varied depending on the type of organic material, most of the N was released within the cropping season. Particularly for vermicompost, only one third of its initial dry mass was decomposed, thus leaving significant amounts of residues for soil organic matter build-up. Model-based explorations were developed to assess the consequences of the experimental results at the field level for whole-farm performance. Results for eight case study farms demonstrated that changes in crop nutrition and animal husbandry can increase farm family income and improve organic matter balances. However, strategies to achieve these goals most effectively were distinct. To maximize family income required fertilizer-based cropping strategies, while rebuilding soil organic matter required investment in retaining, obtaining and applying sources of organic matter. Farms responded differently to the explored options, highlighting the need for crop nutrition strategies that are adjusted to the soil fertility status of individual fields to be most efficient. The explorations also showed that for six out of the eight farms the minimum family income standard could not be attained. The results imply that the current emphasis in policies to support smallholders by fertilizer subsidies requires adjustment to include promotion of technology development aimed at regeneration of the degraded resource base and to offer off-farm economic options.

Keywords: farm diagnosis, farming systems, soil degradation, intercropping, maize, roselle, legumes, nutrient management, vermicompost, crop residues, decomposition, explorations.

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Chapter 1

General introduction

1. Smallholders systems

In developing countries, the majority of farmers are smallholders. Worldwide there are about 500 million farms with less than 2 ha of land (Wiggins et al., 2010), operating under heterogeneous and marginal conditions (Anthony and Ferroni, 2012). These systems are managed by farm families, who use mostly their own labour (Berdegué and Fuentealba, 2011). Of these farms, 87% is located in Asia (Nagayets, 2005); Latin America is reported to have nearly 16 million small farms. In Latin America smallholders produce 51% of maize, 77% of beans and 61% of potatoes needed in the region, totaling around 41% of domestic consumption (Altieri et al., 2012). There are around 40 million small livestock producers, most of whom depend on maize to a large extent (Thornton et al., 2002).The contribution of livestock production accounts for 40% of consumption in the region (McDermott et al., 1999).

Increasing rural populations and input prices, and decreasing product prices have prompted smallholders to intensify production by increasing cropping frequency up to continuous cultivation, increasing stocking rates and removing forest for agricultural production. This has resulted in land degradation (soil erosion, nutrient depletion, chemical pollution), which may threaten long-term crop productivity, food security and rural welfare (Andersson et al., 2011; Gomiero et al., 2011). At the same time, Hyman et al. (2008) conclude that agricultural research and development have had little impact on farming systems of marginal environments worldwide.

In Mexico, farms up to 3 ha account for 71% of all farms (Figure 1) and represent around 5 million ha. These smallholders are mainly maize producers.

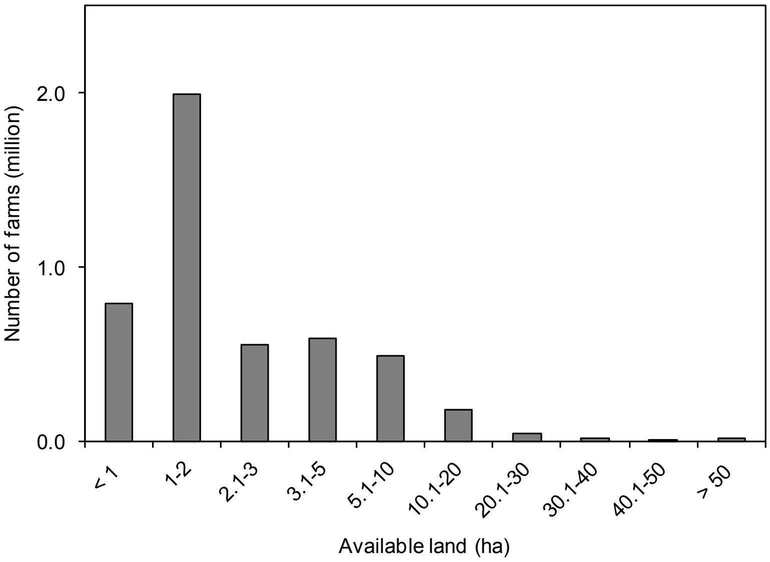

Figure 1. Distribution of farm sizes in Mexico. Source: Rascón et al. (2006).

Mexico is the centre of origin of maize, which has a strong social and cultural significance in the Mexican society (Boege, 2008; Mann, 2011). The consumption of maize in the country is around 30 million ton, of which 22 million ton is produced domestically (SIAP, 2011). In 2010, maize was cultivated on 51% of the agricultural land (SIACON, 2012), mostly under rain-fed conditions (FAO, 2012). Maize systems in Mexico are diverse with large differences between small-scale and large-scale farmers in terms of their access to land, credit and inputs. Smallholder maize production comprises 42% of maize area, resulting in 22% of the national maize production (Gómez, 2010).

Most smallholder maize producers are found in the central and southern states of Mexico: Chiapas, Guerrero, Hidalgo, Oaxaca and Veracruz; states with a high degree of marginalization[1] (Figure 2) (Gómez, 2010). In the state of Guerrero around 1.04 million of people (79%) are smallholders (Bartra et al., 2009). In the Costa Chica region of Guerrero the peasant economy is based on maize, which is cultivated on 81% of the agricultural area.

Figure 2. Levels of marginalization in Mexico. Source: CONAPO, 2011.

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[1] Consejo Nacional de Población (CONAPO, *Mexican Population Council*) uses four structural dimensions (education, housing, income from labor and population distribution) and nine variables (percentage of illiterate population over 15 years of age, percentage of population without complete elementary school over 15 years of age, percentage of houses without sewage or bathroom, percentage of dwellers in houses without drinking water, percentage of dwellers without electricity, percentage of houses with overcrowding, percentage of occupants in houses with soil floor, percentage of population in areas of <5000 inhabitants, and percentage of employed population with an income of less than two minimum wages) to develop marginalization indices using principal component methods. Five levels of marginalization are defined: very low, low, medium, high, and very high (CONAPO, 2011) (for details see Marginalization Index Annex C (in Spanish at http://www.conapo.gob.mx/publicaciones/margina2005/AnexoC.pdf).

2. Rural policies and research aimed at Mexican smallholders

2.1. National rural policies

In response to the macro-economic crisis in the 80's, Mexico began a series of reforms of domestic policies aimed at stabilizing the economy and stimulating sustainable growth by means of structural changes and market liberalization (Nadal, 2000). Driven by neo-liberal viewpoints, the reforms were focused on the reduction of government intervention in the economy in general and in the agricultural sector in particular. Implemented in the 90´s, structural reforms included reduction of public investment, the removal of subsidies, and the abolition of price guarantees for staple crops through the state-owned enterprise *Compañia Nacional de Subsistencias Populare*s (CONASUPO, National Company for Social Subsistence) which had been established in 1965. The government abolished other state-owned enterprises linked to agricultural inputs such as *Industria Mexicana de Fertilizantes* (FERTIMEX, Mexican Fertilizer Industry) and *Programa Nacional de Semillas* (PRONASE, National Seed Program). Extension and technology transfer were assigned to the private sector (Appendini, 2001). After first reducing credit subsidies of BANRURAL (*Banco Nacional de Crédito Rural*, National Rural Credit Bank) the institution was abolished in 2003 due to economic problems (Groenewald and Van Den Berg, 2012). These changes strongly decreased small farmers' access to services and inputs, increased production costs and decreased profitability.

The reforms became part of the restructuring needed to implement the North American Free Trade Agreement (NAFTA) in 1994 (King, 2006). This trade agreement stimulated a profound transformation of Mexican agriculture, reorienting it to highly competitive systems. However, only market-oriented fruit and vegetable growers with access to credits, inputs and technology were able to adjust to the rules and incentives of NAFTA (Polanco and Flores, 2008). Smallholders were the category most affected due to lack of natural resources, and low access to technology, inputs and markets. In particular they were exposed to competition from the subsidized and technologically advanced US maize farmers. The price of maize received by Mexican farmers declined by 25% between 1996 and 2005, but the cultivated area did not decrease (Figure 3). Still, Mexican production has been insufficient to meet domestic consumption, and maize imports from USA have increased (FAO, 2012). Strategies that smallholder implemented to face these economic difficulties included engaging in off-farm activities to diversify their income sources (contract work, migration, remittances, etc.) (Yúnez and Taylor, 2006).

To alleviate the impacts of NAFTA and reduce poverty the Mexican government implemented the cash-transfer program *Programa de Apoyos Directos al*

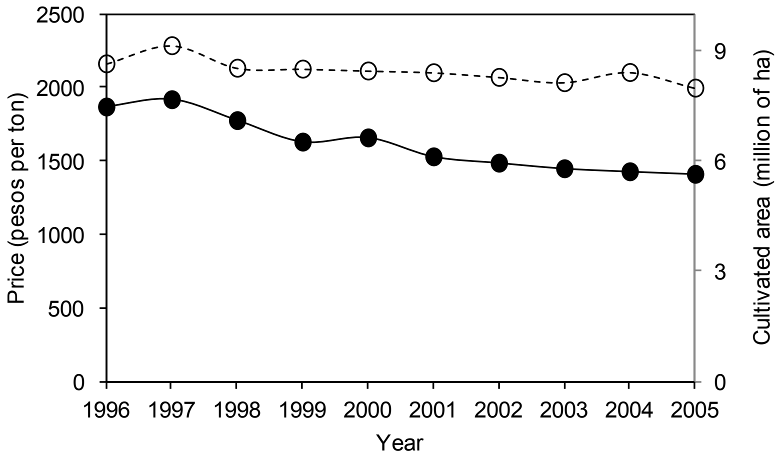

Figure 3. Cultivated maize area (---) and average producers prices (—) in Mexico from 1996 to 2005. Source: SIAP (2007).

Campo (PROCAMPO, Program of Direct Support to the Countryside), which is currently still in place (SAGARPA-ASERCA, 2012). PROCAMPO is designed to provide cash to small farmers to compensate them for potential losses during the process of transition to a free market. However, this program did not target crop productivity increases or smallholder competitiveness, which are the main goals of the agricultural policy in Mexico (Sierra, 2010). The other established program to alleviate poverty is *Oportunidades* which provides cash to poor households, and focuses on maternal nutrition and education (Winters and Davis, 2009; Hellin et al., 2012). Recently, the Federal Government announced the implementation of *Modernización Sustentable de la Agricultura Tradicional* (MASAGRO, the Sustainable Modernization of Traditional Agriculture). The program is aimed at increasing maize production of smallholders in rainfed areas through improving agronomic practices and the use of improved maize varieties (González-Rojas et al., 2011).

2.2. Rural policies in the state of Guerrero, Mexico

In the state of Guerrero, southwest Mexico, in addition to the federal programs PROCAMPO and *Oportunidades*) several state programs were implemented to improve agricultural productivity and reduce poverty. In 1994, the Government of the State implemented the *Programa de Apoyo a la Producción Primaria* (Program of Support to Primary Production). The program's objectives were: a) to improve the standards of living of farmers and their families; b) to provide fertilizers in the State; and c) to increase maize grain yield and the volume of production (Díaz, 2008; Ríos et al., 2009). The main policy instrument was the provision of mineral fertilizers to farmers at subsidized prices. The program was designed to support farmers with poor soils and low productivity; only farmers with maize yields up to 2 t ha^{-1} were eligible. At its start in 1994, the program's target population was 148,000 farmers who cultivated 222,000 ha of maize. The amount subsidized was based on 90-00-00 kg ha^{-1} N-P-K for a maximum of two ha. The federal and state Governments contributed 75% of the cost of fertilizer; the remainder needed to be borne by participating farmers. The program only distributed ammonium sulfate and this fertilizer was widely used by farmers. The program recommended application of the fertilizer as a single dose despite agronomic data on the agro-ecological heterogeneity of the State. In 2002, the fertilizer rates and types eligible for subsidy were adjusted. The fertilizer di-ammonium phosphate was included, and the subsidized rate changed to 69-30-00 kg ha^{-1} N-P-K, still for a maximum of 2 ha.

In 2005, the Ministry of Rural Development initiated a policy pilot called *Programa Piloto de Fertilizantes Orgánicos* (Pilot Program of Organic Fertilizers), which was supported by 18 farmer organizations in 36 municipalities. The program distributed compost among 1,958 farmers producing on 2,400 ha at a rate of 1 t ha^{-1}. The compost came from the state of Tamaulipas (Northeast, Mexico) with an average N-P-K content of 7-0.9-1.5 kg ton^{-1} and a total OM content of 62%. The results were not satisfactory because the compost was used as the only source of nutrients resulting in low maize grain yields. Consequently the program was terminated after one year.

Also in 2005, the *Programa de Apoyo a la Producción Primaria* was reoriented and was called *Programa de Subsidio al Fertilizante* (Fertilizer Subsidy Program). The aims of the program were: a) to improve the provision of fertilizers (deliver fertilizers to farmers on time, i.e. before sowing); b) to provide mineral fertilizers according to soils characteristics; and c) to provide benefit to all 81 municipalities of the state. The new program promoted different rates and types of fertilizer depending on soil pH, and the use of bio-fertilizers. Fertilizer packages were based on recommendations of the *Instituto Nacional de Investigaciones Forestales y Agropecuarias* (INIFAP, the National Institute for Forestry, Agricultural, and Animal Husbandry Research). Two packages were defined. For acid soils, the recommended fertilizers were phospho-nitrate and di-ammonium phosphate at a rate of 59-12-00 kg ha^{-1} N-P-K. For alkaline soils the recommended fertilizers were ammonium sulfate and di-ammonium phosphate at a rate of 60-10-00 kg ha^{-1} N-P-K. It remains unclear why K was not included. Both packages, still for a maximum of two ha, included the bio-fertilizers *Azospirillum brasilense* (350 g) and Mycorrhizae *Glomus intraradices* (1 kg) (Secretaría de Desarrollo Rural de Guerrero, 2007). The reorganized program also included technical support to farmers.

Along with the two new packages, some municipalities continued promoting ammonium sulfate and di-ammonium phosphate at a rate of 69-30-00 kg ha^{-1} N-P-K.

Thus farmers could choose among three packages. Three years after the beginning of the program, most farmers had adopted the fertilizer recommendation of the Ministry of Rural Development (CEE-Guerrero et al., 2010).

Originally, the program was aimed at small farmers. Currently it has state-wide coverage, including both small farmers (86%) and commercial farmers (14%). The program has given subsidies to around 300,000 farmers covering an area in excess of 471,000 ha (Ríos et al., 2009).

2.3. Agricultural research for maize-based systems in the state of Guerrero.

The Mexican policy of research and technology transfer is focused on the dissemination of technological packages (e.g. hybrids, mineral fertilizers, pesticides, tillage) developed in experimental stations. Agricultural research in Mexico has been mainly carried out by INIFAP, although other government agencies and universities are involved in agricultural research (Gert and Beintema, 2009). INIFAP as the main national research institution has had little interaction with farmers (Ekboir et al., 2009). For the entire state of Guerrero, INIFAP has one experimental station (Iguala), which is located in the north of the state where edapho-climatic conditions are highly different from those in the other regions of the state.

In the state of Guerrero the area of maize is around 470,000 ha, but despite this considerable extent there is no research and technology development master plan for maize. There are few institutions devoted to research, and there is lack of funds and planning for technological innovations. Consequently the state is characterized by low technological development. Farmers' demands, which are not considered in setting the research agenda include: breeding of maize land races, optimum plant density, development of fertilizer recommendations based on soil properties, combined use of mineral and organic fertilizers, maize for forage, determination of potassium requirements (SAGARPA-Secretaría de Desarrollo Rural - Fundación Produce de Guerrero A.C., 2008).

INIFAP classified maize regions within the state on the basis of their productive potential as low (2.5 t ha^{-1}), medium (4.5 t ha^{-1}) and high (5 t ha^{-1}). For each level INIFAP proposed a specific technological package. The packages include recommendations on mineral fertilizers, bio-fertilizers, improved varieties and hybrids, herbicides, insecticides, and crop management. The latter comprises sowing density recommendations ranging from 47,000-55,000 plants ha^{-1} depending on type of sowing (hand or mechanized) and maize genotype, (INIFAP - SAGARPA, 2007). The fertilizer rate (60-10-00 kg ha^{-1} N-P-K) recommended in the Fertilizer Subsidies Program corresponds to the low production potential conditions. For regions with medium and high potential the INIFAP fertilization recommendation is 90-26-00 kg ha^{-1} N-P-K. As 82% of the maize area in Guerrero was classified as having medium productive potential, fertilizer rates recommended in the Fertilizer Subsidies Program are below the INIFAP recommendations (INIFAP - SAGARPA, 2007; Gómez et al., 2007). The Ministry of Rural Development did take up the INIFAP recommendation to distinguish soil pH in the fertilizer packages.

Application of K is absent in the current nutrient recommendations although depletion of soil K in the regions Costa Grande and Costa Chica has been acknowledged in farmer leaflets (Gómez et al., 2007). Just before the restructuring of the fertilizer subsidies in 2002, INIFAP published the booklet "New alternative technology to produce maize-roselle in areas of Guerrero" where a fertilizer package of 135-40-83 was recommended (Navarro et al., 2002). The Fundación Produce de Guerrero A.C. (2004) published the experience of technology transfer for the production of maize QPM (quality protein maize), under conservation tillage with small farmers in the regions Costa Chica, Central, Montaña, and Alto Balsas. Their technology package considers N, P and K in a combination of 68-30-25 kg ha^{-1}. Experiences with this package showed average grain yield of 3.6 t ha^{-1}, even exceeding the planned target of 2.5 t ha^{-1}. However, there are no publications that show that these innovations have been adopted by farmers.

3. The Costa Chica case study region

3.1. Overview

The Costa Chica is an economic and cultural region along Mexico's Pacific coast in the state of Guerrero. It is bordered on the North by the regions La Montaña and Center, on the South by the Pacific Ocean, on the East by the state of Oaxaca, and on the West by the region Acapulco. The Costa Chica has an area of 8,699 km^2, divided over 15 municipalities. The study described in this thesis was carried out in the municipality of Tecoanapa (16°48'N, 99°09'W) which is located in the foothills of the South Sierra Madre and the Pacific Coastal Plain (Figure 4). Tecoanapa consists of 56 communities and covers an area of 777 km^2, which represents 14.8% of the Costa Chica. The main climate type in the region is A (w2) tropical, semi-wet, with two marked seasons: the rainy season from June to October, and the dry season from November to May. Average annual rainfall varies between 1200 and 1700 mm depending on altitude. Average annual temperature is 25^{o}C. The relief is characterized by irregular topography (Presidencia Municipal de Tecoanapa, Gro. and Instituto de Investigación Científica Area Ciencias Naturales - UAG, 2001).

Tecoanapa covers an altitudinal range between 200 and 1,000 meters above sea level. The topography includes wide mountainous areas and some plains dispersed

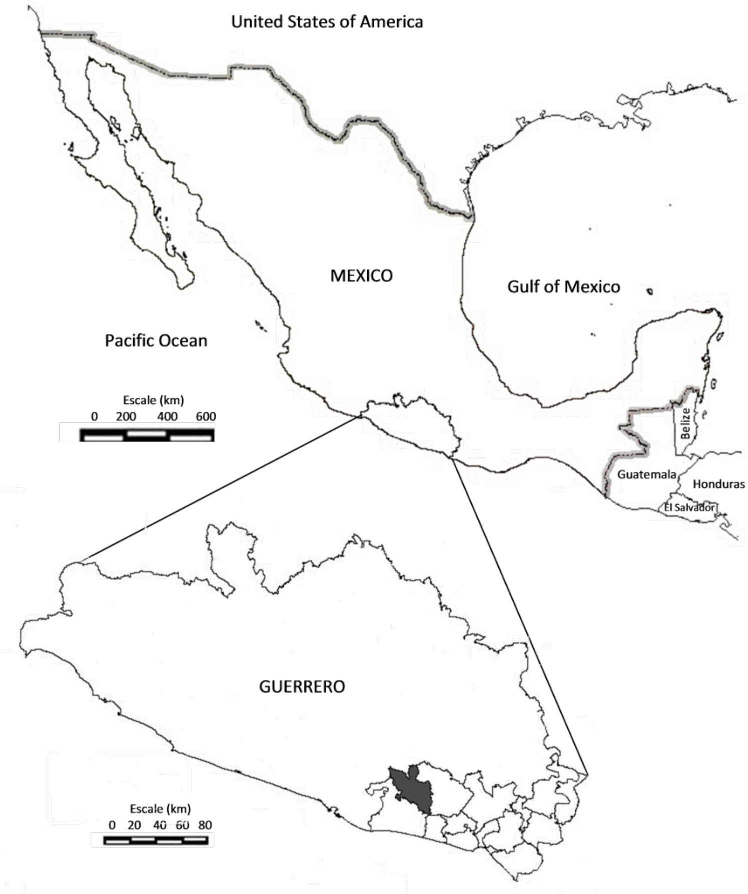

Figure 4. Map showing the state of Guerrero in Mexico, with the 15 municipalities of the Costa Chica in the south-east. In gray the municipality Tecoanapa.

between mountains and hill slopes. Soils are of volcanic origin. There are different soil types and soil associations. The most common soil is Regosol and besides there are associations of Feozem-regosol, Regosol-Litosol, Cambisol-regosol and Regosol-cambisol. In general, the soils have a sandy texture, low soil organic matter content and are relatively acid (Presidencia Municipal de Tecoanapa, Gro. and Instituto de Investigación Científica Area Ciencias Naturales - UAG, 2001).

The population in the Costa Chica is around 428,500 inhabitants, 50% of which live in the municipalities Ayutla, Ometepec, Tecoanapa, and San Marcos (Secretaría de Desarrollo Social, 2007). The region is classified as having a high and very high degree of marginalization (Consejo Nacional de Población, 2011). Migration out of the region increased during the last decade as a result of rural unemployment and poverty (Quiroz, 2009). Emigrants from the state of Guerrero account for 2.4%, and the state for 4.7% of Mexican migrants to the U.S.A (INEGI, 2009b). The state receives around 5.6% of all remittances from the U.S.A to Mexico (Banco de Mexico, 2012), benefitting about 5% of households in the state, which represent around 50% of total income (Esquivel and Huerta-Pineda, 2007).

Agricultural production, the major economic activity is dominantly organized in smallholdings, available land per farm in the region ranging between 1.3 and 4.6 ha (INEGI, 2009a). Around 61% of the population is engaged in primary agriculture; in Tecoanapa this is more than 66% of the population. In 2006 the number of farmers was around 39,000, 12% of whom lived in Tecoanapa. Agricultural land comprises 128,500 ha, with rainfed production on 90% of the area. In Tecoanapa about 13,300 ha are used for crop production (Secretaría de Desarrollo Social, 2007).

3.2. Farming systems

Farming activities depend on rain, resulting in a single growing season. The cropping pattern in the Costa Chica is dominated by maize (*Zea mays,* L.), roselle (*Hibiscus sabdariffa*, L.), bean (*Phaseolus* spp.), squash (*Cucurbita pepo* L.), sesame (*Sesamum indicum* L.), watermelon (*Citrullus lanatus* (Thunb)), green pepper (*Capsicum annuum* L.*)* and grasses (*Panicum* sp., *Cynodon* sp., *Andropogon* sp.). Maize is cultivated under rainfed conditions on 81% of the land, and is the main staple crop. Of the production 59% is estimated to be for self-consumption, 27% is marketed, and 14% is used as animal feed (Ríos, 2009). Average maize grain yields ranges between 1000 and 2000 kg ha^{-1} (Gómez, 2007). Roselle is an important cash crop in the region; it is grown on around 11,600 ha, or 8% of the agricultural area, often intercropped with maize. The municipalities of Ayutla and Tecoanapa account for about 30% of the roselle cultivated area of the Costa Chica. Squash is increasingly being cultivated as monocrop and is becoming an important source of income.

Livestock is an important activity in the Costa Chica, characterized by extensive grazing systems. The largest number of heads is concentrated in the municipalities Cuajinicuilapa and San Marcos on the coast and Ayutla. In Tecoanapa, livestock production, mainly cows and goats, only comprises 979 ha and is of less importance than cropping (Secretaría de Desarrollo Social, 2007). Livestock production faces problems such as the poor facilities and equipment, low genetic quality of the herds, low levels of production and insufficient availability of credit (Secretaría de Desarrollo Social, 2007).

The traditional cropping system in smallholder farms is called *milpa*, which includes maize as main crop intercropped with common bean (*Phaseolus vulgaris* L.), and squash (*Cucurbita pepo* L.), and edible weeds are tolerated. In the *milpa* diversification is a key factor to meet family needs and to regulate biological processes associated with pest control and maintenance of soil fertility (Brush et al., 2003; Zizumbo-Villareal and Colunga-García Marín, 2010). In the *milpa* fallowing was a key means to control weeds and manage soil fertility. This practice has been gradually abandoned and it is now common to find continuous cropping of maize and roselle without rotation. Development of weed populations is directly related to land-use intensification, i.e. the abandonment of a fallow phase and weeding practices. To control weeds, herbicides (mainly paraquat) are widely used. Subsidized mineral fertilizers have become the main source of nutrient inputs. The topography of the area forces farmers to crop on slopes up to 40%, mostly without significant cultural practices to control soil erosion. Although crop residues are left on the field after harvesting, during the dry season (December to May) the bulk of residues is removed by roaming animals and by burning (*rastrojear*), which some farmers use to facilitate sowing. The lack of cover makes the soil prone to erosion at the start of the rainy season.

3.3. Research challenges

Improvement of the livelihoods of resource-poor farmers in marginal environments requires increasing yields by improving the resource base, preserving soil fertility, and optimizing nutrient use efficiency, an approach denoted as ecological intensification (Cassman, 1999; Hyman et al., 2008; Gomiero et al., 2011; Fonte et al., 2012). Research and public policies in the Costa Chica have aimed at increasing productivity, particularly through fertilizer packages, but have largely ignored resource base conservation. The scientific basis for the policies and extension guidelines is weak as empirical data on farming and cropping systems in the region are lacking. Research is needed that addresses productivity increases at the short and middle term, and that is appropriate in the context of the diverse smallholder livelihoods. This requires a systems approach to ensure that recommendations fit not only the biophysical reality of farmers, but also fall within the cash flow and labour constraints that are typical for smallholders.

4. Objectives

The overall objective of this thesis is to contribute to resilient livelihoods of smallholders in maize-based farming systems in the Costa Chica, Mexico by improving crop yields and resource use efficiency at field and farm level. A secondary objective is to provide knowledge for science-based policy development on crop nutrient provisioning. There are four specific research objectives:

1) To diagnose biophysical and management aspects of current farming systems in representative communities of the Coast Chica*;*

2) To identify the main constraints in crop productivity and their causes at farm and field level;

3) To evaluate alternative maize cropping systems which include use of intercrops and cover crops as well as alternative crop nutrition strategies;
4) To explore the potential of these alternative maize cropping systems for improving farm level performance.

5. Methodological approach

To contribute to resilient livelihoods of maize-based systems through an ecological intensification approach requires knowledge of agroecological processes, environmental conditions, and socio-cultural relationships and their interactions (Pretty, 2008). In this thesis participatory rural appraisals and production ecological analysis are used to describe, quantify and analyse components and processes in farming systems, and identify, design and explore alternative land use systems at field and farm level. The integration of these approaches has been an effective means to study and develop scenarios in smallholder farming systems (Ojiem et al., 2006; Tittonell et al., 2008), and to assess impact of crop-livestock interventions (Thornton et al., 2003).

As a first step, social-economic and production ecological surveys were applied, complemented with model-based calculations, to diagnose the extent and causes of the perceived low productivity of maize-based smallholder systems in the Costa Chica. In five communities farming systems analysis, rapid rural appraisals and participatory rural appraisals (Chambers, 1994; Ye et al., 2002; Röling et al., 2004) were carried out to identify constraints to farm productivity. The information obtained gave elements to set up the detailed system characterization in two representative communities. This way of working helped to build relations with the farm community and identify ideas for system improvement. At farm scale, participatory tools allowed obtaining information of qualitative nature, and could provide a general understanding of characteristics and main constraints of farming systems. At field scale, quantitative systems analysis and modelling to elucidate causes of observed or perceived inefficiencies or lack of productivity complemented the qualitative approaches.

The second step was design and implementation of on-farm experiments. On-farm experiments are the only form of experimentation that is possible in the region due to lack of formal research institutions. The lack of researcher control is offset by the expectation that results are more realistic in terms of scale, management practice and constraints identified by farmers (Drinkwater, 2002). In the experiments, key causes of soil fertility constraints identified in previous phase were addressed. Guiding ideas for experiments came from Vereijken (1997) who advocated multifunctional cropping systems and integrated nutrient management as important agronomic practices to enhance farm performance. In the region, positive experiences were reported with well-chosen leguminous intercrops and external inputs of manure, compost (Ortiz-Ceballos and Fragoso, 2004; Lawson et al., 2007). These provided a starting point for on-farm experimentation.

The final step in the methodology concerned the integration of the field-level results at the whole farm level and to explore the potential of different farming strategies. The integration was supported by models that quantitatively describe system components and the flows among them (Groot et al., 2012). Modelling allowed quantifying the contribution of animals within the farm, and evaluating farm-level impacts of alternative crop management on identified constraints, farm production, technical feasibility, and profitability.

6. Outline

The research questions are addressed in five Chapters and a General Discussion. In Chapter 2 an analysis is made of the biophysical and socio-economic context at the regional, the farm and the field level (Step 1, Figure 5). The extent and causes of low productivity of maize-based systems in communities of the Costa Chica are diagnosed for both the management systems and the production systems. Chapters 3 to 5 zoom in at the field level in selected communities (Step 2, Figure 5). In Chapter 3 on-farm experiments are presented to investigate consequences of intercropping maize and maize-roselle mixtures with the legumes canavalia and mucuna on maize and roselle yields, nutrient uptake and weed suppression. In Chapter 4 fertilizer strategies with inorganic and organic components are evaluated in maize and maize-roselle cropping systems. The evaluation addresses yields, nutrient uptake and physiological nutrient use efficiency. A greater input of organic matter requires information on its fate in cropping systems. In Chapter 5 rates of degradation of different sources of organic matter are assessed using litterbags. In Chapter 6 findings at the field level are combined with data of individual farms in a regional context to explore options for improvement at the farm level (Step 3, Figure 5). The explorations address specific farms to demonstrate how their resource availability affects opportunities for sustaining livelihoods. The General Discussion (Chapter 7) discusses the contribution of this study to the scientific knowledge basis and the implications for sustainable development of maize-based farming systems in Guerrero.

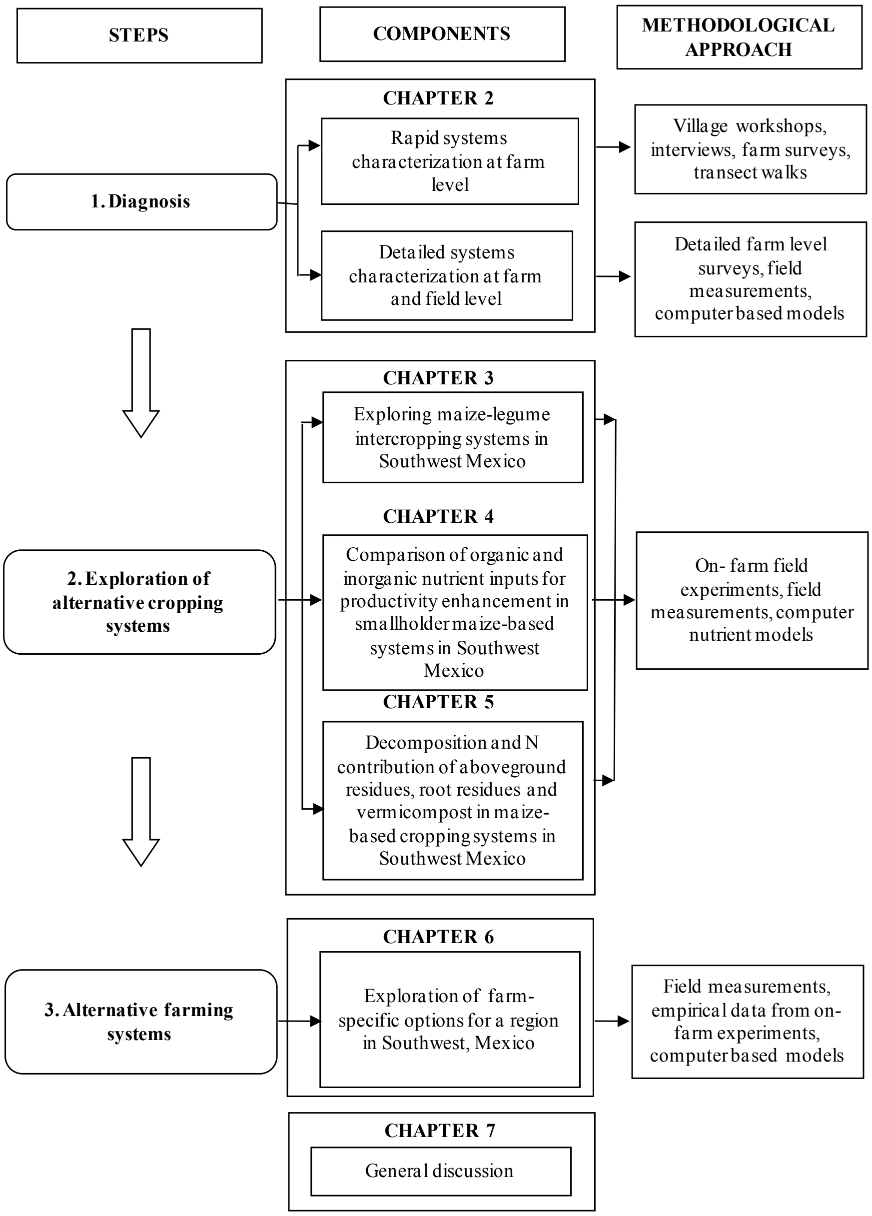

Figure 5. Framework applied in this thesis to diagnose current and explore alternative maize-based farming systems in the Costa Chica, Mexico.

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Chapter 2

Diagnosis for ecological intensification of maize-based smallholder farming systems in the Costa Chica, Mexico

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DOI 10.1007/s10705-011-9455-z and extended with data of 3 other communities to
enhance representativeness)

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Abstract

Enhanced utilization of agro ecological knowledge and insight to improve food and feed production starts from location-specific knowledge of production constraints. A diagnostic systems approach which combined socio-economic and production ecological methods at farm and field level was developed and applied to diagnose the extent and causes of the perceived low productivity of maize-based smallholder farming systems in five communities of the Costa Chica in Southwest Mexico. Socio-economic and production ecological surveys were applied and complemented with model-based calculations. The results demonstrated that current nutrient management of crops has resulted in nutrition imbalances, resulting in K- and N-limited production conditions that are reflected in low yields of the major crops maize and roselle, and low resource use efficiencies. Production on moderate to steep slopes was estimated to result in considerable losses of soil and organic matter. Poor crop production, lack of specific animal fodder production systems and strong dependence on animal grazing within communal areas limited recycling of nutrients through manure. In combination with low prices for the roselle cash crop, farmers are caught in a vicious cycle of cash shortage and resource decline. The production ecological findings complemented farmers opinions by providing more insight in background and extent of livelihood constraints. Changing fertilizer subsidies and rethinking animal fodder production as well as the use of communal lands requires targeting both formal and informal governance structures. The methodology has broader applicability in smallholder systems in view of its low demand on capital intensive resources.

Keywords: diagnosis, farming systems, nutrient use efficiency, nutrient balance, plant nutrition, erosion, maize.

1. Introduction

The majority of farmers in Central America are smallholders who produce on small plots of land, often in marginal environments (Altieri, 2002). These regions with high agroecological variability tend to be complex and diverse. Farming systems are centered around maize that has a key role both culturally and nutritionally. Depending on the level of production, farmers produce for local markets or focus on self-sufficiency. Rural development policies have generally emphasized external inputs as a means to maintain and increase food production. Worldwide the global use of pesticides, inorganic fertilizer, animal feedstuffs, and machinery has strongly increased since the 1960s. The rural development policies did not everywhere lead to sustainable systems and some systems have become more vulnerable to degradation (Pretty, 1997; IAASTD, 2009). It has become clear that in order to conserve or restore the natural resource base, rebalancing of inputs and ecosystem processes is needed. In addition to concerns about resource management, smallholders are faced with socio-economic developments, such as loss of economic viability of small to medium scale agriculture due to factors external to the farm enterprise (e.g. vertical integration of production and processing, lack of market specialization for some commodities and costs of production inputs), food quality, and the steady exodus from rural to urban areas (Safley, 1998).

The Costa Chica region in Mexico is among the poorest in the country, severely lagging behind in education, housing quality and employment, as indicated by a high marginalization index value (Consejo Nacional de Población, 2011). Tecoanapa is one of the 15 municipalities that comprise the region. In Tecoanapa farming on moderate to steep slopes is the major source of livelihood with over 66% of the population involved in primary agriculture. Maize (*Zea mays* L.) is the major staple crop, often grown for subsistence. Roselle (*Hibiscus sabdariffa* L.) is grown as a cash crop, often intercropped with maize. Nitrogen (N) and phosphorus (P) fertilizers are subsidized as part of government subsidy packages. Fallowing as a means to restore soil fertility has been gradually abandoned. Population increases cause pressure on land and contribute to intensification of crop production. Widespread use of herbicides, largely without technical advice, has replaced manual weeding and soil tillage. Despite these external inputs, farmers stated that maize yields are low and are perceived not to increase.

Ecological intensification is an approach aimed at exploring alternative farming systems by means of integrating ecological processes in crop and soil management (Cassman et al., 1999; CIRAD, 2010). In this approach intelligent management of ecological processes aims to complement or even partly reduce the needs for purchased inputs through enhancing the uptake and use efficiency (Malézieux et al., 2009). The first step towards such re-design is diagnostic and aims at identifying constraints and possible alternatives in close cooperation with farmers. The diagnosis process and its results (i) provide a richer understanding of farmer realities by the researcher, (ii) build trust relations between the researcher and farming community, and (iii) stimulate co-construction of changes in systems management (Pretty, 1995). A range of methods has been proposed to understand farmer realities, such as rapid rural appraisals, participatory rural appraisals, agroecosystem analysis (e.g. Röling et al., 2004). Tittonell et al. (2008) distinguished on-farm and computer-based methods for analysis of farming systems. The on-farm methods start from a rapid description of the farming systems in terms of agroecological and socio-economic components, followed by more detailed sub-systems analysis. Models are used to analyze the subsystems from an agroecological perspective and to explore options for change.

In this paper we diagnose the extent and causes of the perceived low productivity of maize-based smallholder systems in five representative communities of the Costa Chica municipality of Tecoanapa, which is representative for the Costa Chica region. A set of on-farm methods, and social-economic and production ecological surveys were applied and complemented with model-based calculations. The methods were used to: a) acquire insight in the diversity of natural resource conditions and the associated management by farm households; b) identify main production constraints and their causes at field and farm levels.

2. Materials and methods

2.1. General description of the study areas

The municipality of Tecoanapa (16°48’ N, 7°11’ W) is located in Costa Chica, a hilly region on Mexico’s Pacific coast in the state of Guerrero. Tecoanapa comprises 15% of the area of the Costa Chica, 10% of the total population and 12% of the farm population, and 16% of the cultivated maize area (Secretaría de Desarrollo Social de Guerrero, 2007; OEIDRUS, 2011). The municipality has an area of 777 km^2 and consists of 38 communities situated between 200 and 1000 m above sea level (masl). Population was 44,079 in 2010 (INEGI, 2011). Similar to the rest of the Costa Chica, average annual rainfall in the area is approximately 1,300 mm concentrated between June and October. Maximum and minimum temperatures vary with altitude. In the highest areas (900 masl) the temperature range is 12 to 27^{o}C; in the middle area (300-900 masl) 15 to 30^{o}C; and in the low areas (less than 300 masl) 18 to 33^{o}C. (Presidencia Municipal de Tecoanapa, Gro., and Instituto de Investigación Científica Área Ciencias Naturales-UAG, 2001). Most of the area is covered by forest (63%). Agricultural land use is confined to 14,272 ha, approximately 35% of the total area.

Soils in the region are of volcanic origin and predominantly classified as Regosols. Cropping is synchronized with rainfall and limited to one cropping cycle a year as most farmers do not have access to irrigation water and thus do not crop in the dry season.

2.2. System diagnosis

The diagnosis comprised two phases; a rapid system characterization, which was followed by a more detailed system characterization. Figure 1 summarizes the two phases and their respective components and methods applied. The rapid system characterization was carried out in 2003 and focused on obtaining information from farmers, their household situation and their management systems in five communities of the municipality: Cruz Quemada, Las Animas, Saucitos, Tecoanapa and Xalpatlahuac. These communities comprised around 22% of the cultivated area and 25% of the farm population of the municipality (Secretaría de Desarrollo Social de Guerrero, 2007). Methods used over the course of one year included workshops during which also training on technical skills was provided, farm visits and transect walks with the farmers and surveys. The information obtained in the first phase gave elements to set up the detailed system characterization in two representative communities. The second phase was carried out in 2005 and aimed to provide insight in agronomic variables at the field level both by measurements and by calculations using models.

2.3. Rapid system characterization

Several tools from Participatory Rural Appraisal and the agroecosystems approach (Chambers, 1994; Ye et al., 2002) such as workshops, seasonal calendars, interviews, transect walks were applied to identify and understand systems, their functioning and perceived problems. Information was organized into two aspects: 1) description of farming systems and their perceived constraints; 2) description of crop production systems and their management. Farmers participating in workshops were asked to: 1) identify and rank the major problems they perceived in their farming and cropping systems; 2) describe causes of the stated problems; 3) propose possible solutions to the problems and the actions needed to solve them. Accompanied by local authorities and farmers, three transect walks were carried out in each community to understand farmer perceptions of variation in the landscape, the types of soils and the cropping systems with their specific problems in the communities.

Following the workshops in the five communities, farmers were invited to participate in a survey to characterize their farming systems. In total 39 farmers participated. The survey included an inventory of resources and production systems, and was accompanied by soil and crop sampling in one field per farm. Within each field five areas (5 x 0.9 m^2) were selected to estimate maize grain yield. The cobs were harvested and oven dried at 70°C for 24 hours. Grains were weighed, adjusting maize grain moisture to 15.5%. In each field 20 soil samples (0-30 cm) per hectare were taken and combined to one composite sample which was used for analysis. The soil properties analyzed were soil organic matter (SOM; wet oxidation Walkley-Black), total N (Kjeldahl-N), P (Olsen-P), and K (exchangeable by ammonium acetate at pH 7.0).

In 2005, two of the five communities were selected for further characterization, based on contacts with the Tecoanapa community leadership and farmers, and based on willingness to collaborate and think about innovations in soil fertility management. The two communities, Las Animas (173 households) and Xalpatlahuac (373 households), are located in the central part of the municipality. In both communities the municipality had established small-scale vermicomposting facilities as part of re-thinking soil management. Las Animas was the community with the higher soil P-values in the sample, and Xalpatlahuac had a similar soil fertility as the other communities (see results section 3.1). Las Animas was generally seen as experiencing more resource degradation than Xalpatlahuac. Also, social structures in the two villages differed, with more social control and cooperation related to natural resource

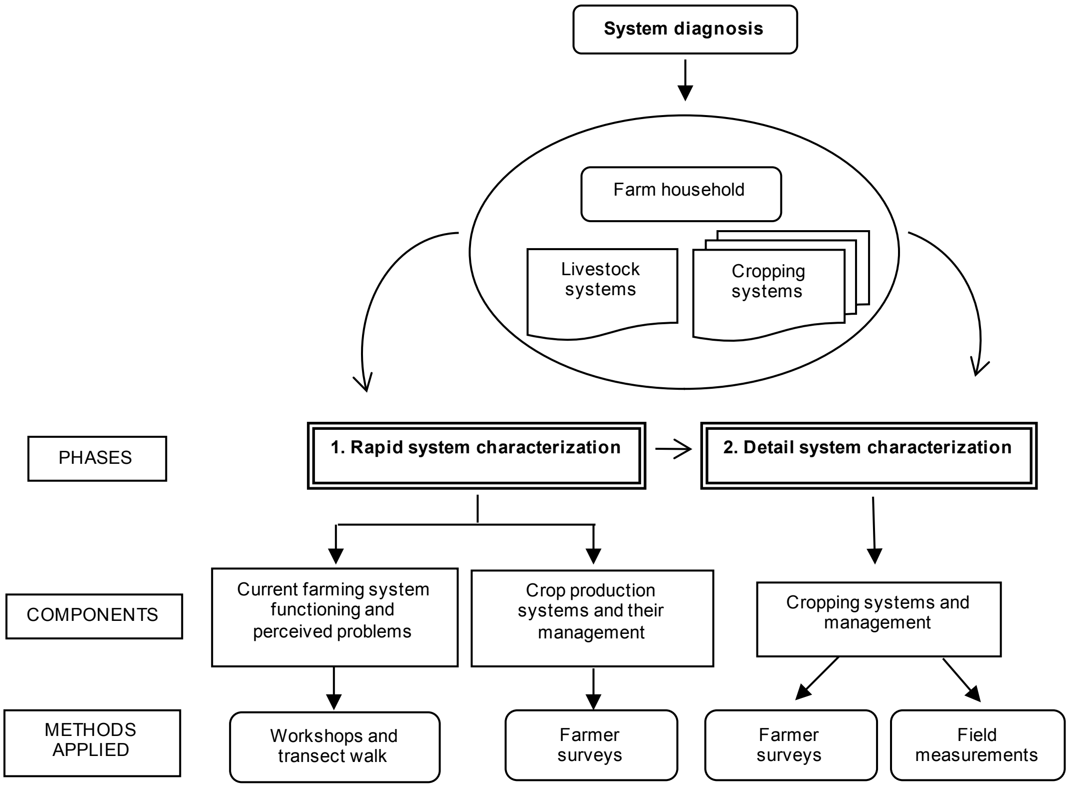

Figure 1. Methodological framework.

use and management being in place in Xalpatlahuac, where for instance forest protection was organized, than in Las Animas. Both communities were organized in villages. Most of the arable fields could only be reached on foot or horseback, and were dispersed in the surrounding forested area. In total 30 farmers were invited to participate in a structured survey to characterize farming systems in the growing season of 2005, 14 farmers in Las Animas and 16 in Xalpatlahuac. Criteria to select farmers were their well-connectedness in the community and an interest in thinking about systems redesign. The farm level survey included questions related to: a) wealth and endowment; b) production systems and management; c) perceptions of land use; d) opportunities for developing local innovations, ranked on a scale ranging from low (0) to moderate (1) and high (2). Results from surveys were organized in three domains: environmental, agronomic, and socio-economic and presented in a radar graph.

2.4. Detailed system characterization

A total of 8 farmers out of the 30 (4 from each community), previously interviewed, were invited to participate in a detailed system characterization. The farmers were selected to represent local variation in terms of availability of land, cropping and animal systems, cultural practices and socio-economic farming strategies. In a structured survey qualitative and quantitative information was sought on: a) cropping systems: crop sequences grown and associated cultural practices, seasonal calendars/labour calendars, pest and diseases, inputs; b) livestock: type of animals, size of herd, feeding during dry and wet seasons, animal health, inputs, manure management; c) farm economics: commercialization and subsidies.

Each field of the 8 farmers was sampled once before maize harvest in November 2005 to characterize soil fertility and crop productivity. This resulted in 22 sampled fields. During transect walks slope, exposure and soil fertility level as described by the farmer were established. From each field top soil samples (0-20 cm) were taken with a shovel at 20 points per ha. The samples were mixed, and one composite sample per field was sent for analysis. The soil properties analyzed were texture (Bouyoucos hydrometer), pH (1:2 soil:water), soil organic matter (SOM; wet oxidation Walkley-Black), total N (Kjeldahl-N), P (Bray-1), Ca, Mg and K (exchangeable by ammonium acetate at pH 7.0).

In each field, crop and weed aboveground biomass were sampled at 5 random locations at crop physiological maturity. Maize grain yield, roselle calyx yield and crop residues were based on samples of 5 × 1 m^2 and expressed in kg ha^{-1} after oven drying at 70°C for 24 hours, adjusting maize grain moisture to 15.5% which value is used throughout this paper. From the 5 × 1 m^2 area a random sample of 0.40 × 0.50 m^2

was taken to visually estimate ground cover. Weeds were cut at ground level and oven-dried at 70°C for 24 hours to estimate aboveground biomass dry weight (kg ha^{-1}). Plant residues, products (maize grain and roselle calyxes) and weeds were sent to the laboratory to be analyzed for N, P and K content. Total N was analyzed using the semi-micro-Kjeldahl procedure (Bremner, 1965). P and K were analyzed by inductively coupled plasma spectrometry (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA) (Alcántar and Sandoval, 1999).

To define field distance from homestead three classes were distinguished based on time spent walking: near (10 to 20 minutes), mid (between 21 and 40 minutes) and far (more than 40 minutes).

2.5. Data analysis

Biomass – nutrient relations

The effect of nutrient supply on biomass and yield was analyzed in terms of the graphical analysis proposed by van Keulen (1982). Total nutrient uptake (N, P and K) was plotted against grain yield (adjusted to 15.5% moisture content) and aboveground biomass, respectively. The values of maximum accumulation and maximum dilution of N, P and K for grain and aboveground biomass (kg DM ha^{-1}) were estimated according to the values proposed by Nijhof (1987) and van Duivenbooden et al. (1996), using the average harvest index of 0.38 established in the current study. Nutrient uptake was plotted as a function of N and P application (K was never applied).

Nutrient uptake was related to potential soil supply of N, P and K calculated according to QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils; Janssen et al. 1990). In this static model, potential indigenous soil supplies of N (SN), P (SP) and K (SK) on the basis of chemical soil data were estimated according to:

$$SN = fN * 68 * N \quad (1)$$

$$SP = fP * 0.35 * C + 0.5 * P \quad (2)$$

$$SK = (fK * 400 * K) / (2 + 0.9 * C) \quad (3)$$

$$fN = 0.25 * (pH-3) \quad (4)$$

$$fP = 1 - 0.5 * (pH-6)^2 \quad (5)$$

$$fK = 0.625 * (3.4 - 0.4 * pH) \quad (6)$$

where C represents soil organic carbon (g kg^{-1}), assuming 58% C in soil organic matter, total nitrogen (%), N represents total N (g kg^{-1}), P represents plant available soil phosphorous measured as P-Bray-1 (mg kg^{-1}) (B.H. Janssen; personal communication), K represents exchangeable K (cmol kg^{-1}) and pH is pH (H_2O).

Maximum recovery fractions of applied N and P were 0.5 and 0.1, respectively as suggested by Janssen et al. (1990).

The QUEFTS model was used to predict maize grain yield both with and without fertilizer application. For this purpose, uptake rates of N, P and K were predicted based on the potential soil supply and fertilizer rates, and default recovery values of applied nutrients used by QUEFTS (Janssen et al., 1990): 0.5 for N and 0.1 for P. Yield ranges were estimated on basis of the predicted uptakes of N, P and K considering maximum accumulation (i.e. the nutrient is not yield-limiting) and maximum dilution (i.e. the nutrient is yield-limiting). In the last step, yield was predicted based on the interactions among the three yield ranges.

Soil erosion

To estimate the annual average soil erosion the Revised Universal Soil Loss Equation (RUSLE) was used, proposed by Renard et al. (1997):

$$A = R * K * LS * C * P \tag{7}$$

where A is the average annual soil loss per unit (t ha^{-1} yr^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); K is the soil erodibility factor (t ha h MJ^{-1} mm^{-1} ha^{-1}) which represents the soil loss rate per erosion index unit for a specific soil. The K factor integrates the effect of rainfall, runoff and soil characteristics such as texture, structure, organic matter content and soil permeability on soil loss; LS (-) is the combination of the slope length (L) and slope steepness (S) (unitless); C (-) is the cover and management factor which estimates the soil loss ratio (SLR). The factor C integrates the effects of crop characteristics, soil cover, and soil disturbing activities on erosion and corresponds to the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. P (-) is the support practice factor: the ratio of soil loss with a support practice such as contouring or terracing, and soil loss with straight-row farming up and down the slope. The model is empirical. Here we describe adaptations to the model variables R, LS, C and P based on use of local data sources. The variable K was used as described by Renard et al. (1997), using expert opinion to determine the soil structure code.

Rainfall erosivity factor (R)

In the original model, rainfall erosivity R was estimated using EI_{30}, the product of total storm energy (E) and the maximum 30 minute intensity (I_{30}). Since these data were not available for our study area, we estimated R from measured annual rainfall (mm). The estimation is based on work by Figueroa et al. (1991) who calculated R for 14 different regions using data on annual amounts of precipitation and intensity values from 53 climate stations distributed around the country. The equation for our study area was:

$$R= 8.8938x + 0.000442x^2 \tag{8}$$

where x represents measured annual rainfall (mm).

Slope length and steepness factors (LS)

The LS factor represents erodibility due to combinations of slope length (L) and steepness (S) relative to a standard unit plot. Slope length (L) was calculated using the original equation (Renard et al., 1997):

$$L = (\lambda/22.1)^m \tag{9}$$

where L is slope length factor normalized to the 22.1 m (unit plot length); λ is slope length; and m is a variable slope length exponent. According to Liu et al. (2000), $m = 0.5$ is appropriate for steep slopes, such as in the study area where the average slope was 27%. To estimate steepness (S) the equation proposed by Nearing (1997) for steep slopes was used. The equation takes the form of a logistic function. It is based on the RUSLE relationships for slopes up to 22%, and was found to also fit data for slopes greater than those from which the RUSLE relationships were derived:

$$S = -1.5 + 17/[1 + \exp(2.3 - 6.1 \sin \theta)] \tag{10}$$

where θ is the slope angle.

Cover management factor (C)

The cover management factor reflects the effect of cropping and management practices on erosion rates. Factor C is calculated using the following equation (Renard et al., 1997):

$$C = \Sigma i \ (SLR_i * EI_{30i}) \tag{11}$$

where SLR_i is the loss soil ratio during a time interval i of 15 days. The soil loss ratio describes the ratio of soil loss under actual conditions and losses experienced under reference conditions. EI_{30i} is the fraction of the yearly rainfall erosivity (R) occurring during the same period of time that SLR_i is calculated. Since only monthly rainfall data were available, EI_{30i} and SLR_i were estimated for monthly time intervals using data from Figueroa et al. (1991) for Mexican conditions and no-tillage cropping systems with 30% residue retention.

Support practice factor (P)

The support practice factor (P) is the ratio of soil loss with a specific support practice to the corresponding loss with upslope and down slope tillage. As in the study area no soil conservation practices are used to control erosion, P was assumed to have a value of 1.

Nutrient and OM balances at farm level

Plant nutrient (N, P, K) and organic matter (OM) balances at farm level were estimated based on quantitative estimates of the nutrient flows within the farm and across farm boundaries. Transfer within the farm occurred between animals and fields based on manure produced while the animals were fed on the yard. There were no direct flows between fields. The group of farms selected consisted of 1 to 4 fields per farm located at 10 to more than 40 min walking distance from the homestead. The Farm DESIGN model, a static balance model, was used to estimate flows of OM, N, P and K (Groot and Oomen, 2011; Groot et al., 2012) between four main components; crops, animals, soil and manure. The crop component comprised the farm's land use systems, i.e. maize and roselle as monocrop, and/or maize – roselle intercrop, as well as the land use system products, i.e. maize grain, maize residues, roselle calyx, roselle residues, and weeds. The products were characterized in terms of observed yield and N, P, K contents, ash contents on each field (Mitra and Shanker, 1957; Burgess et al., 2002; Colunga et al., 2005; Harrington et al., 2006). Total amounts were calculated by multiplying amounts per area by field area. Effective OM (EOM) was defined as the organic matter remaining from crop residues one year after application. Four indicators of feed value were taken into account and derived from the literature; feed saturation value, feed structure value, energy content (in VEM; Dutch net energy for lactation) and crude protein content (Mourits et al., 2000; CVB, 2008). Land use system products had one or several destinations: soil (crop residues and weeds left on the field), animals (crop residues and weeds fed to animals), home use (consumption by the farm family) and market. The animal component included cows and goats. Numbers of each animal type and average weight (450 kg per cow, 75 kg per goat) were specified. Feed balances and manure produced by animals were estimated for the part of the dry season that the animals were around the homestead. When local parameters were not available, standard values were taken based on expertise. Soil properties included in the model were bulk density, texture, pH (H_2O), soil organic matter content, and soil-N, -P and -K. Since only measurements of soil OM content were available for the 0-20 cm layer, we assumed that under the existing conditions of no-tillage, topsoil OM content was twice that of the subsoil (up to 40 cm). This resulted in a lower overall SOM content for no till systems (e.g. West and Post, 2002). In the manure component of the model, imported fertilizers with their nutrient contents and applied amounts were specified, along with the calculated amounts of manure produced by cattle around the homestead and losses in OM and N resulting from storage in loose heaps. Details are provided in Groot and Oomen (2011) and Groot et al. (2012). Here, we provide more details on the OM balance calculations in which adjustments to local conditions were made.

In the organic matter balance five different input and output processes were distinguished: net accumulation of root crop residues, aboveground crop residues and manure (residues and manure corrected for degradation during the year of production), soil OM decomposition, and erosion. The balance was calculated as the difference between input and output.

The net accumulation of root and aboveground crop residues was quantified as the amount of organic matter remaining one year after application (EOM) in the field (Groot and Oomen, 2011). Root biomass was estimated as 15% of total crop biomass (Rodriguez, 1993). The mono-component model of Yang and Janssen (2000) was used to predict EOM from the amount of roots per field and parameters calibrated on litterbag experiments in farmers' fields (Chapter 5).

Of the aboveground crop residues of maize and weeds, 30% was assumed to remain in the field where they were produced, the remainder being taken up by animals. In case of farm owned animals, the resulting manure was assumed to stay within the farm. If the farm did not own animals, roaming animals were assumed to export the organic matter from the farm system. Roselle residues were assumed to be not suitable for animal consumption and remained in the field. Similarly, no export was assumed from fenced fields.

Degradation of soil organic matter in field c, DOM_c, (Mg year^{-1}) was calculated as

$$DOM_c = A_c * d * BD * AOM_c * k * 10^{-4} \qquad (12)$$

where A_c is the area of field c (ha), d is soil depth (m), BD (Mg m^{-3}) is bulk density of the soil, AOM_c is the active OM in field c (%), and k is the annual rate of SOM decomposition (% year^{-1}) and 10^{-4} balances the units. AOM_c was estimated as the difference between the measured total SOM percentage and the minimum SOM percentage, estimated as function of soil texture according to the equation proposed by Rühlmann (1999) and assuming 58% C in SOM:

$$C_{min} = 0.017 * B - 0.001 * \exp(0.075*B) \qquad (13)$$

where C_{min} is the minimum content of organic C (%) and B is clay and silt content (%). Bulk density was assumed to be 1.3 Mg m^{-3}, depth of the soil were taken from field measurements and degradation rate k was estimated from data of Grace et al. (2002) for no-tillage conditions in long term trials at CIMMYT, central Mexico.

Erosion was considered a cause of organic matter and plant nutrient losses. Loss rates were calculated using RUSLE estimates of soil loss, multiplied by OM, N, P or K fractions as established in the field survey.

2.6. Statistical analysis

Soil properties and yields of 2003 and 2005 were subjected to analyses of variance to test for differences among communities. Variables were log transformed where needed to meet the assumptions of homoscedasticity. For the 2005 data, analyses of variance were used to test the effect of the distance from the homestead on soil properties and yields. Means separation was performed when the F-test indicated significant ($P<0.05$) differences among communities and among distances from homestead (Tukey's studentized range HSD test). The analyses were performed using SAS Version 9.1.

For the detailed system characterization a nested statistical analysis based on the residual maximum likelihood method was used to elucidate the effect of community, farmer and field on economic yield and total biomass observations. Residual maximum likelihood (REML) allows fitting models in which each observation is expressed additively in terms of fixed and random effects (Clarke, 1996). The method can cope with unbalanced designs, as is the case in this study where the number of fields per farmer and the number of farmers per community differ. The REML method was applied iteratively, first including community as fixed term and farmer and fields as random terms, then including the combination community-farmer as fixed and fields as random, and finally testing all three as (nested) fixed terms. The analysis was programmed in Genstat 5. The statistical significance of fixed terms as they were added to the model was evaluated by comparing the Wald test statistic with critical values of F-test ($P<0.05$).

3. Results

3.1. Rapid system characterization

The farming systems in the five communities were organized in small production units, land holdings ranging from 0.75 to 9 hectares and number of fields varying from 1 to 5 per farm (Figure 2). The cropping pattern was dominated by maize, which was generally cultivated for self consumption. Both cobs and grains were stored to satisfy the families' needs. Maize was mainly intercropped with roselle. Squash (*Cucurbita pepo* L.) and beans (*Phaseolus vulgaris* L.) were also intercropped with maize but at low plant densities. Maize and roselle were also grown as monocrops. The main cash crop was roselle. Squash traditionally was cultivated for self consumption, but was increasingly cultivated for seeds and has become an important source of income. Domestic prices for these crops were stagnant or declining as a result of decreased levels of domestic market protection in NAFTA.

The main objective of keeping animals was to build a cash resource. Donkeys, horses and mules were present on 26% of the farms (on average two per farm). They were used for transport of materials to and from the fields and in rare cases, used for traction. Pigs and poultry (chickens, turkeys) were kept for domestic consumption on 37% of the farms, on average 3 pigs per farm. Goats and cows were owned by 8% and 29% of the farms, respectively, with an average density for each type of 6 and 9 animals per farm, respectively. These animals were kept as capital and only sold in case of urgent need of cash. Calving patterns were irregular. Donkeys, goats and cows were fed through cut-and-carry foraging around the farmstead during the growing season and by roaming-grazing unfenced fields in the area which during the dry season are considered communal lands.

Farming activities represented the main source of income for 38% of the farms;

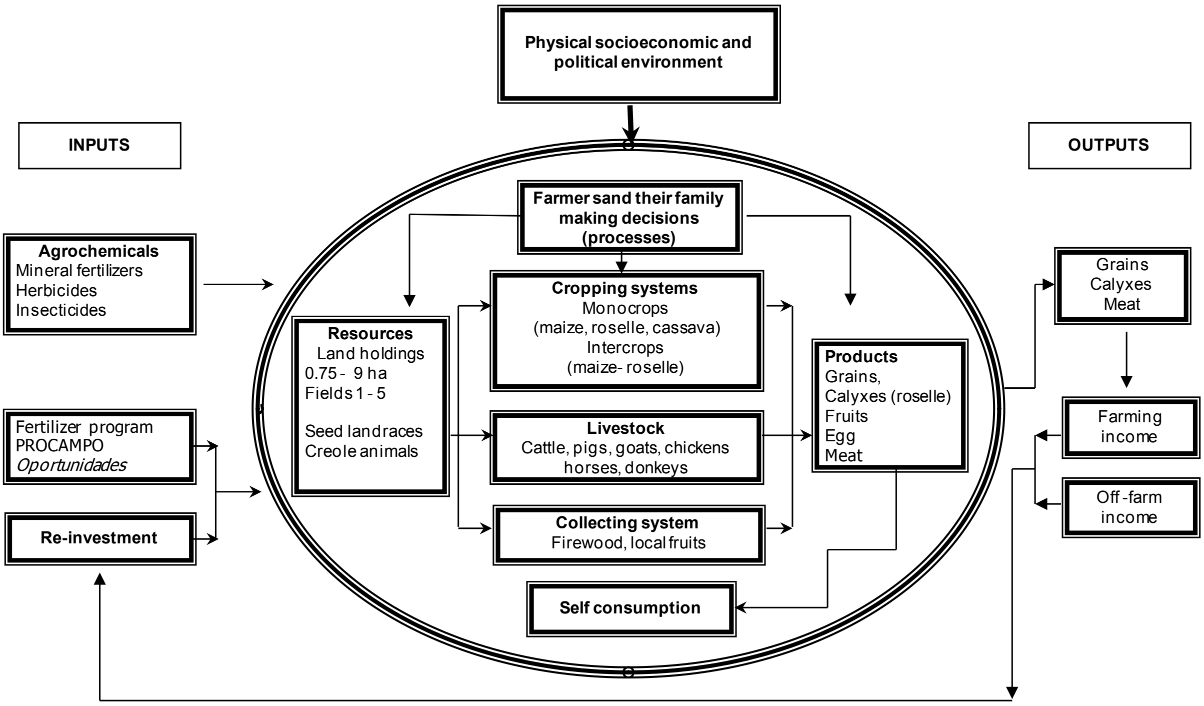

Figure 2. Components of farming systems in the Costa Chica, Mexico.

the other farmers had important off-farm activities. These activities comprised commerce, masonry and farm labor, and were carried out mainly in the dry season. Also some members of the family worked in other Mexican cities and abroad. The households received federal support from the programs PROCAMPO (Program for Assistance in Agriculture) and *Oportunidades* (a program to alleviate poverty), and received subsidies for fertilizers from the state of Guerrero.

Maize-roselle was the main cropping system (Table 1) which was practiced by 54% of the farmers, maize as monocrop was cultivated on 38% of the farms, 5% grew roselle as monocrop, and around 3% cultivated grasses. The rates of fertilizers were very variable among the farmers. Most of them applied N and P, while only 5 out of 39 farmers applied NPK.

Grain yields ranged from 1122 to 3588 kg ha^{-1}, the average grain yield being 2260 kg ha^{-1}. An ANOVA test indicated that grain yields did not differ significantly among communities.

Soil organic matter (OM) content in the selected fields ranged from 7 to 31 g kg^{-1}. Most fields had values of less than 15 g kg^{-1}. Total N (Nt) ranged from 0.35 to 1.55 g kg^{-1}. Values of P ranged between 1 and 37 mg kg^{-1}. K values ranged between 0.1 and 0.5 cmol kg^{-1}. Differences among communities were not significant for OM, Nt and K. P values in Las Animas were significantly ($P=0.05$) higher than those in Tecoanapa, Saucitos and Xalpatlahuac, but not different from those in Cruz Quemada. There was no clear relationship between P inputs and soil P contents (Table 1)

Based on these results, the communities Las Animas, representing relatively high soil P contents, and Xalpatlahuac representing average soil chemical properties were selected for detailed systems characterization. Farmers in these communities were highly interested in exploring innovations aimed at improving soil fertility.

Farmers in the five communities faced diverse environmental, technical and socio-economic constraints; however, six main problems were indicated by farmers (Table 2). Low soil fertility was the major concern of the farmers, which they attributed to abandonment of fallowing and continuous maize cultivation. The main means to maintain soil fertility and crop nutrition were mineral fertilizers which were widely used, promoted by municipal government subsidies. Farmers paid 25% of the cost of a package containing 4 bags (of 50 kg) ammonium sulfate (21-00-00 N-P-K) and 3 bags di-ammonium phosphate (18-46-00 N-P-K), equivalent to 69 kg N and 30 kg P, meant for 2 ha. As most farmers owned more than 2 ha, farmers rationed amounts or bought extra fertilizer. Applications were made on the soil surface around the planting hole at sowing and around the plant base before tasseling. Organic matter, if applied, originated from manure of own animals and from crop residues.

Soil erosion was attributed to cropping on steep slopes, the lack of contouring and terracing, and the lack of soil cover during dry season due to overgrazing.

Low yields, mentioned as another key problem were attributed to reliance on chemical fertilizers as the only source of plant nutrients, which according to the farmers made

Table 1. Cropping systems, nutrient applied, grain yield and chemical soil properties of 5 communities in the Tecoanapa municipality, Guerrero, Mexico in 2003.

Community	Farmer	Cropping system*	Nutrient applied (kg ha^{-1})			Maize grain yield (kg ha^{-1})	Soil properties			
			N	P	K		OM (g kg^{-1})	Nt (g kg^{-1})	P Olsen (mg kg^{-1})	K (cmol kg^{-1})
Xalpatlahuac	Xa1	MR	70	31	58	1969	31	1.55	9	0.5
	Xa2	MR	53	30	0	2132	24	1.20	4	0.4
	Xa3	MR	68	30	0	2463	16	0.80	5	0.3
	Xa4	M	41	20	0	1768	22	1.10	3	0.3
	Xa5	M	89	30	0	2460	13	0.65	2	0.3
	Xa6	MR	198	61	0	1752	11	0.55	3	0.3
	Xa7	MR	98	40	0	1570	7	0.35	10	0.2
	Xa8	R	-	-	-		15	0.75	1	0.3
Las Animas	LA1	MR	123	0	0	1399	12	0.60	37	0.3
	LA2	MR	82	0	0	2635	13	0.65	3	0.2
	LA3	M	77	0	0	1721	9	0.45	13	0.2
	LA4	MR	72	0	0	1941	9	0.45	16	0.2
	LA5	M	103	81	0	2743	17	0.85	13	0.2
	LA6	M	103	0	0	1250	8	0.40	19	0.2
	LA7	MR	164	0	0	2424	16	0.80	22	0.2
	LA8	M	18	2	4	1647	16	0.80	6	0.2
Saucitos	Sa1	MR	59	20	0	1122	14	0.70	2	0.1
	Sa2	MR	40	10	0	2459	14	0.70	1	0.3
	Sa3	M	99	30	75	3588	8	0.40	18	0.2
	Sa4	MR	59	20	0	2625	8	0.40	6	0.3
	Sa5	M	71	10	25	1363	12	0.60	2	0.4
	Sa6	MR	107	51	0	2454	7	0.35	2	0.2
	Sa7	MR	68	30	0	2799	9	0.45	1	0.5
	Sa8	MR	68	30	0	2419	9	0.45	1	0.2
Tecoanapa	Te1	MR	89	30	100	3477	10	0.50	1	0.4
	Te2	M	68	30	0	2465	8	0.40	5	0.2
	Te3	M	77	40	0	3115	14	0.70	1	0.2
	Te4	M	77	40	0	2935	12	0.60	3	0.3
	Te5	M	96	51	0	1718	9	0.45	9	0.1
	Te6	M	99	30	0	2255	12	0.60	2	0.1
	Te7	M	133	0	0	3427	7	0.35	1	0.1
Cruz Quemada	CQ1	MR	51	0	0	1453	20	1.00	21	0.2
	CQ2	MR	72	0	0	1606	8	0.40	3	0.3
	CQ3	MR	184	91	0	2034	13	0.65	6	0.1
	CQ4	M-R	59	20	0	2424	10	0.50	5	0.4
	CQ5	M	41	0	0	2523	35	1.75	7	0.3
	CQ6	MR	72	0	0	3235	13	0.65	13	0.4
	CQ7	G	-	-	-		9	0.45	6	0.1
	CQ8	R	-	-	-		15	0.75	1	0.3

* *MR:* intercrop maize – roselle, *M:* maize monocrop, *R:* roselle monocrop, *G:* grasses

soils tired and ‘scrawny’.

The incidence of pest and diseases was an important issue, mainly in roselle due to the incidence of leaf-cutting ant (*Atta mexicana* Smith) and roselle´s crown rot (*Phytophthora parasitica* Dastur). Perceived problems were attributed to the continuous cultivation and the lack of technical training to control the pests.

Paraquat was the most common herbicide used by over 80% of the farmers. Herbicide use varied from 1 to 9 L ha^{-1}, while recommended rates were 2 L ha^{-1}. Few farmers used hand weeding to complement herbicide applications. High production costs was also an important issue indicated by the farmers. Fertilizers and herbicides constituted around 20% of the production costs. Limited and monopolized commercialization channels put pressure on revenues and gross margins.

Other concerns indicated by farmers were the food insecurity, the high reliance on inputs, and the need to improve the quality of the roselle product to meet market standards. High incidences of weeds, loss of biodiversity, low water retention capacity of the soil, and the strong migration of youths to the USA were mentioned as problems. In addition to causes, farmers suggested alternatives as described in Table 2, a number of which they were eager to pursue.

Figure 3 summarizes the qualitative indicators established in the analysis in Las

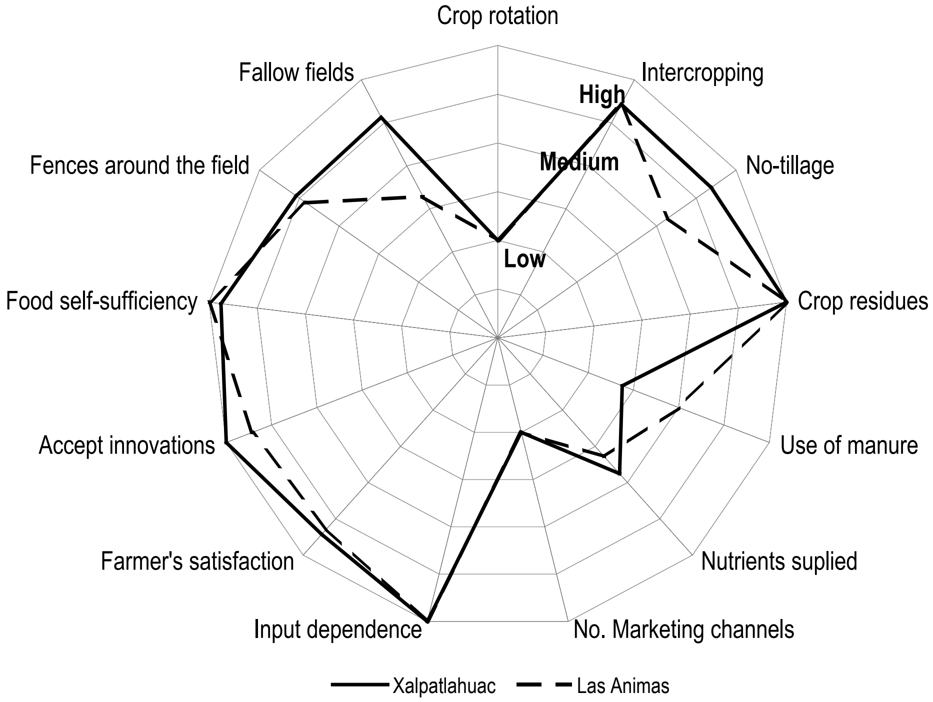

Figure 3. Comparison of the environmental, agronomic, and socio-economic performance of farming systems in the communities of Xalpatlahuac and Las Animas in Costa Chica, Mexico as part of rapid system characterization in 2005.

Animas and Xalpatlahuac in 2005 and shows that differences between the two communities are small. Compared to Las Animas, farmers in Xalpathlahuac had more fields in fallow, practiced more no-till and used less manure. Some indicators can explain the problems indicated by farmers. Low soil fertility and yields, and productions costs could be linked to the absence of crop rotation, low use of manure, unbalanced nutrient supply (mainly N and P), and high input dependence.

Table 2. Main problems of farming systems, their causes and solutions mentioned in a survey of 5 communities in the municipality of Tecoanapa, Costa Chica, Mexico, in 2003.

Component	Perceived problem	Suggested causes	Suggested alternatives
Environmental	Low soil fertility	Chemical fertilizers are the main source of plant nutrients, leading to 'superficial' soils. Manure is hardly applied. Continuous cultivation has replaced fallow periods.	Use alternative sources of nutrients such as manure and compost.
	Soil erosion	Cultivation in steep slopes without terracing. Lack of soil cover due to overgrazing	Terracing, fencing and increase crop residue retention.
Agronomic	Low yields	The soils are "tired", chemical fertilizers are the main source of plant nutrients, and most of the farmers use nitrogen and phosphorus fertilizers.	Improve soil fertility by means of soil management that includes both chemical and organic fertilizers. Promote training programs and experimental trials.
	Incidence of pest and diseases	Lack of training and measures to control pest and diseases	Promote training programs
Socio-economics	High production costs	Inputs are expensive, and they have to be purchased in the market. Labor is expensive due to migration.	Training programs about efficient use of input and dissemination of low input technologies.
	Few commercialization channels and low prices of products	Lack of plans and infrastructure for marketing. Local monopolistic intermediaries.	Promote farmer organizations and along with municipality to search alternative ways for marketing.

3.2. Detailed system characterization

Soil properties

The texture of the majority of the fields was sandy loam (Table 3). Values for soil nutrient levels were low and pH indicated acidity. Soil organic matter and total soil N were significantly higher in Xalpatlahuac than in Las Animas ($P<0.05$). Of the 22 fields, 7 were near, 5 were at mid distance and 10 were far from the homestead.

Differences in soil chemical parameters and SOM were not significantly related to distance from the homestead.

In Xalpatlahuac soil K contents in 2003 were higher than those in 2005 ($P<0.001$). However, in both cases K values were low (SEMARNAT, 2002).

Table 3. Area and physic-chemical properties of farmers fields in the detailed system characterization.

Farmer[a]	Area (ha)	Slope	Sand	Silt	Clay	Soil texture	Soil depth	pH-H_2O	OM	Nt	Bray P-1	K
		%					Cm		g kg^{-1}		mg kg^{-1}	cmol kg^{-1}
A1a	3.0	25	57	28	16	SL	40	5.3	11	0.57	11	0.24
A2a	1.0	31	54	35	12	SL	50	5.7	11	0.53	21	0.21
A2b	1.3	46	47	32	21	L	50	5.3	7	0.36	15	0.21
A2c	1.3	19	62	18	20	SL	62	6.0	27	1.37	3	0.28
A2d	0.5	31	58	24	18	SL	50	5.4	16	0.82	2	0.17
A3a	1.0	20	49	29	22	L	55	5.5	17	0.83	12	0.19
A3b	1.0	20	49	37	14	L	55	5.7	6	0.29	11	0.10
A3c	0.3	20	42	42	16	L	55	6.1	10	0.52	15	0.16
A3d	1.0	55	56	28	16	SL	60	5.5	9	0.43	10	0.09
A4a	0.8	36	46	38	16	L	60	5.5	11	0.54	12	0.15
A4b	0.8	36	50	34	16	L	60	5.4	6	0.30	7	0.10
A4c	1.1	30	54	30	16	SL	40	5.3	22	1.11	27	0.16
A4d	1.5	41	60	28	13	SL	60	5.3	12	0.59	14	0.14
X1a	1.5	21	38	34	28	SL	50	5.0	19	0.95	7	0.13
X1b	0.5	21	45	34	21	SL	49	4.8	21	1.04	12	0.21
X1c	0.5	26	60	19	22	SCL	60	5.3	25	1.26	11	0.26
X2a	1.0	25	51	25	24	SCL	50	5.1	20	1.01	4	0.19
X3a	1.0	19	60	28	12	SL	57	5.1	10	0.52	22	0.14
X3b	0.8	19	66	24	10	SL	57	5.0	20	0.98	39	0.13
X3c	1.3	6	68	20	12	SL	50	4.9	10	0.50	29	0.13
X4a	0.3	5	59	27	14	SL	65	5.2	20	1.02	5	0.13
X4b	1.0	43	60	26	14	SL	54	5.7	22	1.08	6	0.17

SL sandy loam, *L* loam, *SCL* sandy clay loam

[a] The first letter corresponds to the community A: Las Animas, X: Xalpatlahuac, the number corresponds to the farmers and the minuscule letter to the fields

Nutrient supply and crop uptake

Large ranges in N and P fertilization rates were observed and farmers generally over-applied N and under-applied P when compared to recommendations (Figure 4). No statistically significant relation was found between N application rates and N uptake in the combined biomass of maize, roselle and weeds (Figure 3A), whereas for P only a very small response of uptake to application (0.17 kg/kg; $P<0.05$) was observed (Figure 3B).

Relationships between potential nutrient supply from soil and fertilizers and nutrient uptake rates by total plant aerial biomass (of maize, roselle and weeds jointly) are presented in Figures 5A to 5C, and by the maize component only in Figures 5D to 5F. The potential nutrient supply was calculated from soil supply (SN, SP and SK) and fertilizer application rates were corrected for the maximum recovery proposed in QUEFTS. There was no clear relation between potential nutrient supply and uptake. N and K uptake was lower than the calculated potential supply, but uptake of P exceeded calculated potential supply. The underestimation of P supply may be due to underestimation of residual P release in the following years after application (van Reuler and Janssen, 1996). K supply presented less variation than the N and P supply. Most of the values were concentrated between 40 and 60 kg K ha^{-1}. External sources of K as chemical fertilizer were not applied by the farmers, because it was not considered in the municipal subsidies.

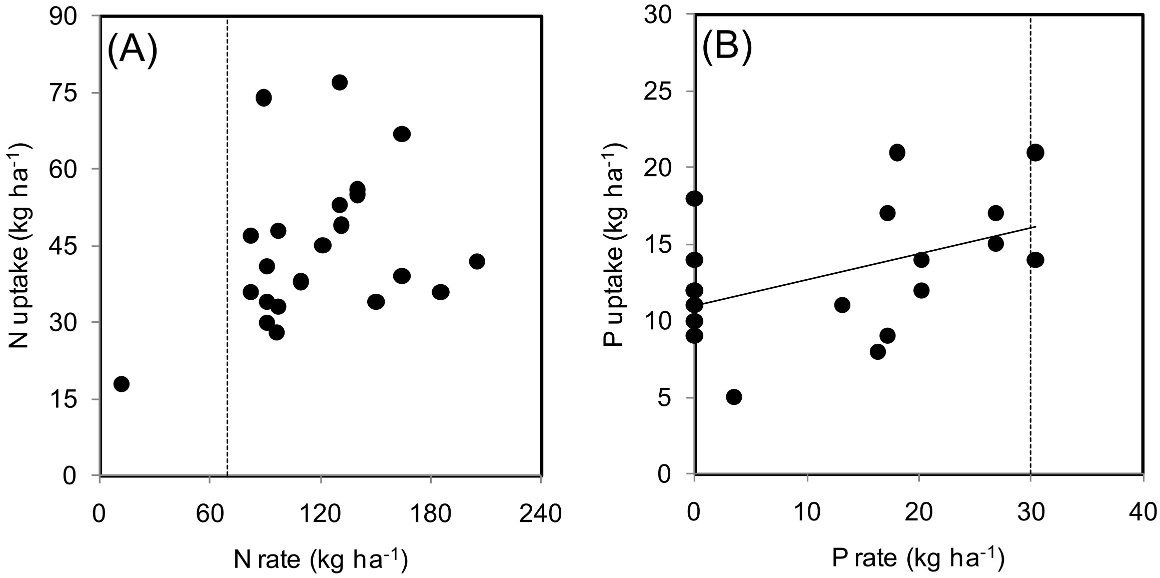

Figure 4. Relationship between stated application rates and measured total uptake of N (A) and P (B) by maize, roselle and weeds in different farmers' fields. *Dotted lines* indicate application rates recommended by the government. The *solid line* in B represents the relation between P application and uptake ($Y = 11.0 + 0.17 X$; $r^2_{adj} = 0.24$; $P = 0.0213$); for N no significant relation was found.

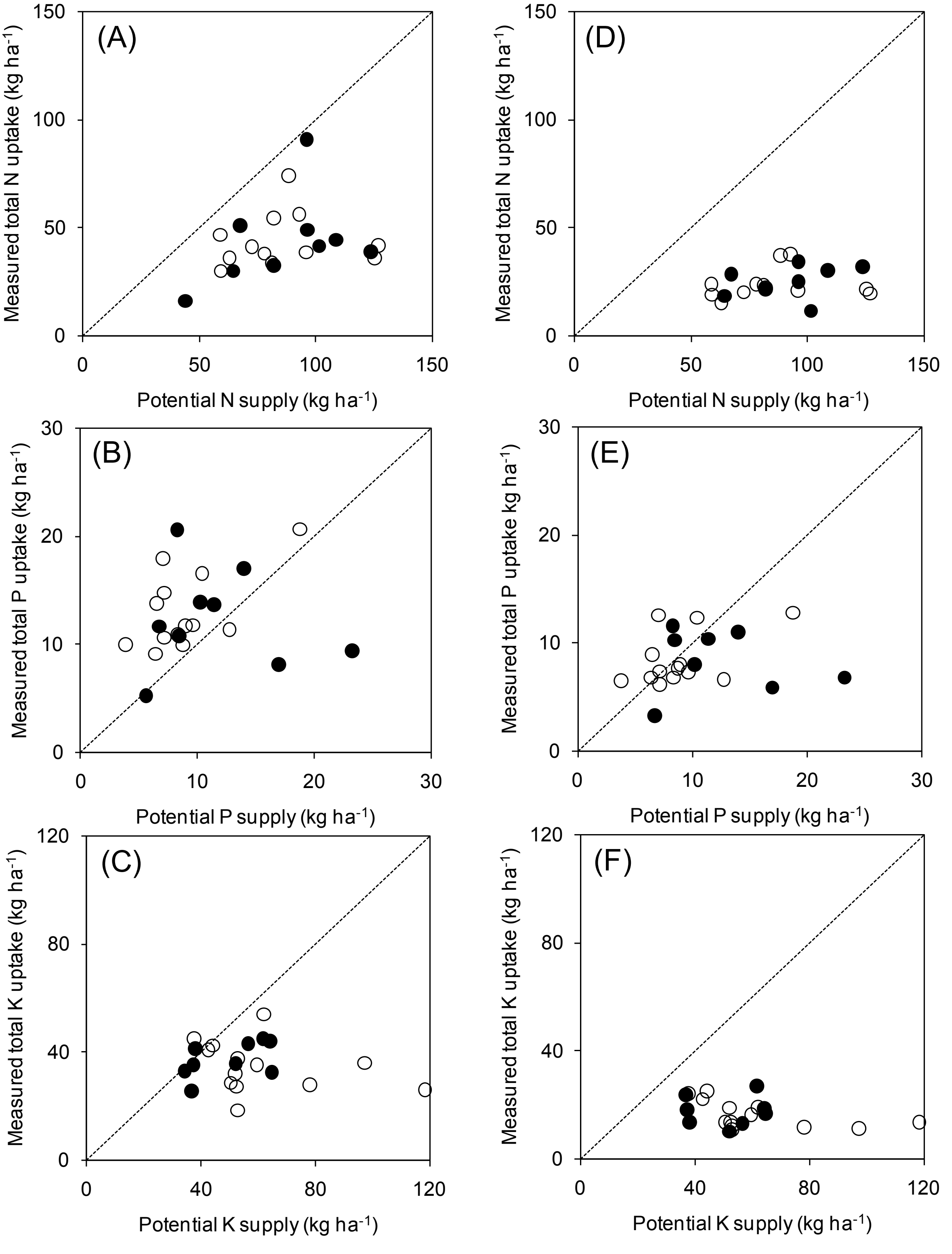

Figure 5. Measured total uptake of N (A, D), P (B, E), and K (C, F) by maize, roselle and weeds jointly (A-C) and by maize only (D-F) as a function of potential nutrient supply from soil calculated according to QUEFTS in Xalpatlahuac (*filled circles*), and Las Animas (*open circles*).

Nutrient uptake and crop yield

Nutrient uptake and yields of maize and roselle are presented in Table 4. Average aboveground biomass of maize in the fields ranged from 1837 to 7660 kg ha^{-1}, and grain yield from 763 to 3057 kg ha^{-1}. Harvest index averaged over all fields was 0.38, and ranged from 0.33 to 0.55. Maize biomass and grain yield were not significantly different between communities or farmers within communities, but significant differences were found among fields of farmers ($P<0.05$).

The total uptake of nutrients by maize ranged from 11 to 44 kg N ha^{-1}, 2 to 11 kg P ha^{-1} and 11 to 27 kg K ha^{-1} (Table 4). Similar to biomass and yield, nutrient uptake was significantly different among fields of farmers, but not between farmers or communities ($P<0.05$).

Table 4. Nutrients added by farmers, average aboveground biomass, grain and calyx yield and nutrient uptake for various fields under different cropping systems in two communities.

Farmer	Cropping system	Nutrient supply (kg ha^{-1})		Maize (kg ha^{-1})					Roselle (kg DM ha^{-1})					Weeds (kg DM ha^{-1})			
		N	P	AGB^{a}	Grain^{b}	N^{c}	P	K	AGB	Calyx	N	P	K	AGB	N	P	K
A1a	MR	82	0	3872	1465	15	6	11	10	2	0.06	0.02	0.05	1376	21	4	25
A2a	MR	205	0	3916	1483	20	7	12	196	22	0.6	0.2	0.3	1077	22	5	16
A2b	MR	164	0	3879	1584	21	7	13	1033	43	3	1	4	1139	15	3	9
A2c	MR	164	0	6844	2808	44	13	25	759	85	4	1	5	1100	19	4	12
A2d	MR	185	0	3458	1544	22	6	14	1024	145	4	1	5	772	10	2	10
A3a	M	91	0	4251	1872	23	8	19	-	-	-	-	-	665	11	2	13
A3b	M	91	0	3839	1698	19	7	13	-	-	-	-	-	690	11	2	14
A3c	M	91	0	3803	1967	20	7	11	-	-	-	-	-	1332	21	4	27
A3d	M	82	0	5098	2261	24	9	22	-	-	-	-	-	2004	23	5	19
A4a	MR	140	27	7208	2810	38	12	16	768	15	2	0.6	2	865	17	4	16
A4b	MR	140	27	4189	1758	22	7	19	1054	247	5	2	8	1426	28	6	27
A4c	M	89	18	7660	2898	37	13	24	-	-				1618	37	8	21
A4d	MR	109	0	4464	1973	24	8	12	1291	121	6	2	2	571	8	2	4
X1a	M	130	30	6016	3004	34	12	13	-	-				1954	43	9	28
X1b	M	130	30	4467	1932	25	8	27	-	-				1271	28	6	18
X1c	MR	121	20	4796	3057	30	10	13	261	67	1	0.5	2	2398	13	3	28
X2a	MR	131	20	1837	763	11	3	10	941	103	3	1	6	1742	34	7	20
X3a	MR	97	17	6441	2742	29	11	19	3227	122	16	5	20	462	4	1	5
X3b	MR	97	17	3578	1687	22	7	18	741	110	3	0.8	4	1092	8	2	13
X3c	MR	96	16	3248	1400	18	6	17	446	119	2	0.6	3	713	8	2	13
X4a	R	12	4	-	-				5556	467	13	4	30	256	5	1	3
X4b	M	150	13	5704	2451	32	10	24	-	-	-	-	-	135	3	1	2

MR intercrop maize – roselle, *M* maize monocrop, *R* roselle monocrop,

[a] aboveground biomass on DM basis (in case of maize and roselle, it includes grain and calyx, respectively)

[b] grain yield adjusted to 15.5% moisture

[c] nutrient uptake in aboveground biomass

Roselle biomass varied between 0.01 and 5.55 Mg ha^{-1}, with calyx yields varying between 2 and 467 kg ha^{-1}. Harvest index averaged over all fields was 0.13. Nutrient uptake was very variable (Table 4) due to variation in plant density (3,200 - 86,000 per ha) which was the result of irregular sowing, incidence of pests and mono- versus mixed cropping systems.

Relationships between aboveground biomass, grain yield and N, P and K uptake are presented in Figure 6. Upper and lower boundary lines indicate the theoretical maximum dilution and accumulation of each nutrient derived from QUEFTS. Observed values for N in maize grains and aboveground biomass were scattered around the maximum dilution line. The same applied to K, although with a large variation. This indicated relative shortages for N and K. In case of P, values for grain were close to the maximum accumulation line, while values for aboveground biomass were clustered around a line halfway the envelope suggesting optimal P-levels (Janssen and de Willigen, 2006). Yields and above-ground biomass of maize did not show any signs of flattening off with increasing nutrient uptake, and regression analysis showed that a quadratic component was never significant for the relation between uptake and biomass production. This suggests that resource use was still in the lower, linear part of the response curve, thus well below attainable yield (de Wit, 1992).

Crop residues left on the field immediately after harvest amounted to an average 2.9 Mg ha^{-1} for maize, 1.1 Mg ha^{-1} for roselle and 1.1 Mg ha^{-1} for weeds. On average 34% of N, 40% of P and 16% K taken up in plant biomass were exported from the field in grain and calyxes. N uptake by weeds was on average 38% of total uptake, and about 56% of N remaining in the fields was captured in weeds. Thus, weeds contributed considerably to low crop N use efficiencies.

Predicted yield based on potential soil nutrient supply

Figure 7 shows the relation between measured maize grain yield and maximum attainable grain yield calculated by QUEFTS for unfertilized crops as well as based on the recorded rates of application of NPK fertilizers and the maximum recovery of nutrients for all fields in the two communities. Measured maize grain yield in both communities was on average 1973 kg ha^{-1}. Based on the default maximum recovery fractions of 0.5 for N and 0.1 for P, maximum attainable yield according to QUEFTS was 3398 kg ha^{-1} (open symbols Figure 7). RMSE in this case was 1578 kg ha^{-1}. An average yield of about 1503 kg ha^{-1} would have been attainable under unfertilized conditions (closed symbols in Figure 7), with an RMSE of 865 kg ha^{-1}. Thus, average grain yield was only 60% of the maximum attainable yields given the production situation and nutrient recoveries were variable and considerably lower than the proposed maximum values.

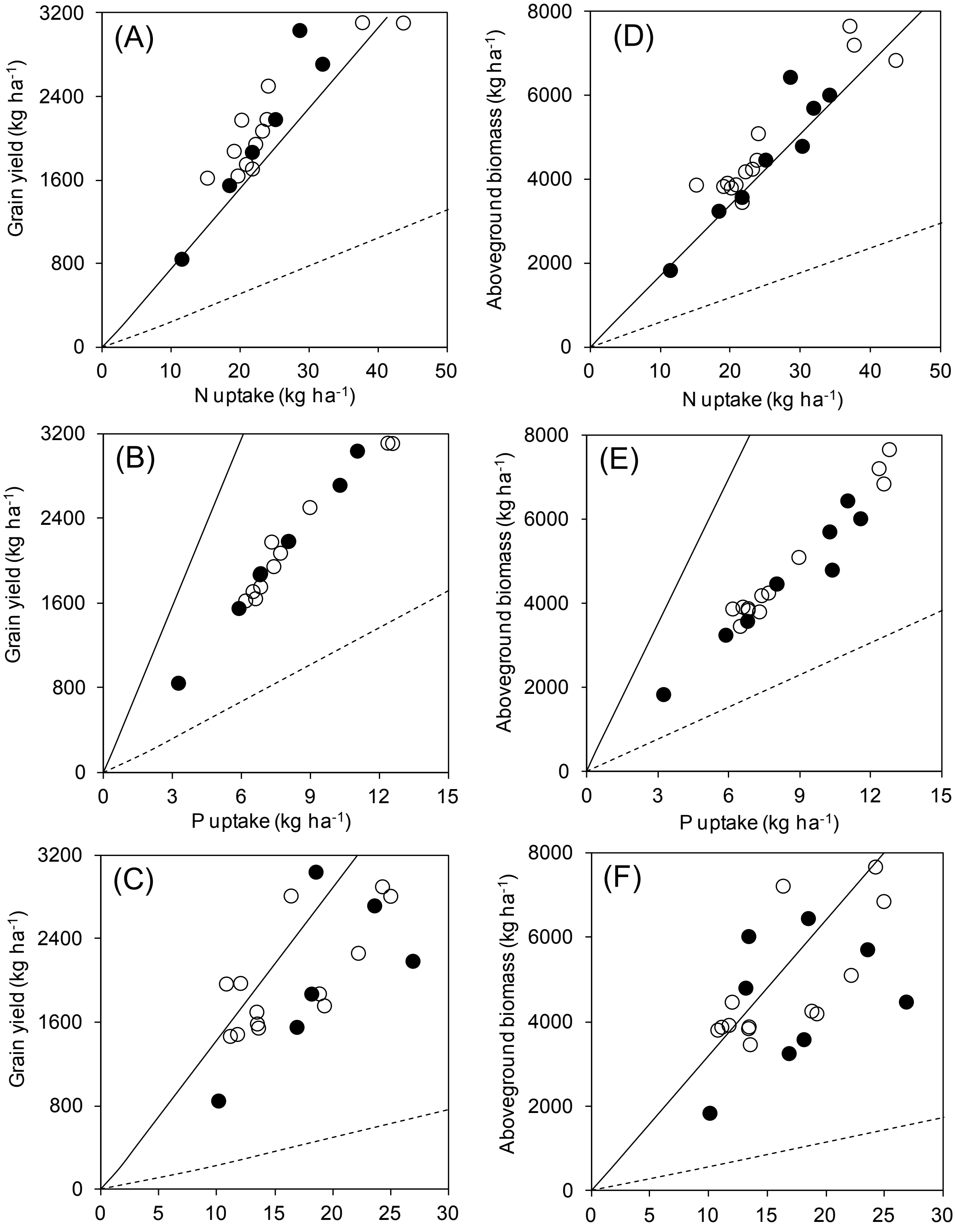

Figure 6. Relationships between measured grain yield (A-C; 15.5% moisture) and aboveground biomass (D-F) related to measured N (A, D), P (B, E) and K (C, F) uptake in farmers' fields in Xalpatlahuac (*closed symbols*), and Las Animas (*open symbols*). *Solid lines* represent maximum nutrient dilution and *dashed lines* indicate maximum nutrient accumulation, as described by Nijhof (1987), using an average harvest index of 038 as found in the samples.

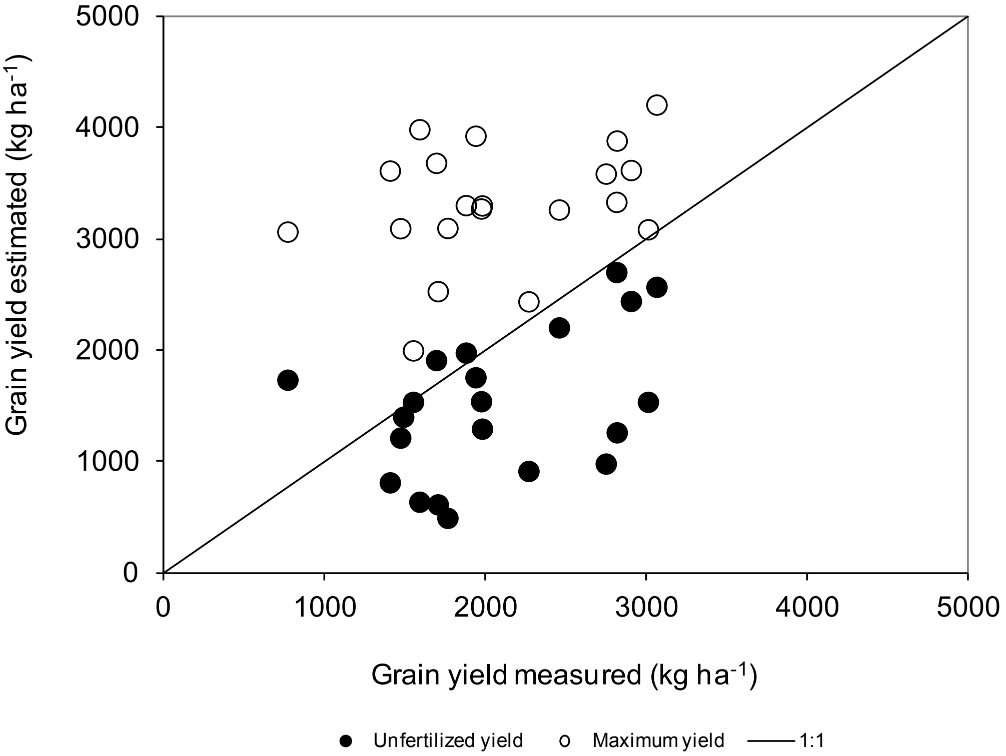

Figure 7. Relationship between grain yield measured and grain yield estimated using QUEFTS, assuming no fertilizer input (*filled circles*), and maximum attainable yield based on QUEFTS default recoveries (0.5 for N and 0.1 for P) for nutrients in fertilizers, at application rates stated by farmers (*open circles*). Grain yield was adjusted to 15.5% moisture.

Soil erosion

Average amount of crop residues at the start of the rainy season was 2.7 Mg ha^{-1}. Using the approach of Figueroa et al. (1991) we estimated the amount of maize residues at 3 Mg ha^{-1}. Using their data and assuming 30% soil cover we calculated soil erosion values between 2 and 73 Mg ha^{-1} year^{-1} (Table 5). Average estimated erosion was significantly higher in Las Animas (A) than in Xalpatlahuac (X) (t-test, $P<0.05$) . Classification of the predicted erosion according to the classes proposed by SEMARNAT and UACH (2002) showed moderate erosion (10–50 Mg ha^{-1} year^{-1}) in 73% of the fields, severe erosion (>50 Mg ha^{-1} year^{-1}) in 14%, and very slight soil erosion (0–5 Mg ha^{-1} year^{-1}) in another 14%. Erosion rates were not correlated with the yield gap calculated in Figure 7 (data not shown).

Nutrient and OM balances at farm level

The 8 farms that were analyzed with Farm DESIGN (Table 6) varied in area from 1.0 to 4.2 ha, with one to four fields per farm. The main cropping system was maize with roselle as intercrop. On four farms maize was grown as monocrop, roselle only

Table 5. Soil erosion kg ha^{-1} year^{-1} calculated with the RUSLE model assuming 3 Mg ha^{-1} of maize residues and 30% soil cover at the start of the rainy season and severity of erosion according to SEMARNAT and UACH (2002).

Farmer	Cropping system [a]	Slope (%)	Potential soil erosion	
			t ha^{-1} year^{-1}	severity
A1a	MR	25	30	m
A2a	MR	31	42	m
A2b	MR	46	55	se
A2c	MR	19	5	n
A2d	MR	31	26	m
A3a	M	20	20	m
A3b	M	20	32	m
A3c	M	20	22	m
A3d	M	55	42	m
A4a	MR	36	73	se
A4b	MR	36	67	se
A4c	M	30	28	m
A4d	MR	41	38	m
X1a	M	21	16	m
X1b	M	21	12	m
X1c	MR	26	14	m
X2a	MR	25	14	m
X3a	MR	19	23	m
X3b	MR	19	17	m
X3c	MR	6	2	vs
X4a	R	5	2	vs
X4b	M	43	30	m

Severity classes: vs: very slight (0-5); s: slight (5-10); m: moderate (10-50); se: severe (>50).

MR intercrop maize – roselle, *M* maize monocrop, *R* roselle monocrop

occurred once as monocrop. Total aboveground biomass production ranged between 4520 and 7644 kg ha^{-1}. The sample included four farms with animals; cows and goats in different combinations. Estimated average soil erosion at farm level varied between 13 and 48 Mg ha^{-1} year^{-1}.

Nutrient inputs were fully based on mineral fertilizers and varied from 73 to 131 kg ha^{-1} for N and from 0 to 28 kg ha^{-1} for P on average (Table 6). Outputs with maize grains and roselle calyces ranged from 15 to 64 kg ha^{-1} for N, 4 to 14 kg ha^{-1} for P, and 4 to 30 kg ha^{-1} for K. Estimated nutrient losses by erosion varied greatly due to the varying slopes of the fields, but were for N on some farms as high as the amount of

Table 6. Nutrient balances at farm level for the Costa Chica case study based on data and calculations for the year 2005.

Farm	Area (ha)	Number of fields	Cropping systems	AGDM (kg ha^{-1})^{a}	Number of animals		Erosion t ha^{-1}year^{-1}	Nutrient balances (kg ha^{-1})									Use efficiencies^{c}		
								Input^{b}			Output			Balance					
					Cows	Goats		N	P	K	N	P	K	N	P	K	N	P	K
A1	3.0	1	MR	5258	0	0	30	82	0	0	28 (18)	9 (0.3)	26 (3)	36	-9	-29	0.12	-	-
A2	4.1	4	MR	6584	12	0	33	73	12	0	24 (26)	8 (0.4)	7 (3)	23	4	-10	0.03	0.63	-
A3	3.3	2	M	5481	14	14	30	88	0	0	11 (15)	3 (0.3)	3 (2)	62	-3	-5	0.05	-	-
A4	4.2	4	MR, M	7644	7	0	48	116	19	0	17 (34)	6 (0.8)	6 (3)	65	13	-9	0.15	0.27	-
X1	2.5	3	M, MR	7421	0	0	15	128	28	0	50 (14)	14 (0.1)	30 (1)	64	14	-31	0.28	0.50	-
X2	1.0	1	MR	4520	0	0	14	131	20	0	35 (14)	8 (0.1)	24 (1)	82	12	-25	0.16	0.40	-
X3	3.1	3	MR	6512	0	10	13	97	16	0	27 (8)	8 (0.4)	23 (1)	62	8	-24	0.20	0.48	-
X4	1.3	2	M, R	5833	0	0	24	118	10	0	24 (26)	8 (0.1)	17 (2)	58	2	-19	0.02	0.79	-

MR maize – roselle intercrop, *M* maize monocrop, *R* roselle monocrop

[a] Aboveground biomass of maize, roselle and weeds

[b] Inputs: chemical fertilizers only; output: exports in crop and animal products, erosion losses between parentheses; Balance: input minus export minus erosion losses

[c] NPK output in products (excluding erosion losses) divided by NPK input

N exported in products. The balances showed an average surplus of 58 kg ha^{-1} for N, 5 kg ha^{-1} for P and -19 kg ha^{-1} for K. Efficiencies of N and P use (Table 6) were 0.12 and 0.51 on average. Animals on the farm did not lead to higher than average nutrient use efficiencies except in one case (farm A2).

OM inputs (173 - 1024 kg ha^{-1}) to the soil system and outputs (329 - 1054 kg ha^{-1}) from the system varied widely among farms (Table 7). High inputs were associated with manure production and high plant biomass production. High outputs were associated with erosion. Manure was an important source of OM on farms with animals, representing 58% of OM inputs on average. The OM losses due to soil erosion were on average 66% of total losses. Balances varied around 0 kg ha^{-1} as can be expected for these systems where practices were maintained over at least two decades.

Table 7. Organic matter balances for farms in Costa Chica, Mexico based on data and calculations for the year 2005.

	Farm							
	A1	A2	A3	A4	X1	X2	X3	X4
Inputs (kg ha^{-1})								
Root residues	51	64	64	102	72	44	93	57
Aboveground residues	122	290	141	556	218	180	249	219
Manure	0	552	743	366	0	0	0	0
Total	173	906	948	1024	290	224	342	276
Outputs (kg ha^{-1})								
Manure degradation	0	397	493	244	0	0	0	0
SOM degradation	0	157	20	54	124	145	72	234
Erosion losses	329	501	317	640	295	286	164	503
Total	329	1054	811	938	419	431	236	737
Balance (kg ha^{-1})	-156	-148	118	87	-129	-206	106	-461

4. Discussion

4.1. Field and farm diagnosis

Smallholder farming systems in a poor region of Mexico were diagnosed using a combination of qualitative and quantitative methods that did not require important financial resources. Rapid system characterization showed that farmers face social, economic and agronomic constraints which influenced the current farming activities in the five communities in a similar way. Farming systems were strongly influenced by the external rural environment, including policies and institutions, and markets which is a common pattern in developing countries (Dixon et al., 2001).

Off-farm activities were seen as an important component of livelihood strategies among rural households and together with the federal cash-transfer programs PROCAMPO and *Oportunidades* constituted an important source of income to maintain farming activities and guarantee the socioeconomic reproduction of the households (De Janvry and Sadoulet, 2001; Ramírez, 2008).

The main problems perceived by farmers were low soil fertility, soil erosion, low yields, incidence of pests and diseases, high production costs and limited commercialization channels, and low prices of products. These series of problems are recurrent in communities in the municipality of Tecoanapa (Navarro, 2004; Secretaria de Desarrollo Rural, Guerrero-FIRCO-SAGARPA, 2002, 2005), and elsewhere in the Costa Chica (Secretaría de Desarrollo Rural-FIRCO-SAGARPA, 2004; Galicia et al., 2008).

The detailed systems diagnosis on the 8 farms concentrated on the agronomic aspects and produced quantitative results. These confirmed the concerns of the farmers with respect to low soil fertility and low yield levels, and demonstrated that N and P uptake in maize were not correlated with chemical fertilizer application rates, soil supply estimates (Figure 4) or with yield (not shown). Analyses with the QUEFTS model indicated that grain yield was considerably lower than the attainable yield at the applied fertilizer rates, due the low nutrient recovery (Figure 6), suggesting major resource use inefficiencies. The model assumed that fertilizer recovery was 0.50 and 0.10 for N and P respectively. Under practical conditions, these values could have easily been lower because farmers left the applied fertilizers on the soil surface. This practice in combination with cultivation on steep slopes makes the fertilizers prone to losses due to run off, reducing both fertilizer recovery and efficiency.

The nutrient use inefficiencies are at least partly attributable to imbalances between macro-nutrients leading to constraints in yield due to limited availability in the maize crop of N and K while P was taken up in relative excess (Figure 5). Visual observations of easily dislodged maize plants, poor cob formation and grain fill support the diagnosis of low K (Lopez and Vlek, 2006). Poor nutrient interception by the roots may be another reason for the low N and K uptake (Figure 4). Ball-Coelho et al. (1998) found more lateral and superficial distribution of maize roots under systems with no tillage such as in the fields of our study area. This type of root development is beneficial for intercepting surface-applied fertilizers but unhelpful for intercepting nutrients that are leached deeper in the soil profile (Ball-Coelho et al., 1998).

Low soil fertility was confirmed by the low SOM contents (SEMARNAT, 2002) which have been found not only in the other communities of Tecoanapa but also in the entire region of Costa Chica (Presidencia Municipal de Tecoanapa, Gro., and

Instituto de Investigación Científica Área Ciencias Naturales-UAG, 2001; Navarro, 2004; OEIDRUS, 2011). On the sandy soils in the area with low SOM contents both N and K are prone to leaching losses (Benton, 2003; Ball-Coelho et al., 1998), contributing to further N and K deficits. These losses may also explain the difference between calculated potential K supply and measured K uptake, especially at high potential K supply rates (Figure 4). Minjian et al. (2007) reported trends in China similar to the ones in our study, where unilateral emphasis on N and P fertilizers and declining OM inputs have led to wide-spread K deficiencies.

In the 1990's the state government of Guerrero implemented a program to subsidize mineral fertilizers as part of policies to mitigate the economic crisis and improve maize production by smallholders. The subsidy comprised a state-wide standard dosage of N and P fertilizers for a maximum of 2 ha per farm. K was not included in the subsidies. The scientific rationale of the programme has not been published. The absence of K in subsidized fertilizer packages apparently prompted farmers to leave out K from their fertilizing strategies altogether. Currently, crop residues and soil stocks are the only sources of K. Field experiments with application of K fertilizer are needed to confirm the indications from this study.

Low soil pH was common in the sampled farmers' fields, in agreement with OEIDRUS (2011) who refer to pH values between 5.1 and 6.5 for the Costa Chica region. It is well documented that soil acidity limits plant growth, nutrient uptake and yields due to low availability of nutrients (Granados et al., 1993; Baligar et al., 1997). Under acid soil conditions ammonification is largely carried out by fungi, and nitrification by bacteria is suppressed. The assimilated N is taken up by the pool of soil biota (Mengel, 1996), thus reducing its availability to plants (Hodge et al., 2000). Liming is not a feasible option to raise soil pH, due to lack of availability in the region, and costs of transportation and application to the fields. Application of organic matter and animal manure may offer an opportunity as they are known to increase soil pH over time (Ouédraogo et al., 2001; Eghball, 2002; Eghball et al., 2004).

Another major cause of inefficiency was the large biomass of weeds which took up on average 40% of the total amount of N, 29% of P and 44% of K (Table 3; Figure 5). Weeds thrived despite the intensive use of herbicides, at rates of four times and even higher than those recommended. These results showed that attention should be given to the efficacy of weed control as well as that of fertilizers.

Also at the farm level (Figure 3 and Table 5), the results clearly indicate that purchased inputs had very low efficiencies. Based on actual inputs (Figure 3) efficiencies were nil for N and 0.17 for P. Efficiencies estimated with a whole-farm model (Table 5) were higher; 0.12 for N and 0.51 for P, possibly due to underestimated erosion losses and lack of information on export of animal products (milk, meat). Farm nutrient use efficiency was not related to presence of animals that could contribute to recycling of organic matter and nutrients on the farm by utilizing crop residues. This aspect requires further investigation, as data on where the animals were kept, how they were fed and how manure was collected and stored were based on interviews and expert opinion. However, manure input on farms with animals was an important source of organic matter, with, on average 50% of OM recycling on the farm and on average 13, 3 and 16 kg ha^{-1} of N, P and K. Manure thus has potential as soil improving factor (Dogliotti et al., 2006; Herrero et al., 2010). However, this study confirmed other studies with smallholders in tropical areas that revealed that available manure did not match nutrient needs to sustain crop production (Tittonell et al., 2009; Rufino et al., 2010). We calculated that at the current production levels, during the dry season (November to May) the animals can only be fed on-farm for 105-130 days (data not shown). The introduction of drought tolerant legumes such as canavalia (*Canavalia brasiliensis* Mart. Ex. Benth) can be a source of forage during dry season (Douxchamps et al., 2010). Giving attention to producing feed for the animals may provide additional sources of manure as well as income. This would require further elaboration in the region.

Estimated organic matter balances showed that the systems were close to equilibrium. Absolute levels of soil organic matter were generally close to those estimated using the relation proposed by Ruhlmann (1999) for minimum level of SOM (data not shown), suggesting that clearly positive OM balances would be desirable to enhance soil functioning. Higher crop yields are an effective way of increasing organic matter inputs through crop residues and roots. These additions may be further enhanced by growing leguminous intercrops which do not interfere with maize and roselle production in a negative way. Farmers stated that the soil is 'tired' and that it is impossible to get yields without fertilizers. Fallowing to recover soil fertility was a common practice some 30 years ago but has been abandoned coinciding with artificial fertilizer availability and shortage of land. Currently, fallowing does not seem feasible in view of the small farm sizes, low production levels and household needs.

Soil erosion estimates classified the majority of fields as having moderate erosion (10 - 50 Mg ha^{-1} yr^{-1}) which corresponds to the main class of erosion present in 37% of the land of the state of Guerrero (SEMARNAT and UACH, 2002). Farmers voiced concerns over erosion, but saw this as part of the problem of low yields and loss of soil fertility. Land scarcity forced the farmers to practice agriculture on extremely steep slopes; the average slope in the sampled fields was 27%. It has been demonstrated that residue retention provides protection from raindrop impact, and causes an increase in soil roughness reducing the runoff flow velocity and flow transport capacity. This also limits evaporation and is thereby increasing the amount of water available for plant uptake (Gilley et al., 1987; Fowler and Rockstrom, 2001; Hartkamp, 2002; Tiscareño et al., 2004). As a rule of thumb, 30% ground cover is recommended by various authors (Lal, 1976; Uri and Lewis, 1999; Scopel et al., 2004; Tiscareño et al., 2004). More knowledge on the relation between ground cover and erosion is needed to understand the trade-off between crop residues for animal feed and for soil protection. Additionally, the feasibility of control measures such as terracing and strip cropping to prevent the runoff of water and erosion should be evaluated and integrated as part of the sustainable management and conservation of the resources (Sanders, 2004; Kuypers et al., 2005).

Calculated erosion rates for 86% of the fields were higher than the tolerable soil loss limit of 11.2 Mg ha^{-1} year^{-1} proposed in the USA for similar soil types (El-Swaify et al., 1982). High erosion rates were particularly due to large slope-length (LS). Although threshold values may vary depending on type of soil and specific agroecological conditions (Skidmore, 1982; Jha et al., 2009; Li et al., 2009), values in the area are cause for concern.

Contrary to expectation, differences in social organization between the two communities did not impact on any of the quantitative variables on nutrient use efficiency and crop yields. Also, differences between farms were not significant. In contrast, fields within farms and communities differed significantly, suggesting that field specific approaches are needed to understand and improve production conditions.

4.2. Methodology

The methodology mobilized in this study relied as much as possible on observations and measurements that could be performed without sophisticated analytical equipment and that were supported by model-based calculations. Important model-based calculations included soil erosion using RUSLE, soil production potentials using QUEFTS, and balances of soil organic matter and animal feed rations using Farm DESIGN. As much as possible information from similar Mexican production conditions was used, and conclusions from observations were used to cross-check model-based results. QUEFTS requires validation of potential grain yield of local criollo varieties, recovery fractions and the integration of soil erosion. More detailed information on the animal component, e.g. feeding regimes, amount of time spending around the farm, manure collection systems, use of manure, would have increased the accuracy of calculations. Particularly for crop nutrient use efficiencies it was possible to obtain a consistent set of results using both measurements and models. Results on erosion and soil organic matter balances were based on modeling only, but resulted in estimates which for erosion were recognizable in the region, and for organic matter were plausible given the cropping history. Particularly for erosion, more detailed observations on the fate of crop residues in the course of the dry period, with and without animal exclusion would provide more information to support both erosion and organic matter balance calculations.

4.3. Policy implications

Price support of chemical fertilizers as a policy to maintain crop nutrition and improve yields has not been effective due to lack of balance in nutrient contents and the acidifying potential of the fertilizers (e.g. ammonium sulfate) (Akinrinde, 2000) in the subsidized fertilizer packages. During the time of the study, only a single fertilizer subsidy package existed, which resulted in 75% price subsidy for 69 kg N and 30 kg P, meant for a maximum of two ha. Farmer application rates showed that P application rates were well below those suggested in the subsidy package, while N application rates always exceeded the subsidized 69 kg ha^{-1} for maize (Tables 2 and 4). K content in biomass (Table 2) and K supply (Figure 4) revealed K shortage on most of the fields. The lack of attention for K in the subsidies clearly was not compensated by purchase of K. The subsidy scheme thus seems a clear case where the existing institutional environment has a major impact on resource use efficiencies. Without additional K input, low nutrient efficiencies will continue to exist for applied N and P, along with low yields. The study suggests that a local integrated nutrient management policy is necessary to improve current crop nutrition, maintain or increase yields and enhance the soil fertility.

In agreement with farmers' demands (Table 1) alternative nutrient management strategies could be based on combining chemical and organic fertilizers. Composts as organic amendment could help to remedy the low soil pH in the longer term and are an option in the municipality with the advent of a composting facility. Experiments are needed to evaluate the short-term effect of compost on biomass accumulation and yield. Finally, the strategy also needs to include increasing nutrient use efficiencies through improvements in weed control and cultivar choice. Well-structured experimentation by farmers and researchers may help to find locally adapted solutions.

Although implementation of OM input intensive systems faces the challenge of remote fields with only access on foot or horseback, such systems could be expected to show yield increases even in the short term (see e.g. Scholberg et al., 2010a; 2010b) due to more balanced supply of nutrients and infiltration of water. Such change should be accompanied by other soil erosion measures as erosion constituted an important loss term in the OM balance. Production on the steepest slopes could be reconsidered, along with more attention for retaining soil cover. The latter needs to consider the communal land traditions, which cause cattle to strongly reduce soil cover by crop residues remaining at the start of the next rainy season (Herrero et al., 2010).

Aiming for an ecological intensification of cropping systems in Costa Chica is necessary to improve nutrient use efficiency. It implies promotion of integrated crop management that includes integration of organic and chemical sources of nutrients, multifunctional crops and crop residues management. These strategies can potentially enhance soil properties, conserve the resource base, reduce the reliance on external inputs, maintain crop yields, and minimize impact on the environment (Doran, 2002).

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Chapter 3

Exploring maize-legume intercropping systems in Southwest Mexico

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Abstract

Maize yields in continuous maize production systems of smallholders in the Costa Chica, a region in Southwest Mexico, are low despite consisted inputs of fertilizers and herbicides. This study was aimed at investigating the prospects of intercropping maize (*Zea mays* L.) and maize-roselle (*Hibiscus sabdariffa* L.) mixtures with the legumes canavalia (*Canavalia brasiliensis* Mart. ex Benth) and mucuna (*Mucuna pruriens* L. *var. utilis* (Wall ex Wight) Burk) for improving nutrient uptake and weed suppression. Farmer-managed experiments were established in two communities in the region during 2006 and 2007 using randomized split-plot designs. Maize monocrops and maize–roselle intercrops grown with different sources of nutrients were intercropped with both legume species 4 - 6 weeks after maize. Neither the legumes decreased yields of maize nor roselle, whereas they caused a reduction of the weed biomass by 24 - 55%. Total aboveground biomass returned to the soil increased up to 36% and total N, P and K uptake was increased on average by 52%, 24% and 30%, respectively. Legumes acted not only as a N-fixing crop, but also as a “catch” crop, preventing N and K leaching. With its prostrate growth habit and adaptation to poor soil conditions, canavalia demonstrated agronomic advantages in comparison to mucuna.

Keywords: Intercropping, maize yield, canavalia, mucuna, weed suppression, biological nitrogen fixation

1. Introduction

In Costa Chica, a sub-humid tropical region in Southwest Mexico, smallholder farming systems are characterized by continuous cultivation of maize (*Zea mays* L.) and roselle (*Hibiscus sabdariffa* L.) under rainfed conditions. Maize is grown for self consumption, while roselle is a cash crop cultivated for its calyces. Subsidized N and P artificial fertilizers are the main source of nutrients. Cropping on slopes as steep as 50% makes fertilizers susceptible to run-off. Traditional practices to restore soil fertility such as fallow management have been nearly abandoned. According to farmers' perception, these cropping management changes have led to 'tired soils', an increase in weed pressure and an overall reduction in crop yields. Manual control of weeds is not practiced anymore because it is time consuming, labor-intensive and therefore expensive. Herbicides (mainly paraquat) are widely used at high doses, and they can have potential impact on human and animal health (Jordan, 1996).

Inclusion of legumes like mucuna or velvet bean (*Mucuna pruriens* L. var. *utilis* (Wall ex Wight) Burk), slender leaf rattlebox (*Crotalaria ochroleuca* G. Don), jackbean (*Canavalia ensiformis* L.) and Brazilian jackbean (*Canavalia brasiliensis* Mart. ex Benth) in cropping systems has been shown to play an important role in the N recycling within the systems, improve crop yields, reduce labor for weed control, decrease soil erosion, and improve soil physical properties (Reddy et al., 1986; Becker and Johnson 1998; Tarawali et al., 1999; Buckles et al., 2000; Ortiz-Ceballos and Fragoso, 2004; Lawson et al., 2007). However, benefits depended strongly on local biophysical conditions and crop management as intercropping may cause interspecific competition between the legumes and the main crops (Lawson et al., 2007). To tackle the problem of site-specific competition with the main crop, it has been suggested to delay legume sowing date by about two to six weeks to maintain main crop yields (Akanvou et al., 2002; Eilittä et al., 2003). Mucuna has been integrated in maize systems in different regions of Mexico. In the Costa Chica, a forerunner farmer developed empirically a system that, however, was considered unwieldy by other farmers due to the abundant growth of mucuna.

As part of a larger project aimed at learning about integrated nutrient management, the local farmer's experience with intercropping mucuna inspired researcher-guided, farmer managed experiments with maize and maize-roselle cropping systems. In the experiments, which ran during two years, the effects of intercropping with leguminous crops and different organic nutrient sources were investigated. Overall objective was to explore more productive crop management systems by increasing nutrient use efficiency and reducing inputs of herbicides. In a companion paper the effects of alternative nutrient management are reported (Chapter

4). In this paper, we describe first-year effects of intercropping maize and maize-roselle with mucuna and canavalia. Specific objectives were to determine the effects of intercropped legumes on yields of maize and roselle and on weed biomass suppression of the cropping systems. Besides, the hypothesis was tested that inclusion of legumes in maize and maize-roselle systems contribute to the N cycling within the cropping systems.

2. Materials and methods

Experimental sites

Five field experiments were conducted on farmers' fields located in the municipality of Tecoanapa (16°48'N, 99°09'W), Guerrero, Mexico, in two successive growing seasons (2006 and 2007). Annual rainfall in the experimental area was 1926 mm in 2006 and 1822 mm in 2007, mainly concentrated in the period between June and October. Mean annual temperature was 25^{o}C, with little variation within a year. Two villages were devoted to the experimental study. In 2006, a trial was conducted in the village Xalpatlahuac. In 2007, two experiments were located in Las Animas, and two in Xalpatlahuac (Table 1). Fields belonged to participant farmers, thus the experimental sites varied substantially in terms of slope and soil fertility. The soils in the experimental area were Loamy Eutric Regosols, which have a volcanic origin (SEMARNAT, 2009) and are defined by FAO (2006) as weakly developed with a texture finer than sandy loam. In an earlier survey (Flores-Sanchez et al., 2011) maize was found to be grown on fields with slopes between 5 and 55%. In the region, traits of rill erosion are common and the general level of erosion is classified as moderate (10 – 50 Mg ha^{-1} year^{-1}) (SEMARNAT – UACH, 2002).

2.1. Experimental procedures

Experiment in 2006

A trial was set up in a maize crop on one farm following a randomized block design in a split-plot arrangement with three replications. The main plots included three treatments: *Mucuna pruriens* L. var. utilis (Wall ex Wight) Burk, *Canavalia brasiliensis* Mart. ex Benth, and no legume. Mucuna is a vigorous annual species, with a climbing growth habit, and it produces abundant seed. It performs well in soils from moderate to high fertility and tolerates pH values between 5 and 8, and can grow on sandy soils (Peters et al., 2003; Kass and Somarriba, 1999). Canavalia is an underutilized perennial legume species with a relatively stable biomass production due to its tolerance to adverse environmental conditions, combined with its prostrate growth habit (Humbert et al., 2008). The legumes were sown midway between the rows of maize in an additive design. The sub-plots were fertilized with: 1) vermicompost, 2) goat manure, 3) mineral NPK, and 4) unfertilized control (Table 1). Unfortunately, not enough manure and vermicompost was available to reach the nutrient supply of the NPK treatment, therefore nutrient input levels were diverging. Maize was sown according to farmer's planting pattern and density which varied from 1.8 to 5.3 plants per m^2 (Flores-Sanchez et al., 2011) Farmers indicated to adjust sowing density to maize variety (wider spacing for land races compared to hybrids), available inputs (chemical fertilizers are subsidized for a maximum of two ha per farm) and current soil nutrient status.

Main plots were 20 m long and 5 m wide. Each sub-plot (experimental unit) had an area of 25 m^2. Three seeds of the maize criollo (landrace) "Palmeño" were sown manually 5 cm deep in planting holes spaced at 0.70 m within the row and 1 m between rows. This corresponded to 4.28 seeds per m^2. Sowing was carried out on June 22, 2006. The herbicide paraquat (1 L ha^{-1}) was sprayed one week before sowing and three weeks after sowing according to farmer's practice. Organic and mineral fertilizers were only applied to the maize plants. The organic fertilizers were put in the planting hole during sowing and covered with soil. The inorganic fertilizers urea, di-ammonium phosphate, and potassium chloride were split into two parts: half of the N

Table 1. Experimental sites, cropping systems and treatments evaluated in five experiments.

Year	Exp.	Code	Cropping systems	Main plots	Sub plots	Nutrient inputs (kg ha^{-1})		
						N	P	K
2006	1*	M-1mu		Mucuna	Vermicompost (2.5 Mg DM ha^{-1})	33	2	15
		M-1ca	Maize	Canavalia	Goat manure (2.5 Mg DM ha^{-1})	34	1	18
		M-1nl		No legume	NPK	56	2	24
					Unfertilized	0	0	0
2007	2**	M-2	Maize	Canavalia	Vermicompost (10 Mg DM ha^{-1})	93	24	80
	3***	M-3		No legume	NPK	90	9	75
					NPK (50-4-42) + vermicompost (2.5 Mg DM ha^{-1})	73	10	62
					Unfertilized	0	0	0
	4**	MR-1	Maize-roselle	Canavalia	Vermicompost (10 Mg DM ha^{-1})	93	24	80
	5***	MR-2		No legume	NPK	97	9	81
					NPK (55-5-46) + vermicompost (2.5 Mg DM ha^{-1})	78	11	66
					Unfertilized	0	0	0

Experiment 1 (M-1mu, M-1ca, M-1nl) was set up in the village of Xalpatlahuac

** Experiments 2 (M-2) and 4 (MR-1) were set up in the same field in the village Las Animas

*** Experiments 3 (M-3) and 5 (MR-2) were set up in the village Xalpatlahuac and all of the P and K were applied at sowing and the rest of the N six weeks after sowing (WAS). Mucuna and canavalia were sown 6 weeks after maize in rows midway between the maize rows spaced at 0.50 m. The resulting legume density was 4 plants per m^2.

Experiments in 2007

Observations in 2006 confirmed that mucuna's tendency to climb into the maize plants created problems during harvest. Thus, farmers suggested to continue with canavalia only in 2007. In addition, they suggested to include a maize-roselle intercrop.

Cropping systems of maize (M) and maize-roselle (MR) were established at three experimental sites in the communities of Las Animas and Xalpatlahuac (Table 1). Similar to 2006, the experimental design was a split-plot randomized block with three replications. Canavalia and no legume acted as main plots with four combinations of organic and mineral fertilizers as subplots: 1) vermicompost; 2) mineral NPK; 3) vermicompost + mineral NPK, and 4) unfertilized as control (Table 1). The rates of mineral and organic fertilizers were increased to study the maize response to increased input levels. Similar to 2006, experimental units had an area of 25 m^2 consisting of five maize rows, 5 m long, spaced 1 m apart and plants spaced at 0.7 m within the row. Sowing of the maize landrace "Palmeño" took place during the last week of June. Maize seed density was again 4.28 per m^2. Also for roselle a landrace was used. Roselle, local name Jamaica, was sown one week after maize at a rate of three seeds per planting hole located halfway between two maize plants within a row. Thus, interrow spacing for roselle was also 0.70 m. The herbicide paraquat (1 L ha^{-1}) was sprayed twice, one week before and three weeks after sowing. Vermicompost and mineral fertilizers were applied to the maize and roselle plants. No fertilizers were applied to the canavalia. Vermicompost was applied in the planting hole before sowing. Mineral fertilizers were split into three parts: one third of both N and K, and all of the P were applied in the second week of July; the second dose of N and K was applied in the first week of August and the last part at the end of August. Canavalia was sown four weeks after maize midway between the main crop rows at a rate of two seeds per planting hole with an intra-row spacing of 50 cm, resulting in 4 legume plants per m^2.

2.2. Data collection

Physico-chemical analysis of soil and organic inputs

Soil properties are presented in Table 2 and the chemical composition of the organic inputs in Table 3. Soil samples were collected in the surface layer (0-20 cm) at each experimental site two weeks before sowing maize. The soil properties analyzed were

Table 2. Soil physical and chemical properties (layer 0-20 cm).

Year	Exp.	Slope (%)	Sand	Clay	Silt	pH (H_2O)	OM	N_t	Bray P-1 mg kg^{-1}	K cmol kg^{-1}
			(%)				g kg^{-1}			
2006	1	21	45	21	34	4.3	17	0.85	15	0.15
2007	2, 4*	5	51	21	28	4.3	11	0.55	15	0.30
	3	21	40	23	37	3.7	13	0.50	18	0.63
	5	3	71	19	10	3.3	12	0.50	2	0.06

* Experiments 2 and 4 were set up in the same field in the village Las Animas

Table 3. Initial chemical composition of the organic fertilizers.

Year	Organic fertilizer	N	P	K	pH (H_2O)
		g kg^{-1} (DM)			
2006	Goat manure	13.6	0.4	7	8.2
	Vermicompost	13.2	0.7	6	8.3
2007	Vermicompost	9.3	2.4	8	8.0

texture (Bouyoucos hydrometer method); pH (1:2 soil to water ratio); organic matter (Walkley-Black method); total N (Kjeldahl-N method); extractable P (Bray-1 method) and extractable K (NH_4OAc, pH 7 method). The organic amendments were analyzed for pH (1:5 compost/manure – water ratio); total N (Kjeldahl method) and total P and K (inductively coupled plasma spectrometry method) (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA) (Alcántar and Sandoval, 1999).

Maize leaf area index (LAI)

Maize leaf area was estimated at anthesis. Maximum width and length of the second leaf below the cob of five plants in each plot were measured. The area of the sampled leaf was calculated as maximum width × length × 0.75 (Elings, 2000). On the same five plants the number of green leaves was counted. Since not all the leaves were measured, the area of each leaf was estimated by means of the three parameter normal curve (Landsberg, 1977). This equation uses the leaf number relative to a reference leaf as input, along with parameters that describe area of the reference leaf and a dispersion parameter σ. Our reference leaf, that is the one with the greatest area, corresponded to the second leaf below the cob. For σ we used a value of 3.0, which empirically was found to best describe the data. Leaf area per plant was calculated as the sum of the areas of green leaves, and to estimate LAI the leaf area per plant was multiplied by the number of plants per square meter.

Biomass estimation

Maize and roselle

In both years, maize was harvested in the first week of November (20 WAS). All plants in the central row of each plot were harvested except the plants located at the edges. Numbers of plants and cobs were counted to calculate their densities. Aboveground fresh weight of maize was measured in the field. After cutting plants of the central row three plants were chosen randomly and oven-dried at 70°C for 24 hours to estimate aboveground dry matter (DM) content. The dried plants were separated into grains and straw (i.e. leaves and stems) and analyzed for N, P and K. Cobs from the harvested row were weighed and after shelling the maize grains were oven-dried at 70°C for 24 hours to estimate grain yield (kg DM ha^{-1}). In the maize-roselle intercrops, roselle was harvested during the first week of January. The roselle plants were measured from the same central row. The plants were counted and weighed in the field. Three plants were chosen to estimate plant DM content after oven-drying at 70°C for 48 hours. Calyces were removed manually from the plants and also oven-dried at 70°C for 24 hours to estimate yield (kg DM ha^{-1}). N, P and K contents were determined on subsamples of roselle straw (i.e. leaves and stems) and calyces.

Legumes and weeds

In both years biomass of legumes as well as weeds were estimated in the second week of January (22 WAS). A quadrant of 1 × 1 m^2 was placed randomly in each plot. The aboveground biomass of weeds and legumes which were rooted in the square meter including legume branches outside that area were collected, separated and weighed. Sub-samples of legumes and weeds were oven-dried at 70°C for 48 hours to estimate aboveground yield (kg DM ha^{-1}) and their N, P and K contents. In all samples, total N was analyzed using semi-micro-Kjeldahl procedure (Bremner, 1965). P and K were analyzed by inductively coupled plasma spectrometry (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA) (Alcántar and Sandoval, 1999).

Dominant ground cover estimation

A quadrat sampling method was used to estimate dominant ground cover. In both years sampling was carried out in the second week of January. Four cover classes were distinguished: crop residues, legumes, weeds and bare soil. A frame of 1 m^2 divided into 25 smaller squares (0.20 × 0.20 m^2) was placed randomly along the central row of each sub-plot (experimental unit). In all squares the dominant cover class was visually assessed and recorded. Dominant ground cover (%) per class (x) was estimated as: 100 * (# dominant squares of class (x) / total # squares).

Nutrient uptake

Total N, P and K uptake from all the sources at the cropping system level was calculated by summing the aboveground N, P and K uptake by weeds, maize, roselle and legumes.

2.3. Statistical analysis

Data from sub plots were pooled to obtain averages and an analysis of variance (ANOVA) was carried out per experiment to analyze main plot effects (2006) and effects of main plot and location (2007) using SAS 9.1 (SAS Institute, 2002). Means separation was performed by Tukey's Studentized Range (HSD) test when the F-test indicated significant ($P < 0.05$) differences among the treatments.

3. Results

3.1. Effects of intercropping legumes on aboveground biomass and main crop yields

Aboveground biomass of maize was not affected by legume intercrops neither in the maize monoculture nor in the maize-roselle mixture (Figure 1). In 2006, maize aboveground biomass ranged from 3,871 to 4,300 kg DM ha^{-1} (Figure 1A), while in 2007 it was between 2,973 and 11,051 kg DM ha^{-1} (Figure 1B). In case of roselle, in treatment MR-1 aboveground biomass was significantly higher in the presence of canavalia compared to the monocrop (Figure 1C). In both years there were no significant interactions ($P < 0.05$) between the factors legumes and sole maize and maize-roselle and the nutrient amendment treatments (data not shown).

In both years intercropping did not affect grain yield in the maize monoculture or in the maize – roselle mixture. In 2006, maize grain yield was not affected by legume type (Figure 2A). In 2007, maize grain yields varied among experimental sites between 508 and 2,867 kg DM ha^{-1} (Figure 2B), and calyx yields varied between 57 and 121 kg DM ha^{-1} (Figure 2C). In MR-1, calyx yield was increased by canavalia as intercrop. There was a significant effect of experimental site for both experiments. Treatments M-2 and MR-1 (site 2) had the highest values of maize grain yield, while the lowest ones were found in MR-2 (site 5). However, roselle calyx yield was highest in the latter case.

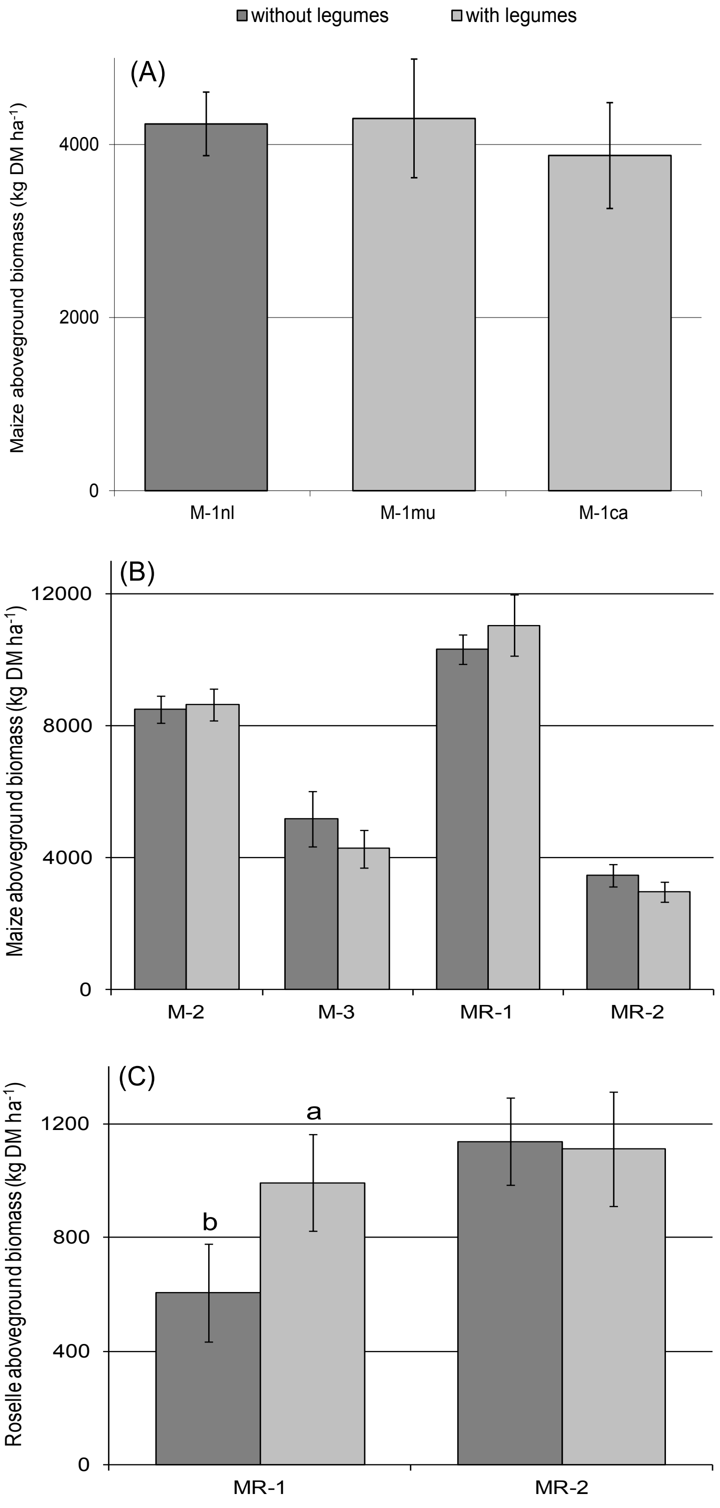

Figure 1. Mean (± SE) aboveground biomass of maize (kg DM ha^{-1}), (A) 2006, (B) 2007, and (C) roselle (kg DM ha^{-1}), with and without intercropping with legumes. Different letters denote significant differences between treatments ($P < 0.05$).

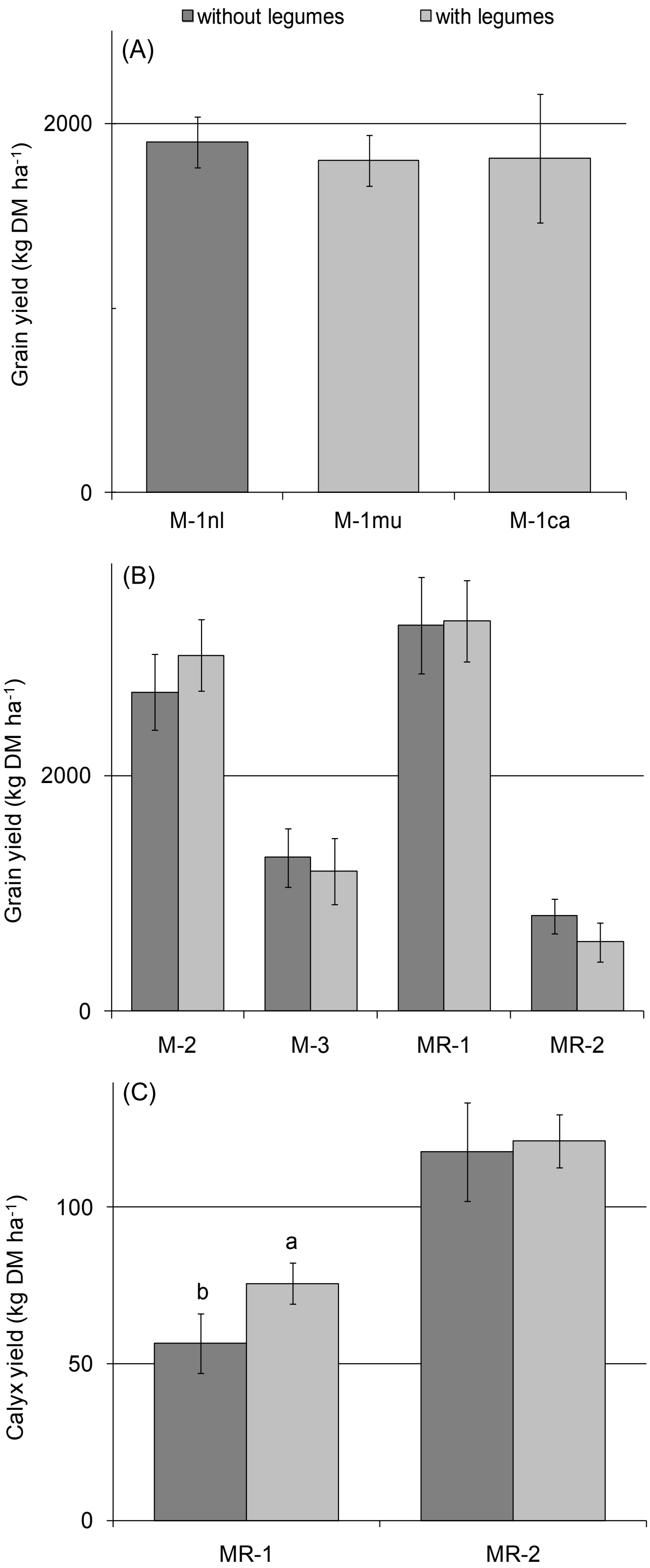

Figure 2. Mean (± SE) maize grain yield (kg DM ha^{-1}), (A) 2006, (B) 2007, and (C) roselle calyx yield (kg DM ha^{-1}), with and without intercropping with legumes. Different letters denote significant differences between treatments ($P < 0.05$).

3.2. Effects of intercropping legumes on leaf area and LAI

Only in M-2 there was a significant but small difference in leaf area between treatments with and without legume (Table 4). In the other treatments leaf area was not affected due to the inclusion of legumes. Besides, the number of leaves and LAI was also not affected by intercropping legumes. In 2006, the estimated LAI ranged from 0.8 to 0.9. This was lower than in 2007 when LAI values varied between 1.1 and 2.0.

3.3. Biomass of legumes

In 2006, mean accumulated aboveground biomass of mucuna and canavalia at 22 WAS was 1797 and 2257 kg DM ha^{-1}, respectively (Figure 3A). However, this difference was not significant. In 2007 accumulated aboveground biomass of canavalia at 24 WAS in maize monoculture (M-2 and M-3) ranged from 1805 to 2082 kg DM ha^{-1}, while in maize – roselle mixture (MR-1 and MR-2) it varied little from 960 to 1000 kg DM ha^{-1} (Figure 3b).

3.4. Weed biomass and ground cover

Weed aboveground biomass was consistently lower in the presence of legumes. In 2006, canavalia and mucuna caused a weed biomass reduction of 24 and 55%, respectively, compared to the maize monocrop (Figure 3A). The highest dominant weed ground cover was found in maize as monocrop (66%; Table 5), whereas it was reduced to only 17 and 26% in the presence of canavalia and mucuna, respectively.

Table 4. Mean (± SE) maize leaf area (cm^2) of the second leaf below the cob, number of green leaves at tasseling stage, plant density and leaf area index with and without intercropping with legumes. Different letters denote significant differences due to intercropping ($P < 0.05$).

Year	Code	Leaf area (cm^2)		Number of leaves		Plant density (m^2)		Estimated LAI	
		With Legume	Without legume	With legume	Without legume	With legume	Without legume	With legume	Without legume
2006	M-1mu	529 (± 48)	484 (± 46)	11 (±0.46)	10 (±0.50)	3.08 (±0.23)	3.01 (±0.12)	0.9	0.8
	M-1ca	486 (±40)	484 (±46)	10 (±0.43)	10 (±0.50)	3.13 (±0.16)	3.01 (±0.12)	0.9	0.8
2007	M-2	793 a	758 b	12 (±0.27)	12 (±0.37)	4.23 (±0.15)	4.29 (±0.18)	2.0	1.9
	M-3	643 (±43)	661 (±54)	11 (±0.35)	11 (±0.51)	4.25 (±0.10)	4.28 (±0.16)	1.6	1.6
	MR-1	793 (±25)	781 (±15)	12 (±0.51)	12 (±0.43)	4.28 (±0.08)	4.30 (±0.17)	2.0	2.0
	MR-2	474 (±14)	458 (±19)	10 (±0.25)	10 (±0.28)	4.28 (±0.11)	4.27 (±0.17)	1.2	1.1

In 2007, canavalia showed again a weed suppressing effect in maize and maize – roselle cropping systems (Figure 3B). In M-2, M-3 and MR-1 the inclusion of canavalia reduced significantly the weed biomass by 39 to 45% compared to the maize monocrop. In MR-2, the reduction of weed biomass was 26%, just not significant. Dominant weed ground cover in the maize monocrop was about 80% (Table 5), and in maize intercropped with canavalia it ranged between 22 and 27%. In the maize-roselle intercrop dominant weed cover was reduced from 79 to 39% in MR-1, and from 58 to 48% in MR-2.

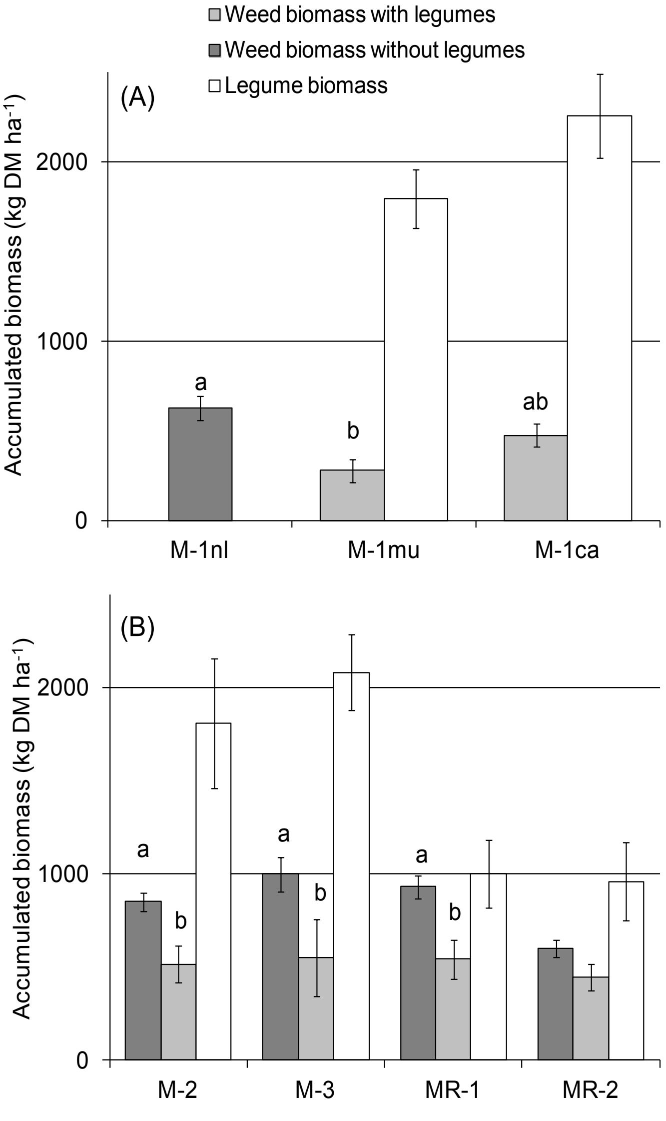

Figure 3. Mean (± SE) aboveground biomass of weeds (kg DM ha^{-1}), and legumes (kg DM ha^{-1}), (A) 2006, (B) 2007 with and without intercropping with legumes. Different letters denote significant differences between treatments ($P < 0.05$).

Table 5. Mean (± SE) percentage of dominance in ground cover by legumes, weeds, crop residues and bare soil at the end of growing season with and without intercropping with legumes.

Year	Code	Treatment	Legume	Weeds	Crop residues	Bare soil
					%	
2006	M-1mu	mucuna	36 (±6)	26 (±5)	20 (±3)	18 (±5)
	M-1ca	canavalia	61 (±3)	17 (±4)	11 (±4)	11 (±4)
	M-1nl	no legume	0	66 (±4)	28 (±4)	6 (±2)
2007	M-2	canavalia	56 (±6)	27 (±4)	14 (±3)	3 (±1)
		no legume	0	80 (±2)	13 (±2)	7 (±1)
	M-3	canavalia	54 (±5)	22 (±4)	17 (±5)	7 (±2)
		no legume	0	82 (±4)	15 (±3)	3 (±2)
	MR-1	canavalia	35 (±3)	39 (±5)	19 (±3)	7 (±3)
		no legume	0	79 (±2)	15 (±2)	6 (±2)
	MR-2	canavalia	23 (±3)	48 (±7)	10 (±2)	19 (±5)
		no legume	0	58 (±5)	19 (±4)	23 (±4)

3.5. Residual aboveground biomass and nutrient uptake

In 2006, the average difference in residual biomass between plots with legumes and without legumes was significant; in 2007 differences were smaller and not significant (Table 6).

For both years, the inclusion of legumes into the maize and maize-roselle

Table 6. Mean total remaining aboveground biomass (kg DM ha^{-1}) at the end of growing season with and without intercropping with legumes. Different letters denote significant differences due to intercropping ($P < 0.05$).

Year	Code	Residual aboveground biomass[a]			
		with legume	without legume	difference	% increase
2006	M-1mu	4818 a	3219 b	1599	33
	M-1ca	5034 a	3219 b	1815	36
2007	M-2	7889 a	6698 a	1191	15
	M-3	5668 a	4771 a	897	16
	MR-1	10168 a	8512 a	1656	16
	MR-2	4698 a	4182 a	516	11

[a] Components of remaining aboveground biomass: maize and roselle crop residues (stems and leaves), legumes and weeds.

cropping systems increased significantly total N, P and K uptake by 52, 24 and 30%, respectively (Table 7). In 2006, canavalia had a much higher N and K uptake than mucuna. In 2007, total N, P and K uptake was clearly higher with maize as monocrop (M-2 and M-3) than in the maize-roselle intercrops (MR-1 and MR-2). That difference was linked to the high amount of canavalia biomass found in maize monocrop (Figure 3b).

Table 7. Mean total N, P and K uptake (kg ha^{-1}) of biomass of maize, roselle, legumes and weeds at the end of growing season. Different letters denote significant differences due to intercropping ($P < 0.05$).

Year	Code	Total N uptake (kg N ha^{-1})		Difference (%)	Total P uptake (kg N ha^{-1})		Difference (%)	Total K uptake (kg N ha^{-1})		Difference (%)
		with legume	without legume		with legume	without legume		with legume	without legume	
2006	M-1mu	47a	34b	38	12a	9b	33	50a	35b	43
	M-1ca	70a	34b	106	12a	9b	33	61a	35b	74
2007	M-2	94a	64b	47	32a	24b	33	54a	47b	15
	M-3	71a	43b	65	16a	13b	23	41a	35b	17
	MR-1	97a	80b	21	36a	34b	6	71a	65b	9
	MR-2	52a	39b	33	14a	12b	17	29a	24b	21
Average				52			24			30

4. Discussion

The results of the study demonstrate that sowing of *Mucuna pruriens* L. var. utilis (Wall ex Wight) Burk and *Canavalia brasiliensis* Mart. ex Benth 4-6 weeks after the main crops resulted in important agro-ecological benefits in maize and maize-roselle cropping systems in the Costa Chica. Compared to conventional practice, undersowing of legumes did not result in yield loss in the main crops due to competition, weed biomass was reduced, total biomass of crop residues was higher and N, P, and K yields were increased both due to N_2 fixation from the atmosphere and enhanced N, P and K uptake from the soil. In this section we relate our findings to other reports on intercropping legumes in tropical maize, discuss the on-farm methodology and draw out consequences for cropping systems in the Costa Chica region.

4.1. Effects of intercropping legumes on main crop yields

Competition between the intercrop and the main crops maize and roselle was avoided due to delayed sowing of the legumes and low planting density of the main crops.

Appropriate choice of sowing date is a key to successful intercropping systems (Akanvou et al., 2002). Even though we did not evaluate the effects of sowing date explicitly, our results indicated that a delay in sowing of four weeks was long enough to avoid interspecific competition for light and nutrients and allow a good establishment of both maize and roselle. These results are in agreement with similar studies in different tropical environments (Gitari et al., 2000; Akanvou et al., 2002; Eilittä et al., 2003; Arim et al., 2006; Monneveux et al., 2006). Other studies showed that sowing legumes two or three weeks after maize did reduce maize yield in a number of cases (Fischler and Wortmann, 1999; Gachene, et al., 2000; Kirchhof and Salako, 2000; Chikoye et al., 2002; Mureithi et al., 2005; Lawson et al., 2007). Optimizing sowing date would require local experiments, preferably supported by model-based analyses to explore sowing strategies under different weather conditions (Kropff and Spitters, 1991).

Plant density affects both intra- and interspecific competition and has particularly a strong effect on grain yield of maize (Sangoi, 2001). Final average plant density in 2006 (3.06 m^2) and 2007 (4.27 m^2) (Table 4) was within the range of 1.8 to 5.3 m^2 found in farmers' fields (Flores-Sanchez et al., 2011). In 2006, plant density was about 30% lower compared to 2007 due to seedling losses caused by continuously heavy rainfall at the end of June and the beginning of July. The associated LAI values at anthesis of 0.8 and 2.0 (Table 4) confirm that these planting densities are low and intraspecific competition can be excluded. Currently, farmers consider higher planting densities not feasible since these would require higher inputs of fertilizers for which the required cash is not available.

The scant literature on roselle mostly reports about intercropping with legumes such as groundnut and cowpea (Sermsri et al., 1987; Fbabatunde, 2003). Fbabatunde (2003) demonstrated that roselle is more compatible with legume intercrops than with cereals probably due to light competition in the latter case. In our experiments roselle responded positively to legume intercropping in MR-1, but was just as for maize not affected in MR-2.

Experiments M-2 and MR-1 gave similar grain yields that were at least twice the average value obtained in experiments M-3 and MR-2. Legume biomass did not follow this pattern, with M-2 and M-3 having higher biomass than MR-1 and MR-2. Weed biomass did not differ between similar treatments (i.e. with and without legumes) across sites. In MR-1, roselle calyx yield was increased due to the presence of canavalia, while in MR-2, the least fertile site, maize biomass and grain yield remained low. However, the soil properties were here better for the performance of roselle. This crop tolerates a wide range of pH values, due to its tap root system has a good capacity to explore belowground sources in the deeper soil layers (McLean, 1973; Fadl and Gebauer, 2004). In view of the importance of roselle as cash crop, further elaboration of the competition in the three-crop species mixture is necessary.

4.2. Nutrient contribution to the system and nutrient uptake

The steep slopes in the study area and the predominantly sandy soils lead to a risk of nutrient runoff, and soil erosion, as well as N and K leaching losses. Legumes as catch crop can reduce nitrate (Thomsen and Christensen, 1999; Vos and van der Putten, 2004) and K leaching (Askegaard and Eriksen, 2008). In our study intercropping legumes caused an increase in accumulated total biomass of up to 36% (Table 6) and N, P and K uptake (Table 7). These findings indicate that both legumes acted not only as a N_2 fixing crop but also as a catch crop by taking up additional soil mineral N, P and K. According to expectations, aboveground biomass of canavalia and associated nutrient uptake was higher than that of mucuna. Also, NPK concentrations in the plant tissues of canavalia exceeded those of mucuna (data not shown). A deeper root system and better adaption to the marginal acid soils (Peters et al., 2003) certainly have contributed to canavalia's better performance. Comparing five annual legumes for fixation of atmospheric nitrogen, soil water uptake, soil P and nitrate recovery, effects on subsequent crops and for phosphorus recovery from Busumbu P rock, Wortmann et al. (2000) also found that canavalia produced the most biomass, fixed the most N_2, was most efficient in extraction of soil nitrate, and supplied most N to subsequent maize and bean crops.

The introduction of legumes described in this study can be seen as an example of ecological complementarity (Erskine et al., 2006; Malézieux et al., 2009). Complementarity may arise from different exploration patterns of the soil profile by the different plant species, and by the different sowing dates. In our study, overall productivity of the system increased due to the presence of the legumes because they also contributed to an increased N, P and K uptake from the soil. These findings make legumes an important tool in the studied cropping systems where N and K are the major yield limiting factors (Flores-Sanchez et al., 2011).

4.3. Legume agronomy

Canavalia accumulated 20% more biomass than mucuna in 2006, although the difference was not significant. Also because of its prostrate growth habit, canavalia was the agronomically preferred species in 2007. The climbing growth habit of mucuna was found to be unattractive by farmers, who needed to slash the vines to harvest maize as also reported by other authors (e.g. Nyende and Delve, 2004). Important for its deployment in the Costa Chica is further that canavalia as opposed to mucuna is well adapted to acid soils (Carsky et al., 2001; Kaizzi et al, 2004), and to low soil fertility conditions in general (Peters et al., 2003; Martens et al., 2008). Despite its slow initial establishment due to a high level of hardseededness, canavalia can develop an extensive root system (Alvarenga et al., 1995).

Another useful characteristic is that the leaves of canavalia remain green and turgid until well into the dry season. In our experiments the January sampling revealed fully green plants of canavalia, while mucuna was withered and dry. When canavalia is grazed it can regrow during the dry season (Douxchamps et al., 2010), thus both providing soil cover during the first rains in June and serving as a source of animal feed (Martens et al., 2008). Besides, several studies revealed that canavalia leaves contain chemical compounds which can affect the growth and development of the leaf-cutting ants, a common pest of roselle in Costa Chica, and inhibits the symbiotic fungus development of these ants (Hebling et al., 2000; Sridhar and Seena, 2006; Valderrama-Eslava et al., 2009).

Intercropping with legumes that provide similar agro-ecological benefits for the cropping systems (e.g. catch crop, soil cover etc.) but in addition also provide a source of additional income for farmers requires attention. Currently, options to sell products like beans are however limited due to lack of marketing infrastructure (Flores-Sanchez et al., 2011).

4.4. Legume effects on weed biomass

Weed biomass reduction was a clear positive benefit of intercropping legumes in maize and maize–roselle cropping systems. First year effects showed weed biomass reductions between 24 and 45% compared to the non-legume treatments. Other authors found similar or stronger effects (Skóra Neto, 1993; Akobundu et al., 2000; Favero et al., 2001; Lawson et al., 2007). In 2006, mucuna was more effective in weed reduction than canavalia. This trend may be linked to its growth characteristics. Mucuna had a relatively fast early growth followed by fast senescence. Weed suppression was linked to shading, and fallen leaves created a ground litter layer of mulch that smothered weeds. Several studies have demonstrated that residue decomposition of mucuna inhibits weed biomass growth due to allelopathic and phytotoxic compounds (L-3,4-diydroxy-phenylalanine). Thus, competition and allelopathic effects may have acted simultaneously to reduce weed biomass production (Fujii et al., 1992; Anaya, 1999; Nwaichi and Ayalogu, 2010).

Intercropping with legumes may also contribute to a long-term weed management strategy. Reliance on herbicides will decrease as a result of reduced weed seed production and a gradual depletion of viable seeds in the soil seed bank. Legume residues generally create a mulching layer that increases the physical barrier for early germination (Teasdale et al., 2007; Bastiaans et al., 2008). Such effects do require sufficient residual organic material on the soil surface at the start of the new rainy season, which not only depends on the amounts produced and the speed of decomposition (Chapter 5) but also on removal by cattle. In the Costa Chica, it is common to have animals roaming the fields in the dry season and removing organic residues.

The absence of negative effects on crop yields and the obvious reduction of weed biomass in the year of implementation constitute important prerequisites for adoption by farmers. Longer term positive effects of soil cover by organic residues on erosion and weed dynamics, and effects on physical and chemical soil fertility by larger organic matter additions to the soil remain to be investigated.

5. Conclusion

Mucuna and canavalia sown as cover crops 4-6 weeks after maize did not decrease yield of maize or roselle grown under current farmer practices in the Costa Chica. Both legumes contributed to the reduction of weed biomass. This opens up perspectives for weed management strategies with reduced number of herbicide applications. Canavalia was found to perform better than mucuna in terms of biomass accumulation, nutrient uptake, and ease of handling. We conclude that inclusion of legumes in maize cropping systems in the Costa Chica is a promising low-cost option to increase N input and reduce nutrient losses.

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Chapter 4

Comparison of organic and inorganic nutrient inputs for productivity enhancement in smallholder maize-based systems in Southwest Mexico

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Abstract

In the Costa Chica, a hilly region in Southwest Mexico, smallholder agriculture is based on continuous maize mono- and intercropping without a fallow period. Crop nutrition is based exclusively on rather intensive use of subsidized mineral NP fertilizers. Current maize grain yields are about 1500 kg ha^{-1}. Intense rainfall events account for considerable nutrient losses through runoff, erosion and leaching processes, thereby limiting an efficient use of the nutrient resources. Here we report efficacy and feasibility of alternative fertilizer management strategies. A set of experiments was conducted during the growing seasons of 2006 and 2007 on farmers' fields using randomized split-plot designs with three replicates. Different sources of nutrients (vermicompost, goat manure, mineral NP, mineral NPK and vermicompost + mineral NPK) were tested in maize monocrops and maize-roselle intercrops. Data on aboveground biomass and grain yield were evaluated by means of nutrient mass fractions, physiological nutrient use efficiencies and crop nutrient ratios. In 2006, at the same level of N input (~ 60 kg ha^{-1}), NPK tended to increase maize grain yield by 45% compared to NP (1,948 vs. 1,336 kg ha^{-1}). However, the crop recovery fraction of the applied K (24 kg ha^{-1}) was only 0.21. Maize grain yields obtained with vermicompost and goat manure, both containing less N than applied with NP, were close to 1,500 kg ha^{-1}. In 2007, highest maize grain yields were around 3,500 kg ha^{-1} and were realized with 95-10-80 kg N-P-K per ha. In both years, N and K appeared to be the most limiting macronutrients for maize production, while clear evidence was found for luxury consumption of P. Calyx yield of roselle increased almost linearly with N uptake, but was not correlated with K and P uptake. It was highest in the least fertile and most acid field, and performed well in the vermicompost treatment. It is concluded that the current subsidized fertilizer practices lead to unbalanced crop nutrition and disappointing maize grain yields. The combined use of mineral and organic fertilizers, both applied in split doses in order to reduce leaching losses of nutrients and organic matter, can equilibrate the balance between short and long-term soil fertility aims. There were strong indications that N and K losses from applied vermicompost at sowing could be reduced by using not more than 2.5 Mg ha^{-1}. Immediate improvements are to be expected from the inclusion of mineral K in the subsidized fertilizer packages.

Keywords: production ecological approach, nutrient mass fractions, physiological nutrient use efficiency, crop nutrient equivalents, nutrient proportions.

1. Introduction

In the Costa Chica, a region in the Southwest Mexican state of Guerrero, farming systems are organized in smallholder units. Maize (*Zea mays* L.) is the main staple crop and is grown mainly for self-consumption. Mostly indigenous land races (*criollos*) are cultivated either as a monocrops or intercropped with roselle (*Hibiscus sabdariffa* L.), squash (*Cucurbita pepo* L.) and common beans (*Phaseolus vulgaris* L.). Currently, crops are managed under no-till systems with widespread use of herbicides and mineral NP fertilizers. Villagers report that water quality from the rivers has decreased due to improper application of agricultural chemicals. Grain yields in the Costa Chica vary from 1,000 to 2,000 kg ha^{-1} (Gómez, et al., 2007). Traditionally, soil fertility was maintained by fallow periods but most farmers abandoned this practice in the late 1970s and started to use mineral fertilizers which were promoted by the state government to maintain crop production. State subsidies were provided for annual inputs of 69-30 kg N-P-K per hectare as ammonium sulphate and di-ammonium phosphate. Since 2007, the state government subsidizes fertilizer packages with reduced P contents, but still without the inclusion of K (Secretaría de Desarrollo Rural de Guerrero, 2007). A regional survey showed that annual application rates among farmers varied widely from 12 to 205 kg ha^{-1} for N, and 0 to 30 kg ha^{-1} for P. Along with this, preliminary agronomic analyses indicated that N and K were the most limiting nutrients (Flores-Sanchez et al., 2011). Farmers perceive that soil productivity has declined and consequently yields remain low. During the growing season rainfall exceeds crop water demand greatly. Soil erosion (2-73 Mg ha^{-1} yr^{-1}) and nutrient losses by runoff and leaching are therefore major concerns because the fields are located on sometimes even steep slopes (5-45%) (Flores-Sanchez et al., 2011). The sole use of mineral fertilizers may have led to a decline in soil organic matter content, soil acidification and soil physical degradation (Doran et al., 1996). A group of farmers, conscious of this soil degradation, was interested in a more efficient use of inputs as well as alternative sources of nutrients in order to improve soil fertility and to increase economic yields. Organic amendments were advocated as a means to improve soil fertility and increase yields since they release nutrients gradually and provide nutrients that are currently lacking in fertilization schemes (K and micronutrients) or are applied at variable rates (Palm et al., 2001). The integrated use of locally-produced organic nutrient sources with complementary mineral fertilizers has been shown to promote a more balanced crop nutrition and thus improve the overall nutrient use efficiency (Makinde, 2007). Different types of organic amendments exist in the region as raw (animal manure) or as processed materials (compost, vermicompost). Vermicompost is the end-product of an accelerated process of composting where the combination of earthworms and microorganisms degrade and refine organic matter, whilst eradicating pathogenic microbes (Lazcano et al., 2008).

In order to explore options for the nutrient management problems in the region (Flores-Sanchez et al., 2011) on-farm experiments were carried out using alternative nutrient sources in maize and maize-roselle cropping systems. In a companion paper, we report the effects of intercropping maize and maize-roselle mixtures with the leguminous species *Mucuna pruriens* L. *var. utilis* (Wall ex Wight) Burk and *Canavalia brasiliensis* Mart. ex Benth. (Flores-Sanchez et al., 2013). Here, the results are reported of a set of experiments which were conducted on-farm during two years to evaluate the effect and feasibility of alternative fertilizer strategies. Specific objectives were to evaluate the effects of mineral fertilizers, goat manure, and vermicompost applied exclusively or as combinations of vermicompost and mineral fertilizers on (a) yield of maize and roselle, (b) nutrient uptake and physiological nutrient use efficiency, (c) leaf nutrient mass fractions and (d) relations between crop nutrient proportions and physiological nutrient use efficiency. In a wider context, the study aimed at increasing the level of understanding of NPK dynamics under the poor soil conditions of the region.

2. Materials and methods

2.1. Experimental sites

Five trials were set up on farmers' fields in two communities of Tecoanapa, Guerrero, Mexico (16°48' N, 99°09' W), during the growing seasons of 2006 and 2007. Average annual temperature was 25°C. Annual rainfall, concentrated in the period between May and October, was 1,929 mm in 2006 and 1,822 mm in 2007 (Figure 1). The soils in the area are Loamy Eutric Regosols, which have a volcanic origin (SEMARNAT, 2009) and are defined by FAO (2009) as weakly developed soils with sandy loam texture. Four experimental sites were selected for the study in the communal villages Las Animas and Xalpatlahuac In each field top soil samples (0-20 cm) were taken two weeks before sowing. The soil properties analyzed were texture (Bouyoucos hydrometer), pH (1:2 soil:water), soil organic matter (SOM; wet oxidation Walkley-Black), total N (Kjeldahl-N), P (Bray-1), and K (exchangeable by ammonium acetate at pH 7.0) (Table 1). Soil organic matter contents were far below the critical level of about 28 g kg^{-1} that is required for sustained soil productivity (Janssen, 2011a). Experimental sites have been cultivated continuously for at least 15 years without fallow periods. During that time span, plant nutrients were supplied through mineral fertilizers (only N and P). Chemical characteristics of the organic fertilizers are presented in Table 2.

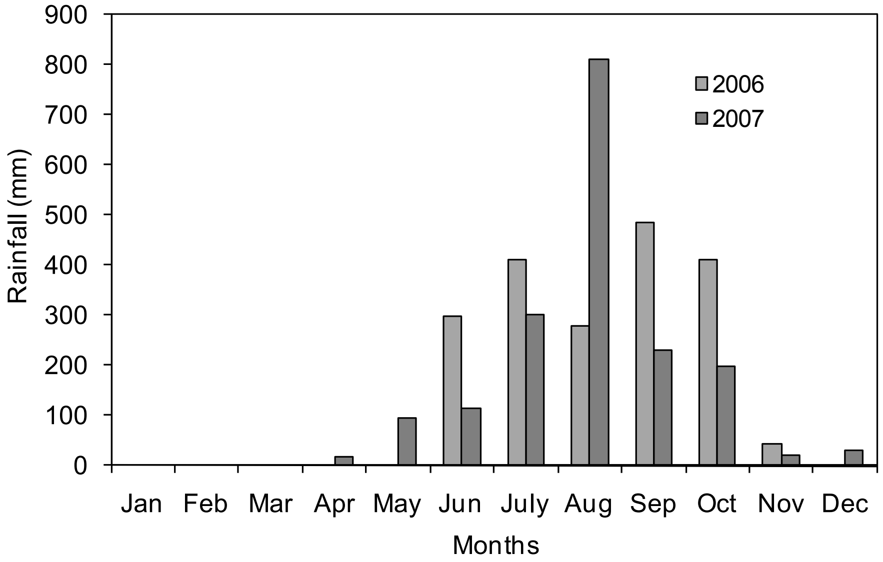

Figure 1. Rainfall distribution during 2006 and 2007 for the weather station Ayutla de Los Libres Guerrero about 30 km away from the experimental sites (*Comisión Federal de Electricidad).*

Table 1. Soil physical and chemical properties (layer 0-20 cm) in the on-farm experiments.

Year	Experiment*	Slope %	Sand	Clay	Silt	pH-H_2O	OM	N_t	Bray P-1	K
			%				g kg^{-1}		mg kg^{-1}	cmol kg^{-1}
2006	M-1	21	45	21	34	4.3	17	0.85	15	0.15
2007	M-2 and MR-1	5	51	21	28	4.3	11	0.55	15	0.30
	M-3	21	40	23	37	3.7	13	0.50	18	0.63
	MR-2	3	71	19	10	3.3	12	0.50	2	0.06

*Experiments M-1, M-3, and MR-2 were set up in the village Xalpatlahuac on different fields; experiments M-2 and MR-1 were set up in the village Las Animas on the same field.

Table 2. Chemical composition of the organic fertilizers applied in the experiments of 2006 and 2007.

Year	Organic fertilizer	Moisture content (%)	N	P	K	pH-H_2O
			g kg^{-1} (DM)			
2006	Goat manure	12	13.6	0.4	7	8.2
	Vermicompost	35	13.2	0.7	6	8.3
2007	Vermicompost	40	9.3	2.4	8	8.0

2.2. Experimental design

The trials belonged to a wider set of experiments where the effects of intercropping with leguminous crops (main plots) and nutrient supply (sub-plots) were investigated (see Flores-Sanchez et al., 2013). In this paper, the data from the main plots without legumes were used.

The experimental treatments are outlined in Table 3. In 2006, five treatments were tested in a maize monocrop: 1) vermicompost, 2) goat manure, 3) mineral fertilization with NP (corresponding to farmers´ practice), 4) mineral fertilization with NPK, and 5) unfertilized control. In the NPK treatment the rate of applied N was set equal to that in the NP treatment. This resulted in much less P than applied in the NP treatment because compound mineral fertilizers, which would have allowed equal P inputs, were not available locally. The amounts of organic fertilizers were based on an estimated average availability to the farmers of 2.5 Mg ha^{-1}. In 2007, four fertilizer experiments were established, two of which were maize intercropped with roselle. This was done in an additive design. In each experiment four treatments were evaluated: 1) vermicompost, 2) mineral fertilization with NPK, 3) vermicompost + mineral fertilization with NPK, and 4) unfertilized control. Compared to 2006, the rates of fertilizers were increased to study the maize response to higher nutrient input levels. In both years the treatments were arranged according to a randomized block design in split-plot arrangement with three replications. Individual plots comprised five rows of 5 m length at a row spacing of 1 m.

Goat manure, composed of a mixture of faeces and straw, was collected, mixed and stored by the farmers. Vermicompost was acquired from the Center of Agricultural Technological Baccalaureate No. 191 in Tecoanapa, Mexico. Vermicompost was elaborated from a mixture of goat manure, dry crop residues, grass hay and leaves of trees, and enriched with an initial amount of about 1000 earthworms (*Eisena foetida*) per m^2 added to the top layers of the compost beds. The volume of each bed was about 4m^3. Earthworms excrete most of the consumed materials in the form of worm casts which are rich in NPK, micronutrients and beneficial soil microbes (Loh et al., 2005; Sinha et al., 2008). Earthworms enhance the process of transformation of organic residues compared to conventional composting (Sinha et al., 2010). The vermicompost was watered every three days to maintain an average moisture content of 80%, thereby following recommendations for optimal growth and development of earthworms (Singh et al., 2004). Vermicompost was ready for use after three months.

Table 3. Experiments, cropping systems and treatments evaluated.

Year	Experiment	Cropping systems	Sub-plots	Code	Nutrient inputs (kg ha^{-1})		
					N	P	K
2006	M-1	Maize	Vermicompost (2.5 Mg DM ha^{-1})	V	33	2	15
			Goat manure (2.5 Mg DM ha^{-1})	GM	34	1	18
			NPK	NPK	56	2	24
			NP	NP	59	16	0
			Unfertilized	U	0	0	0
2007	M-2	Maize	Vermicompost (10 Mg DM ha^{-1})	V	93	24	80
	M-3		NPK	NPK	90	9	75
			Vermicompost (2.5 Mg DM ha^{-1}) + NPK (50-4-42)	V+NPK	73	10	62
			Unfertilized	U	0	0	0
	MR-1	Maize-roselle	Vermicompost (10 Mg DM ha^{-1})	V	93	24	80
	MR-2		NPK	NPK	97	9	81
			Vermicompost (2.5 Mg DM ha^{-1}) + NPK (55-5-46)	V+NPK	78	11	66
			Unfertilized	U	0	0	0

2.3. Experimental procedures

Experiment 2006

The maize variety used was an indigenous *criollo*, locally known as *Palmeño*. Seeds were manually sown 5 cm deep using a stick. Three seeds were sown in hills spaced at 0.7 m within the rows, corresponding to 4.3 seeds per m^2. Sowing was carried out on June 22. The herbicide paraquat was sprayed 7 days before sowing and 24 days after sowing at 1 L ha^{-1}. Vermicompost and goat manure were applied in the planting hole at sowing and covered with soil. In treatments NPK and NP the application was split into two parts: half of N and all of the P and K were applied during sowing, and the remaining N was applied 45 days after sowing. In treatment NPK the sources of nutrients were urea, di-ammonium phosphate, and potassium chloride. In treatment NP the sources of nutrients were ammonium sulphate and di-ammonium phosphate corresponding to farmers´ practice.

Experiments 2007

Maize variety and seed density were similar to 2006. Sowing took place in the last week of June. In maize – roselle intercrops, roselle was sown one week after maize at a rate of three seeds per planting hole, which was located halfway between two maize plants within a row. The herbicide paraquat was sprayed one week before sowing and three weeks after sowing at 1 L ha^{-1}. In the treatments vermicompost and vermicompost + NPK, vermicompost was applied in the planting hole before sowing. In case of maize – roselle intercrops the vermicompost was divided equally over the two crops. Mineral fertilizer application in both maize and maize – roselle was split into three parts: one third of both N and K, and all of P were applied in the second week of July; the second dose of N and K was applied in the first week of August, and the last part at the end of August. Sources of nutrients were ammonium nitrate, di-ammonium phosphate, and potassium chloride.

2.4. Data collection

Nutrient content at silking

Maize crop development was assessed in the central row of each plot. Fifteen plants were monitored regularly and dates of anthesis (at 50% of pollen shed) and silking (50% of visible silks) were recorded. When the silking stage was reached, the leaf below and opposite the ear was collected from five plants in each plot and analyzed for N, P and K.

Biomass estimation

In both years maize was harvested in the first week of November. All plants from the central row of each plot were cut at ground level except the border plants. Numbers of plants and cobs were counted to estimate densities. Aboveground fresh weight was measured in the field. Three of the harvested plants were randomly selected and oven-dried at 70^{o}C for 24 hours for DM determination. The dried plants were separated into grains and straw (i.e., leaves, stems and the core of the cobs) and analyzed for N, P and K. Cobs from the harvested row were weighed and after shelling the grains were oven-dried at 70^{o}C for 24 hours and weighed to obtain grain yield (kg DM ha^{-1}). In the maize-roselle intercrops, roselle was harvested during the first week of January. The roselle plants were cut at ground level and collected from the central row. Three plants were randomly chosen to measure DM content after oven-drying at 70^{o}C for 48 hours. Calyces were removed manually from the plants and oven-dried at 70^{o}C for 24 hours to determine yield (kg DM ha^{-1}). N, P and K contents were measured in subsamples of roselle straw (i.e., leaves and stems) and calyces. In all samples total N was analyzed by means of semi-micro-Kjeldahl procedure (Bremner, 1965). P and K were analyzed by inductively coupled plasma spectrometry (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA) (Alcántar and Sandoval, 1999).

2.5. Data Analysis

Data were analyzed following the production ecological approach in which growth- and yield-defining, - limiting and - reducing factors in agricultural production systems are disentangled (Rabbinge and Van Oijen, 1997; Kropff et al., 2001). In the current study we focused on unravelling the role of the growth-limiting macro-nutrients N, P and K.

Nutrient uptake

Total aboveground crop uptake of N, P and K was calculated by summing the uptake values of each of these nutrients in the respective yield components (grain or calyx, and straw), which in their turn were obtained by multiplying DM yield (kg DM ha^{-1}) and fractional nutrient content.

Harvest index (HI)

The harvest index of maize was calculated as the ratio of grain yield (kg DM ha^{-1}) and total aboveground biomass (kg DM ha^{-1}). In order to visualize variations in HI between the two experimental years, measured maize grain yield was related to aboveground biomass using an expolinear curve (Goudriaan and Monteith, 1990)

$$Y_g = HI_m / R_m * \ln(1 + \exp(R_m(Y_t - m))) \qquad \text{(Eq. 1)}$$

where Y_g is maize grain yield (kg DM ha^{-1}); HI_m is the maximum incremental value of the harvest index; R_m is the maximum relative increase in grain yield ; Y_t is total aboveground biomass (kg DM ha^{-1}) and m is the intercept of the curve at which the harvest index reaches the linear phase.

Parameters HI_m, R_m and m in equation (1) were fitted using nonlinear regression in SPSS V.19.

Physiological nutrient use efficiency

Physiological nutrient use efficiency (PhE) or nutrient efficiency ratio (Gourley et al., 1994; Baligar et al., 2001; Roberts, 2008)for each of the three macronutrients was calculated as grain yield (kg DM ha^{-1}) divided by the total aboveground nutrient uptake at maturity (kg ha^{-1}). The QUEFTS model, developed by Janssen et al. (1990), considers two linear borderlines for the relationship between grain yield and plant uptake of N, P and K at harvest. The lower and upper borderlines describe the yield-uptake relation at maximum accumulation and maximum dilution of N, P and K in the crop, respectively. If these lines go through the origin, their slopes represent minimum and maximum PhE, respectively. When the nutrient is maximally accumulated the yield is limited by other factors than the nutrient concerned. When the nutrient is maximally diluted, it is a yield-limiting factor. The lines for maximum accumulation and maximum dilution were derived from the maximum and minimum nutrient mass fractions (g kg^{-1}) of maize grain and straw given by Nijhof (1987). The values for grain were 9 – 22, 1.6 – 8 and 1.7 - 6 for N, P and K, respectively. For straw the values were 4 – 14, 0.4 – 4 and 4 – 24 for N, P and K, respectively. Based on these values and on the value of the harvest index (HI), the maximum ($PhE_{mx,X}$) and minimum ($PhE_{mn,X}$) values of PhE for nutrient X (i.e. N, P, or K) were calculated as:

$$PhE_{mx,X} = 1000 * HI/(HI * C_{Xg,min} + (1 - HI) * C_{Xs,min}) \qquad \text{(Eq. 2)}$$

$$PhE_{mn,X} = 1000 * HI/(HI * C_{Xg,max} + (1 - HI) * C_{Xs,max}) \qquad \text{(Eq. 3)}$$

Where HI is harvest index, C_{Xg} and C_{Xs} are the mass fractions (g kg^{-1}) of nutrient X in grain and straw, respectively; min and max denote the minimum and maximum values of mass fractions (g kg^{-1}), respectively.

Crop nutrient equivalent (CNE)

The crop nutrient equivalent (CNE) approach developed by Janssen (1998, 2011b) was applied to estimate the level of nutritional balance at two growth stages: silking and maturity. A (k)CNE is the quantity of a nutrient that, under conditions of balanced nutrition has the same effect on yield as 1 (k)g of nitrogen (Janssen, 1998). For the diagnosis of the nutrient status at silking, critical leaf N, P and K mass fraction needed for a balanced growth were taken from Hoeft and Peck (1998) since there were no available data for *criollo* varieties. These values were 29, 2.5 and 19 (g kg^{-1}) in the leaf opposite and below the ear for N, P and K, respectively. Based on these values and applying the (k)CNE approach, 1 kCNE of P was 0.086 kg and 1 kCNE of K was 0.66 kg. Janssen (2011b) denoted these as conversion factors for nutrient X (CFX), so that CFP is 0.086 and CFK 0.66. By definition CFN is 1. For the mature maize crop, first the balanced physiological nutrient use efficiency PhE_X-bal was calculated for each nutrient X as:

$$PhE_X\text{-bal} = 0.5 * (PhE_{mx,X} + PhE_{mn,X}) \qquad \text{(Eq. 4)}$$

Next, CFP was found as the ratio PhE_N-bal/PhE_P-bal and CFK as the ratio PhE_N-bal/PhE_K-bal.

For balanced PhE, the conversion factors of CFP ranged between 0.12 and 0.17 (Figure 2A), while for CFK the values varied between 0.57 and 1.09 (Figure 2B). Both conversion factors depended on harvest index.

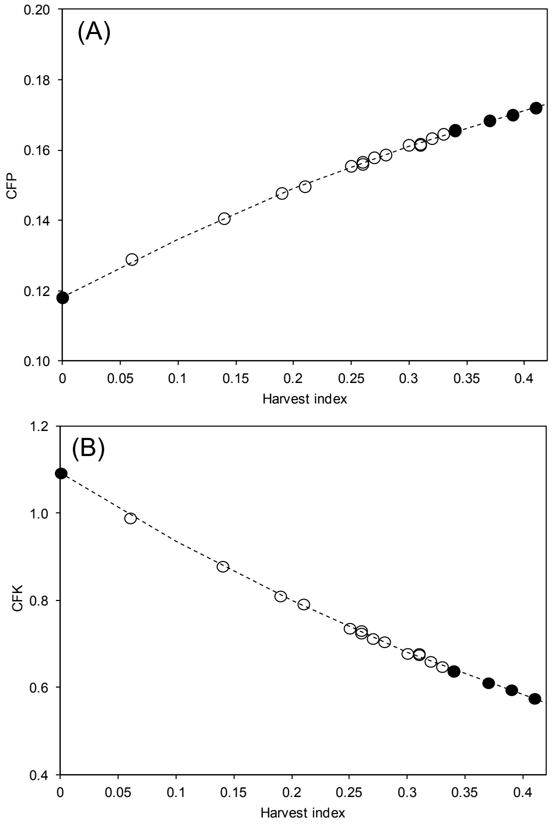

Figure 2. (A) Factors for the conversion of 1 kg of P into kCNE (CFP), and (B) factors for the conversion of 1 kg of K into kCNE (CFK) in relation to the harvest index. ● 2006 measurements, ○ 2007 measurements. (− −) Regression fit (A) $Y=-011x^2+0.18x+0.12$. ($R^2=0.99$) (B) $Y=0.98x^2-1.66x+1.09$ ($R^2=0.99$. It is assumed that nutrient mass fractions have the minimum and maximum values as presented by Nijhof (1987).

In both cases (silking stage and mature harvest), the values of N, P and K expressed in kg were divided by their respective factors, and the resulting values expressed in kCNE were divided by the sum (N + P + K), in order to obtain the proportion of each nutrient in the total NPK uptake. The proportions are henceforth denoted as FN, FP and FK. In case of optimum plant nutrition, FN = FP = FK = 33.3%.

Statistical analysis

The data were analysed in two steps. First, for both years a one-way analysis of variance was performed to test the effect of treatments in each experiment. Second, for 2007 an analysis of variance was used to contrast treatments and experiments. In both steps means separation was done when the F-test indicated significant (P<0.05) differences using Tukey's studentized range HSD test. Statistical analyses were performed with SPSS V.19.

3. Results

3.1 Maize grain yield, aboveground biomass production and harvest index

Maize grain yields obtained in 2006 and 2007 are presented in Table 4. In 2006, maize grain yield ranged from 1,336 to 1,948 kg ha^{-1} in the treatments receiving nutrient amendments. The fertilized treatments did not differ significantly, but the maize crop in the unfertilized control failed to produce any grain. Grain yields were disappointing with only NP, on average 1,336 kg ha^{-1}. Despite an almost 50% lower input rate of N, vermicompost and goat manure resulted in maize grain yields similar to that obtained with NP. In 2007, grain yields ranged from 66 to 3,648 kg DM ha^{-1}, and aboveground biomass varied between 1,035 and 10,335 kg DM ha^{-1}. Significant differences were found among treatments and among experiments. Total NPK input levels varied among treatments, but never exceeded differences of 23% for each of the individual nutrients. Nevertheless, measured maize grain yields differed up to more than a factor

Table 4. Mean maize grain yield, total aboveground biomass (kg DM ha^{-1}) and harvest index**.** Different letters indicate significant (P < 0.05) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

Characteristic	Treatment	2006	2007				
		M-1	M-2	M-3	MR-1	MR-2	*Average**
Grain yield	V	1562a	2027ab	474b	2703ab	575bc	*1445B*
	NPK	1948a	3318a	1942a	3647a	913ab	*2455A*
	V + NPK		2604ab	1811a	3510a	1239a	*2291A*
	NP	1336a					
	GM	1426a					
	U	0b	1426b	299b	1476b	66c	*816C*
	Average	*1255*	*2344A*	*1132B*	*2834A*	*698B*	
Total aboveground biomass	V	3826a	7535a	2348b	9627ab	2722ab	*5558B*
	NPK	5246a	9648a	6211a	10981a	3596a	*7609A*
	V + NPK		8305a	6985a	10335a	4109a	*7433A*
	NP	3797a					
	GM	3637a					
	U	1238b	4676b	1981b	5959b	1035b	*3413C*
	Average	*3549*	*7541B*	*4381C*	*9225A*	*2866D*	
Harvest index	V	0.41a	0.27a	0.19ab	0.28a	0.21b	*0.24BC*
	NPK	0.37a	0.34a	0.32a	0.33a	0.25ab	*0.31A*
	V + NPK		0.31a	0.26ab	0.34a	0.30a	*0.30AB*
	NP	0.34a					
	GM	0.39a					
	U		0.31a	0.14b	0.26a	0.06c	*0.19C*
	Average	*0.30*	*0.31A*	*0.23AB*	*0.30A*	*0.21B*	

* Values refer only to averages of 2007.

of seven in the fertilized treatments. Lowest responses were obtained for vermicompost on the two fields in the village Xalpatlahuac. These fields were characterized by an extremely low value of soil pH (experiments M-3 and MR-2, Table 1).

The relationship between total aboveground maize biomass and grain yield was described well with Eq. 1 for each of the two years separately (Figure 3). The maximum incremental value of the harvest index appeared to be 0.46 for the 2006 data, whereas this was 0.35 in 2007. The x-intersect (Y_t) estimated with the expolinear model was 850 kg ha^{-1} for 2006, and 1,098 kg ha^{-1} for 2007. Following the terminology presented by Goudriaan and Monteith (1990) this may be referred to as the 'lost' biomass.

3.2. Nutrient mass fractions in crop components

K mass fractions in the maize leaf opposite and below the ear at silking stage (Table 5) were all below the minimum content for a good maize plant growth of 19 g kg^{-1} (Hoeft and Peck, 1998). Average N mass fractions were only clearly lower than the critical value of 29 g kg^{-1} in the 2007 experiments M-3 and MR-2. In 2006, P mass fractions in all treatments were about 20% lower than the critical value of 2.5 g kg^{-1}, whereas in 2007 they were all close to it.

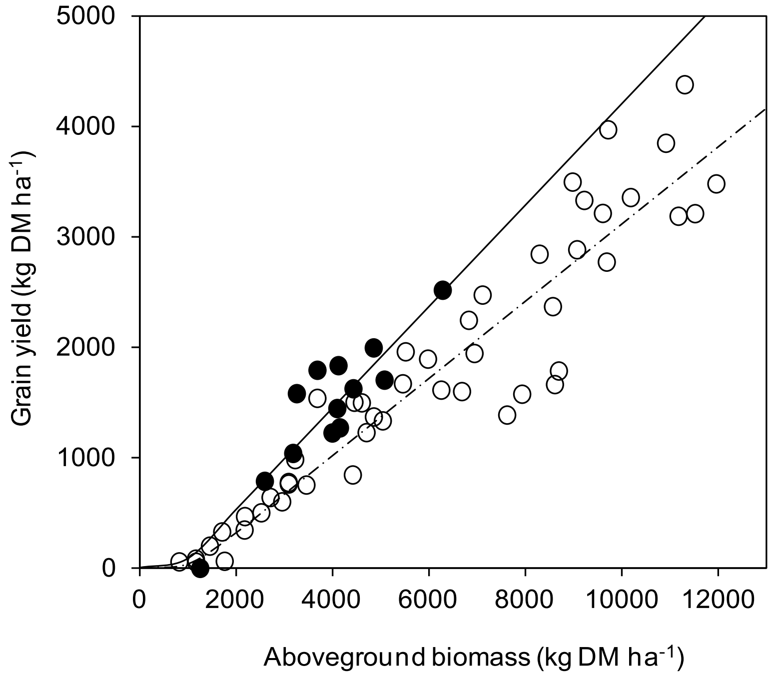

Figure 3. Relationship between maize total aboveground biomass (kg DM ha^{-1}) and maize grain yield (kg DM ha^{-1}). ● 2006 measurements, (—) expolinear fit $Y_g = (0.46/0.0079) * \ln(1+\exp(0.0079*(Y_t - 850)))$; ○ 2007 measurements, (– ·–) expolinear fit $Y_g = (0.35/0.005)*\ln(1+\exp(0.005*(Y_t - 1098)))$.

Table 5. Mean mass fractions of N, P and K (g kg^{-1}) in the leaf opposite and below the ear at silking. Different letters indicate significant ($P < 0.05$) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

Nutrient	Treatment	2006	2007				
Mass fraction g kg^{-1}		M-1	M-2	M-3	MR-1	MR-2	*Average**
N	V	25.5a	22.6b	17.2a	27.2a	19.7a	*22A*
	NPK	30.0a	33.5a	27.2a	31.5a	19.6a	*28A*
	V + NPK		30.5ab	26.5a	34.9a	20.2a	*28A*
	NP	27.6a					
	GM	28.2a					
	U		25.2ab	18.7a	25.2a	19.9a	*22A*
	Average	*28*	*28A*	*22B*	*30A*	*20B*	
P	V	2.1a	3.0a	2.2a	3.3a	3.2a	*3A*
	NPK	2.1a	3.1a	2.6a	2.3a	2.0b	*2A*
	V + NPK		2.4a	3.1a	1.5a	2.6ab	*2A*
	NP	1.9a					
	GM	1.7a					
	U		2.2a	2.5a	2.6a	2.1ab	*2A*
	Average	*2*	*3A*	*3A*	*2A*	*2A*	
K	V	15.0a	10.8a	7.9a	10.1a	11.1a	*10A*
	NPK	15.4a	11.1a	11.3a	10.8a	12.4a	*11A*
	V + NPK		9.0a	13.9a	10.6a	10.6a	*11A*
	NP	15.5a					
	GM	14.3a					
	U		8.6a	9.9a	8.5a	12.5a	*10A*
	Average	*15*	*10A*	*11A*	*10A*	*12A*	

* Values refer only to averages of 2007.

The average N and K mass fractions in maize straw and grain at harvest were around the minimum values (4 g kg^{-1} in straw for both N and K, and 9 and 1.7 g kg^{-1} in grain for N and K, respectively) proposed by Nijhof (1987) (Table 6). However, the P mass fractions in straw and grain were all well above the minimum values (0.4 and 1.6 g kg^{-1}, respectively). Significant differences were found among treatments and experiments. N mass fraction in straw was higher in vermicompost and unfertilized treatments, while K mass fraction was increased in NPK and V+NPK treatments. N mass fraction in grain was also higher in NPK and V+NPK treatments. Experiments M-1 and MR-1 presented the highest N and K mass fractions in grain, and were significantly different from the other two experiments, while experiments M-3 and MR-2 presented the highest N mass fraction in straw.

3.3. Nutrient uptake and physiological nutrient use efficiency

Uptake of the three nutrients (Table 7) from the fertilized plots was two or more times higher than from the unfertilized control (U). Significant differences were found among treatments and experiments. In general the uptake was highest with NPK and V+NPK.

Table 6. Mean mass fractions of N, P and K (g kg^{-1}) in maize straw and grain at harvest. Different letters indicate significant ($P < 0.05$) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

Nutrient	Treatment	2006	2007				
		M-1	M-2	M-3	MR-1	MR-2	Average*
Straw (g kg^{-1})							
N	V	3.5b	4.7a	5.2a	4.7a	5.0a	*4.9A*
	NPK	4.0b	3.7b	4.3ab	3.7b	5.0a	*4.2B*
	V + NPK		4.0ab	4.3b	4.0ab	5.0a	*4.3B*
	NP	4.8b					
	GM	4.0b					
	U	9.4a	4.5ab	5.1ab	4.5ab	5.0a	*4.8A*
	Average	*5.2*	*4.2B*	*4.7A*	*4.2B*	*5.0A*	
P	V	1.1b	1.2a	2.0a	1.2a	2.1a	*1.6A*
	NPK	0.7b	0.9a	1.1a	0.9a	2.4a	*1.3A*
	V + NPK		1.1a	0.9a	1.1a	2.1a	*1.3A*
	NP	1.0b					
	GM	1.1b					
	U	2.1a	0.9a	1.6a	0.9a	2.1a	*1.4A*
	Average	*1.2*	*1.0B*	*1.4B*	*1.0B*	*2.2A*	
K	V	6.5ab	3.9a	5.4a	3.9a	4.5a	*4.4AB*
	NPK	5.1b	5.3a	5.5a	5.3a	4.5a	*5.2A*
	V + NPK		6.0a	5.4a	6.0a	4.2a	*5.4A*
	NP	5.8ab					
	GM	6.2ab					
	U	9.6a	3.3a	4.5a	3.3a	4.5a	*3.9B*
	Average	*6.6*	*4.6A*	*5.2A*	*4.6A*	*4.4A*	
Grain (g kg^{-1})							
N	V	11.8a	11.0a	10.8a	11.0a	10.9a	*10.9B*
	NPK	11.8a	11.3a	11.1a	11.3a	10.9a	*11.1A*
	V + NPK		11.2a	11.1a	11.2a	10.9a	*11.1A*
	NP	12.6a					
	GM	11.9a					
	U		11.0a	10.8a	11.0a	10.9a	*10.9B*
	Average	*12.0*	*11.1A*	*10.9B*	*11.1A*	*10.9B*	
P	V	3.2a	2.4a	2.2a	2.4a	3.6a	*2.7A*
	NPK	2.5a	2.9a	2.9a	2.9a	2.5a	*2.8A*
	V + NPK		2.8a	2.6a	2.8a	2.5a	*2.7A*
	NP	2.9a					
	GM	3.2a					
	U		2.4a	2.8a	2.4a	2.9a	*2.6A*
	Average	*3.0*	*2.6A*	*2.6A*	*2.6A*	*2.9A*	
K	V	4.6a	3.1a	2.8a	3.1a	3.8a	*3.2A*
	NPK	3.4a	3.5a	2.8a	3.5a	3.0a	*3.2A*
	V + NPK		3.4a	1.8a	3.4a	2.6a	*2.8A*
	NP	3.5a					
	GM	4.0a					
	U		3.0a	2.6a	3.0a	2.1a	*2.7A*
	Average	*3.9*	*3.3A*	*2.5B*	*3.3A*	*2.9AB*	

Reference values (g kg^{-1}): Straw N: 4 - 14, P: 0.4 – 4, K: 4 - 24. Grain N: 9 - 22, P: 1.6 – 8, K: 1.7 – 6. Source: Nijhof (1987).

* Values refer only to averages of 2007.

Table 7 Mean total uptake of N, P and K (kg ha^{-1}) and physiological nutrient use efficiency (PhE) for N, P and K (kg kg^{-1}), calculated as: grain yield (kg ha^{-1}) / uptake (kg ha^{-1}). Different letters indicate significant ($P < 0.05$) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

Nutrient	Treatment	2006	2007				
Uptake kg ha^{-1}		M-1	M-2	M-3	MR-1	MR-2	Average*
N	V	26a	48ab	15b	60a	17ab	*35B*
	NPK	36a	61a	39a	69a	23a	*48A*
	V + NPK		52a	42a	64a	28a	*47A*
	NP	29a					
	GM	26a					
	U	12b	30b	12b	37b	6b	*21C*
	Average	*26*	*48B*	*27C*	*58A*	*19D*	
P	V	8a	11ab	5ab	15ab	6a	*9B*
	NPK	8a	15a	10a	19a	9a	*13A*
	V + NPK		13a	9ab	21a	9a	*13A*
	NP	7a					
	GM	7a					
	U	3a	6b	4b	10b	2a	*6C*
	Average	*7*	*11B*	*7C*	*17A*	*7C*	
K	V	60a	28bc	12bc	43a	12a	*24AB*
	NPK	24a	45a	28ab	53a	15a	*36A*
	V + NPK		43ab	30a	55a	15a	*36A*
	NP	19a					
	GM	20a					
	U	12a	15c	8bc	32ab	4a	*15B*
	Average	*19*	*33B*	*20C*	*46A*	*12C*	
PhE (kg kg^{-1})							
N	V	60a	42a	30ab	45a	33a	*38B*
	NPK	54a	54a	50a	53a	39a	*49A*
	V + NPK		49a	42ab	55a	45a	*48A*
	NP	45a					
	GM	55a					
	U	0	47a	24b	41a	12b	*31B*
	Average	*54*	*48A*	*36B*	*48A*	*32B*	
P	V	203a	182a	95b	173a	87a	*134BC*
	NPK	270a	219a	192a	189a	132a	*183A*
	V + NPK		198a	199a	174a	146a	*179AB*
	NP	204a					
	GM	198a					
	U	0	223a	81b	142a	35a	*120C*
	Average	*219*	*205A*	*141BC*	*169AB*	*89C*	
K	V	74a	76a	39a	63a	55a	*58A*
	NPK	91a	75a	74a	70a	61a	*70A*
	V + NPK		60a	60a	70a	83a	*68A*
	NP	68a					
	GM	79a					
	U	0	101a	37a	60a	15b	*53A*
	Average	*78*	*78A*	*53A*	*66A*	*53A*	

* Values refer only to averages of 2007.

Table 7 also presents the values of physiological nutrient use efficiency (PhE) for N, P and K, calculated as grain yield/nutrient uptake (kg kg^{-1}). In 2006, no significant differences were found among treatments, but in 2007 PhE_P and PhE_K were higher in the NPK treatment.

PhE_N and PhE_P differed significantly among experiments. In experiments M-3 and MR-2, PhE_N in fertilized treatments was significantly higher than in the control, while in experiment M-3 this was also true for PhE_P.

Figures 4 A-C show the relations between PhE_X and HI as calculated with the three equations in Table 8 for maximum, maximum and balanced PhE's. The measured points for PhE_N and PhE_K were all between the maximum and the balanced values, and those for PhE_P were all between the minimum and the balanced values, indicating that N and K were in short supply and P was available in relative excess.

The results obtained for roselle in experiments MR-1 and MR-2 demonstrated that calyx yield was primarily driven by the total crop uptake of N (Figures 5A-C). Also total aboveground biomass of roselle was closely related to N uptake (Figures 5D-F). Although the levels of nutrient uptake and crop yield were relatively low, it is apparent that roselle performed better than maize on the pure vermicompost treatment.

Overall, when comparing Figures 4 and 5, maize grain yield was predominantly limited by N and K supply and roselle calyx yield was mainly determined by N supply.

3.4 Crop nutrient equivalent (CNE) at silking and maturity

The fractions of the sum of nutrients expressed in CNE in the leaf opposite and below the ear at silking are presented in Table 9. Across experiments, FP values were highest, and FK values were lowest, especially in the control and vermicompost treatments. In 2007, only in MR-1 and MR-2 significant differences were found for the sum of P and K, respectively (Table 9). FN and FK were significantly different among experiments. K deficiency was least pronounced in MR-2 (Figure 6E), but this was accompanied by the lowest maize grain yield of all experiments due to a very restricted NPK uptake and low PhE's (Table 7).

Table 8. Equations for estimating, maximum, minimum and balanced PhE of N, P and K (kg kg^{-1}); x denotes harvest index (HI).

PhE	N	P	K
Maximum	$Y=-136.74x^2+219.03x+1.33$	$Y=-1482.4x^2+1666.3x+32.49$	$Y=245.75x^2+224.78x+1.25$
Minimum	$Y=-26.85x^2+68.68x+0.12$	$Y=-125.98x^2+227.26x+0.99$	$Y=65.18x^2+32.93x+0.44$
Balanced	$Y=-81.80x^2+143.85x+0.73$	$Y=-804.17x^2+946.78x+16.74$	$Y=155.46x^2+128.85x+0.84$

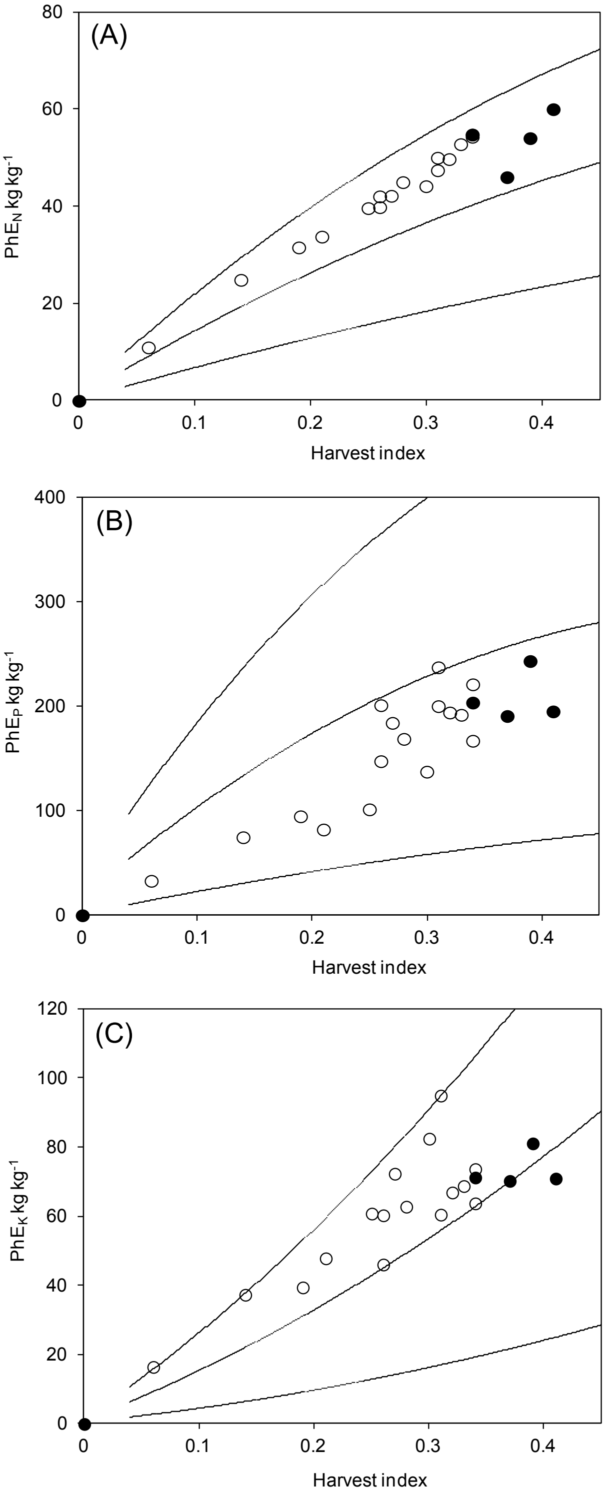

Figure 4. Relationship between PhE_X (x = N, P or K) and HI (A) N, (B) P and (C) K. ● 2006 measurements, ○ 2007 measurements. (− −) The upper lines represent the maximum PhE_X and the lower lines the minimum PhE_X. (---) Mid-way line represents balanced PhE_X. The lines were fitted using Eq. 2, 3 and 4.

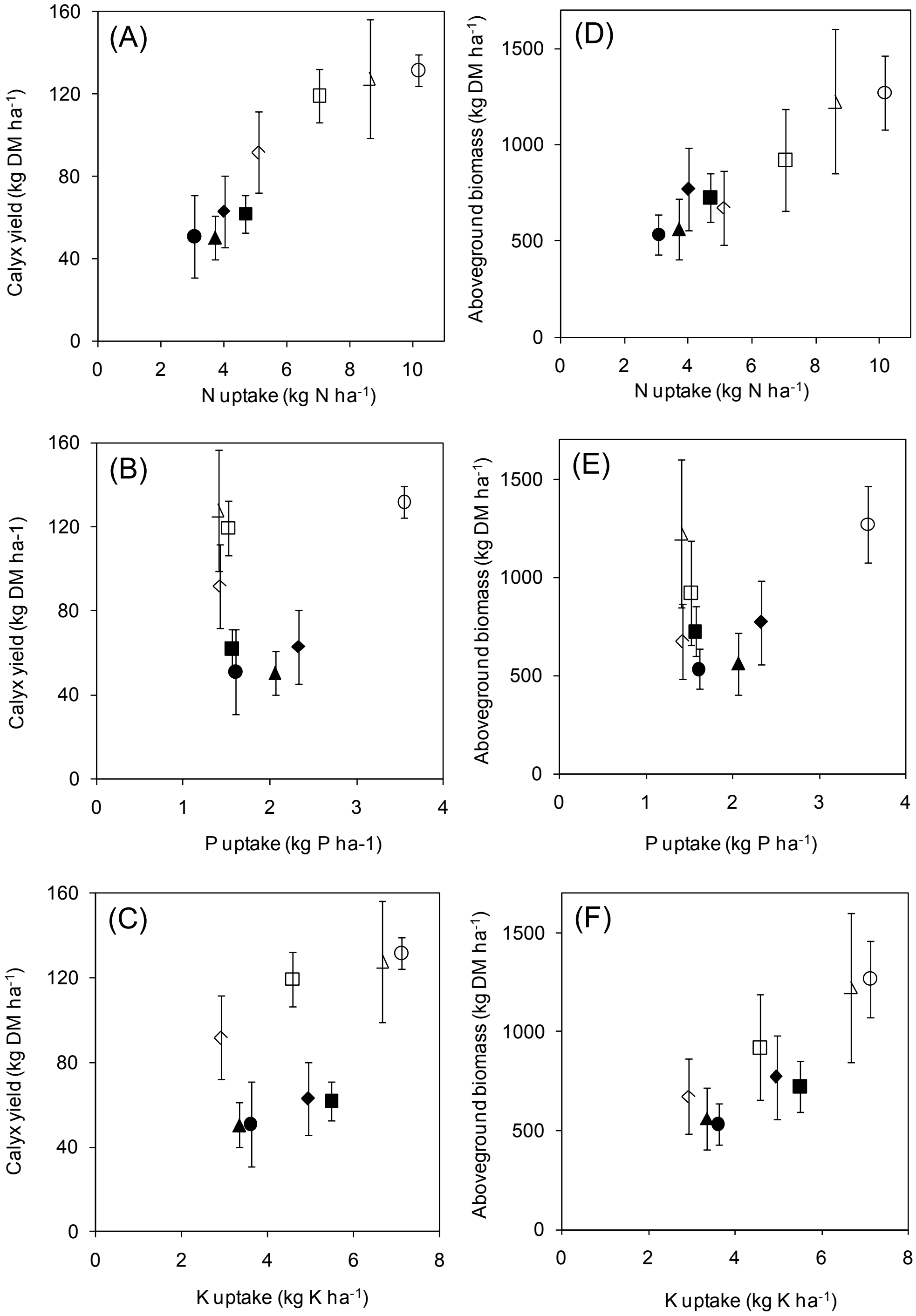

Figure 5. Relationship between roselle calyx yield (kg DM ha^{-1}) and total roselle aboveground NPK uptake (kg DM ha^{-1}) (A) N, (B) P and (C) K, and relationship between total roselle aboveground biomass (kg DM ha^{-1}) and total roselle aboveground NPK uptake (kg DM ha^{-1}) (D) N, (E) P and (F) K in 2007. Legends: MR-1 ● V, ▲NPK, ■ V + NPK, ♦ U. MR-2 ○ V, Δ NPK, □ V + NPK, ◊ U. Bars represent standard errors.

Table 9. Mean N, P and K fractions (F, %) in the sum of NPK in the leaf opposite and below the ear at silking. Different letters indicate significant ($P < 0.05$) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

Nutrient	Treatment	2006	2007				
		M-1	M-2	M-3	MR-1	MR-2	*Average**
F (% of SUM)							
N	V	35a	32a	33a	35a	27a	*32A*
	NPK	39a	44a	32a	51a	32a	*40A*
	V + NPK		43a	37a	44a	32a	*39A*
	NP	38a					
	GM	40a					
	U		40a	31a	41a	32a	*36A*
	Average	*38*	*40AB*	*33B*	*43A*	*31BC*	
P	V	33a	45a	45a	46a	50a	*47A*
	NPK	30a	38a	42a	25b	43ab	*37B*
	V + NPK		38a	40a	37ab	37a	*38B*
	NP	30a					
	GM	27a					
	U		40a	44a	40ab	37b	*40AB*
	Average	*30*	*40A*	*43A*	*37A*	*42A*	
K	V	32a	23a	22a	19a	23b	*22A*
	NPK	30a	18a	26a	24a	25b	*23A*
	V + NPK		19a	23a	19a	31a	*23A*
	NP	32a					
	GM	32a					
	U		20a	25a	19a	31a	*24A*
	Average	*32*	*19B*	*24A*	*20B*	*27A*	

* Values refer only to averages of 2007.

Nutrient proportions of N, P and K in the reference leaf are presented in Figure 6. In 2006, little variation was found among treatments and nutrient proportions tended to be balanced, i.e. close to 33.3% (Figure 6A). In 2007, nutrient proportions were less balanced (Figures 6B-E). FP was on average high (~40%), FK low (~23%), whereas average FN was with about 37% just below FP (Table 9). Highest FN values were found in treatments NPK and V+NPK of experiments M-2 and MR-1 and these all exceeded the FP levels.

In both years, the sum of the uptake of N, P and K (kCNE ha^{-1}) showed significant differences among treatments (Table 10). In 2006, the highest values were found in V and NPK treatments, while in 2007 this was the case for the NPK and V+NPK treatments. Comparisons among experiments showed significant differences. MR-1 presented the highest sum of uptake, and M-3 and MR-2 the lowest values.

In both years, FN, FP and FK of the total aboveground maize biomass at maturity were in all cases unbalanced (Table 10, Figure 7). Whereas FP always exceeded the optimum value of 33.3% and thus was never a limiting nutrient, FN and FK had each in about half of cases the lowest values (Table 10). In 2006, nutrient proportions in the maize monocrops were best balanced with the fertilizer strategy NPK (Figure 7A), whereas in 2007 balanced proportions were best approached with

V+NPK (Figures 7B and 7C).

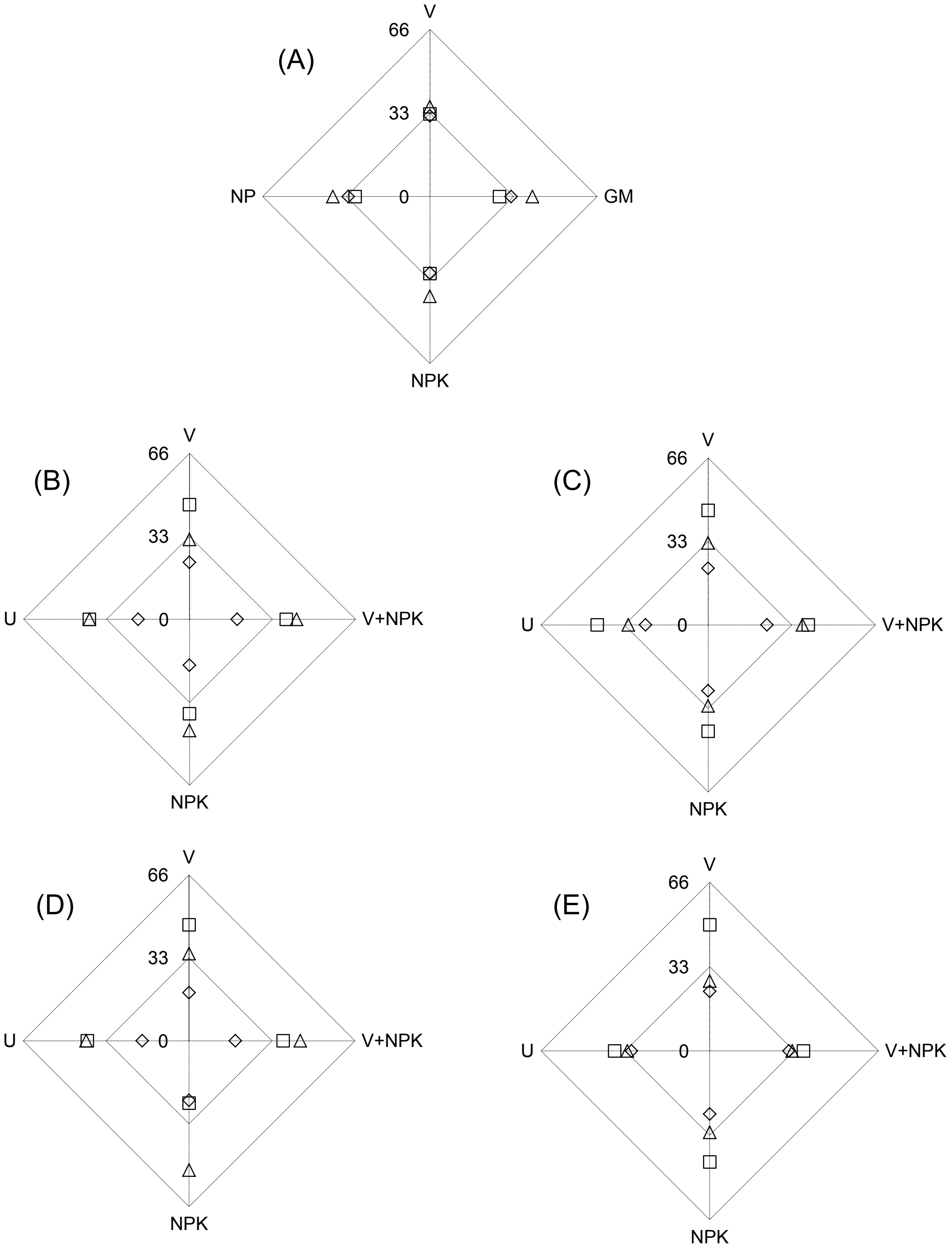

Figure 6. N, P and K in the maize leaf opposite and below the ear at silking stage, expressed as percentage (FN, FP, FK) of total kCNE. (A) M-1, (B) M-2, (C) M-3, (D) MR-1 and (E) MR-2. Legends: Δ N, □ P, ◊ K. The straight lines between the various treatments represent 33.3 and 66.7% of the kCNE sum of N, P and K.

Table 10. Mean values of total kCNE ha^{-1} and mean percentages of the sum of FN, FP and FK (% of SUM) in the total aboveground maize biomass. Different letters indicate significant ($P < 0.05$) differences. For 2006 and 2007 lower-case letters denote differences among treatments within each experiment. For 2007 upper-case letters denote differences among treatments and experiments.

	Treatment	2006	2007				
		M-1	M-2	M-3	MR-1	MR-2	Average*
kCNE ha^{-1}	V	109ab	158ab	62b	220ab	77a	*129B*
	NPK	120a	223a	145a	269a	103a	*185A*
	V + NPK		200a	143a	275a	105a	*181A*
	NP	100ab					
	GM	101ab					
	U	44b	91b	46b	146b	28a	*78C*
	Average	*95*	*68B*	*99C*	*227A*	*78C*	
% of SUM							
N	V	24a	31a	24a	27a	23a	*27A*
	NPK	32a	26a	28a	26a	25a	*26A*
	V + NPK		27a	30a	24a	27a	*26A*
	NP	30a					
	GM	26a					
	U	26a	33a	26a	25a	21a	*26A*
	Average	*28*	*29A*	*27AB*	*26AB*	*24B*	
P	V	41ab	44a	53a	44a	58a	*50A*
	NPK	37b	41a	43b	44a	53a	*45A*
	V + NPK		41a	41b	46a	52a	*45A*
	NP	40ab					
	GM	42ab					
	U	50a	44a	54a	47a	61a	*51A*
	Average	*41*	*43B*	*47B*	*45B*	*56A*	
K	V	35a	25b	23ab	29a	19a	*24AB*
	NPK	31a	33a	29a	30a	22a	*28A*
	V + NPK		32a	29a	31a	21a	*28A*
	NP	30a					
	GM	32a					
	U	24a	24b	20b	28a	18a	*23B*
	Average	*32*	*28A*	*26A*	*29A*	*20B*	

* Values refer only to averages of 2007.

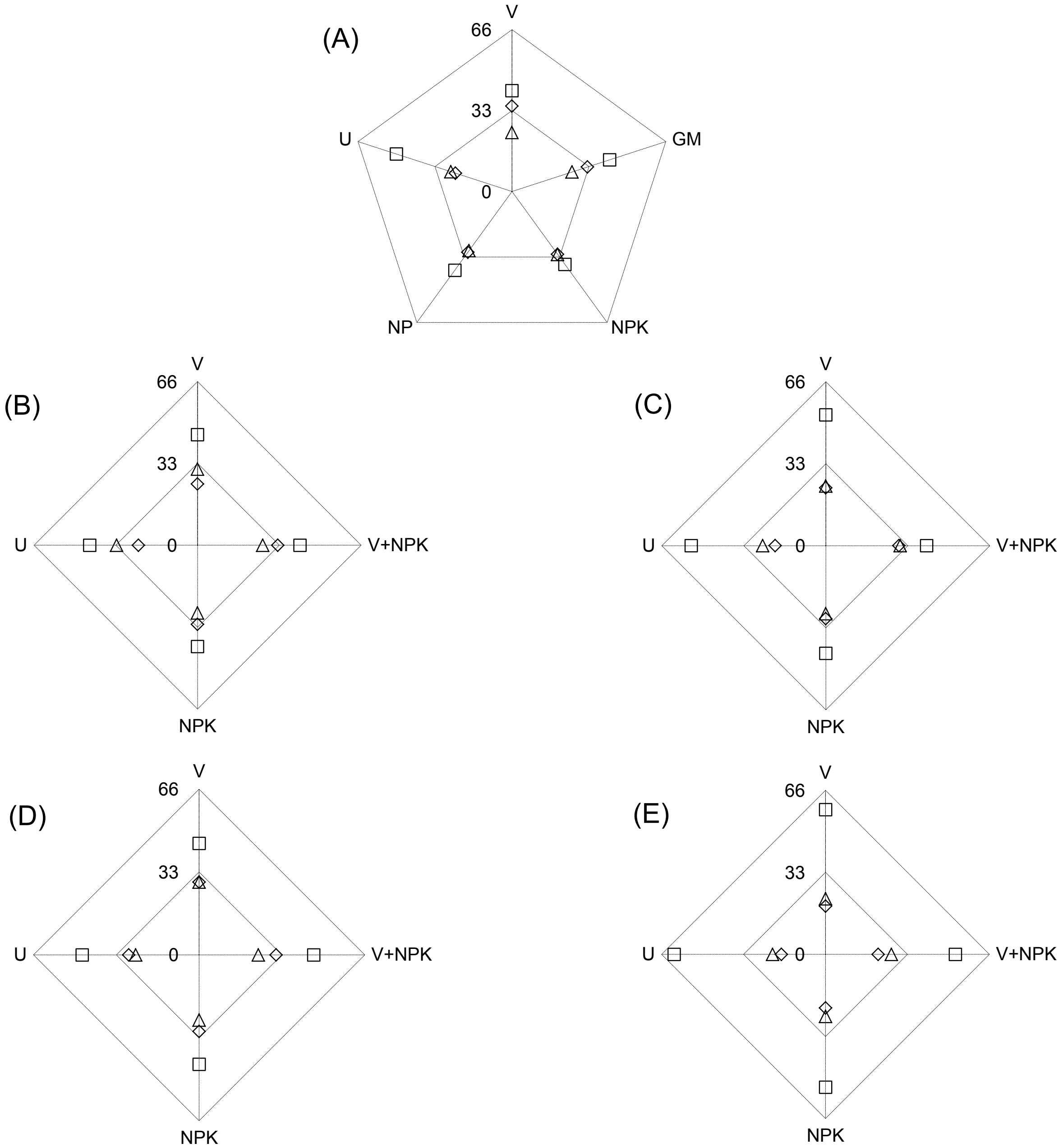

Figure 7. N, P and K in the aboveground maize biomass at harvest, expressed as percentage (FN, FP, FK) of total kCNE. (A) M-1, (B) M-2, (C) M-3, (D) MR-1 and (E) MR-2. Legend: Δ FN, □ FP, ◊ FK. The straight lines between the various treatments represent 33.3 and 66.7% of the kCNE sum of N, P and K.

4. Discussion

Five replicated fertilizer experiments were carried out in farmers' fields with diverging soil properties. Our experimental plots and number of harvested plants were relatively small, but were sufficient to arrive at clear conclusions. In our analysis we implemented elements of the production ecological approach (van Ittersum and Rabbinge, 1997) in order to be able to present a yield gap analysis. In the region of our study rainfall greatly exceeds crop water requirements during the growing season. Therefore, we focussed mainly on the three macro-nutrients N, P and K. Growth-reducing effects due to weed competition could be excluded from the analysis since they were limited as a result of the two herbicide applications during the first month of maize growth. Average weed biomass over the experiments was only 776 kg ha^{-1} which was about 30% lower than found in farmers' fields (Flores-Sanchez et al., 2011)

4.1 Relations between maize yield and soil properties

Grain yields ranged between 0 and 3647 kg DM ha^{-1}. Using the crop growth model LINTUL (adapted from Farré et al., 2000) a potential grain yield of 8,500 kg DM ha^{-1} could be simulated with a harvest index of 0.35 (data not shown). This holds for the situation where nutrients and water are non-limiting and pests, diseases and weeds are effectively controlled. However, in this crop growth model plant density is not a limiting factor. In our experiments we followed the practices of the farmers aiming at a plant density of about 4.5 plants m^{-2}. Under the given conditions they consider this as the optimum density for attaining the highest harvestable grain yield per ha with the local variety used. This plant density is only slightly below the technical recommendations (4.7 plants m^{-2}) for the agro-ecological conditions of the region (marginal soils, traditional crop management). Under optimal conditions (flat lands, fertile soils, access to machinery and hybrids) plant density can be up to 6.2 plants m^{-2} (INIFAP-SAGARPA, 2007). In other studies under more or less similar conditions but on well-fertilized soils, and with plant density of 5.3 plants m^{-2}, maize grain yields up to 8,500 kg DM ha^{-1} have been observed in Mexico (Goldsworthy and Colegrove, 1974; Pandey and Gardner, 1992). This all suggests that in the studied area there is still abundant room for yield improvement through agronomic practices.

The soil of experiment M-1 had the same pH and OM/Nt ratio as the soil of M-2, but M-1 was situated on a much steeper slope (Table 1) which might have affected maize yields negatively due to run-off and erosion losses. As can be seen in Table 4, soil productivity in 2007 decreased in the order: MR-1 > M-2 > M-3 > MR-2. The yields of MR-1 and M-2 were almost equal, because these experiments were carried out in the same field. The lower yields in experiments M-3 and MR-2 were most likely caused by the lower pH and the higher OM/Nt ratio of these soils compared to those of the soil of M-2 and MR-1. It is well established that a low soil pH affects nutrient availability, which in its turn is correlated with the composition and the activity of the microbial community (Marschner et al., 2004). Through the addition of compost both soil pH and mineral N availability are generally increased (Högberg et al., 2007; Onwonga et al., 2008; Khoi et al., 2010).

In Figure 8, maize grain yields of treatments U, V, NPK and V+NPK are plotted against applied N, P and K for the average results of experiments M-2 and MR-1 (soil pH-H_2O = 4.3), as well as those of experiments M-3 and MR-2 (average soil pH-H_2O = 3.5). Regression lines refer to the data of the U, NPK and V+NPK treatments. Three out of four experiments were carried out on different locations and this analysis clearly showed that yields were negatively affected in the fields with lowest soil-pH. Yields in the vermicompost treatment were all far below the regression lines. On the other hand, the combined application of mineral NPK and vermicompost appeared to be very promising since this was just as efficient as NPK alone. Besides, the use of vermicompost has potential long-term effect on building up SOM. According to Table 3, applied amounts of vermicompost in the two V+NPK treatments were only 25% of those in the V treatments, whereas input rates of mineral N and K were reduced by about 20% compared to pure NPK.

In 2007, 60% of the total rainfall amount (1100 mm out of 1760 mm) was concentrated in the months of July and August (Figure 1), when the nutrient uptake capacity of the maize crop was still limited. This excess amount of water might have caused mobile nutrients such as N and K to leach or run off more than in 2006. Besides, experimental evidences regarding N release from vermicompost (Chapter 5) showed that in 2007 already 67% of the total N disappeared from litterbags during the first 30 days of the growing season. This implies that also N mineralized from this organic fertilizer applied at sowing was prone to leaching at relatively high input rates. However, by using only 2.5 Mg DM ha^{-1} vermicompost in the V+NPK treatments, N and K leaching losses seemed to be curtailed.

It was not possible to calculate crop recovery fractions of the applied N, P and K with the exception of one case. In all other cases the three nutrients were applied together. From Tables 3 and 7 it can be calculated that the apparent recovery fraction of K by comparing NPK with NP in 2006 was (24-19)/24 = 0.21. The increased uptake of K in the NP treatment with respect to the control (19 vs. 12 kg K ha^{-1}; Table 7) clearly demonstrates the well-known stimulating effect of especially extra N on the uptake of K in macronutrient deficient soils (Wilkinson et al., 2000; Fageria, 2001). This confirms that more appropriate crop nutrient management can overcome current low yields in the region.

Roselle calyx yield increased almost linearly with N uptake (Figure 5) and the highest yield (130 kg ha^{-1}) was obtained in the least fertile field (MR-2). Besides, organic fertilizers performed relatively well with this crop. This was also found in

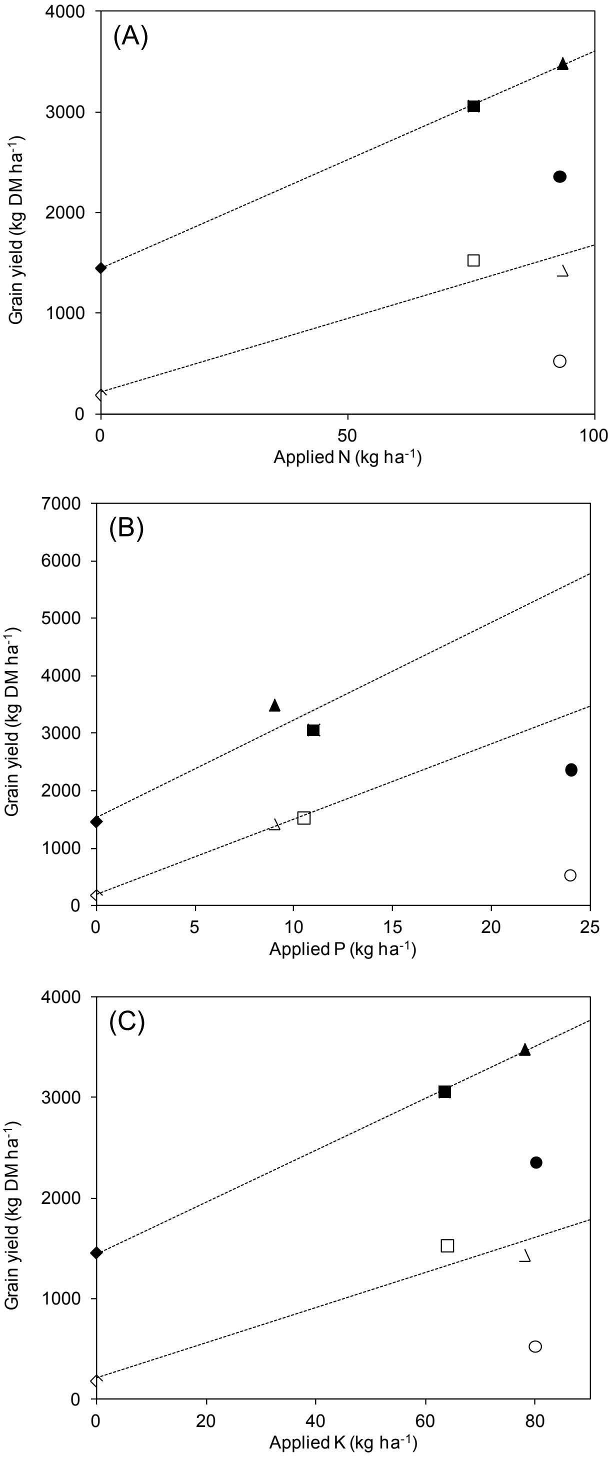

Figure 8. Relationships between maize grain yield (kg DM ha^{-1}) and applied (kg ha^{-1}) (A) N, (B) P, (C) K in the five experiments. Legends: ● ○V, ▲Δ NPK, ■ □V + NPK, ♦ ◊ U. Open symbols fields with pH of 3.5 (M-3 and MR-2), filled symbols fields with pH of 4.3 (M-2 and MR-1). Regression lines were calculated only for treatments NPK, V+NPK and U. (---) Regression fit (A) N open symbols: Y =14.6x+220.9; solid symbols Y =21.6x+1446.5; (B) K open symbols: Y=131.5x+190.21; solid symbols Y = 170.5x+1527.2; (C) K open symbols: Y =17.5x+216.2; solid symbols Y =25.9x+1445.2.

studies reported by El-Keltawi et al. (2003) and El-Sherif and Sarwat (2007). Besides, roselle tolerates a wide range of pH values and, due to its tap root system it has a good capacity to explore belowground sources in the deeper soil layers (McLean, 1973; Fadl and Gebauer, 2004). This agrees well with the perceptions and experiences of the farmers, who stated that roselle performs better in sandy and marginal soils, and has much lower nutrient requirements than maize. Since roselle is a cash crop, there exists a good scope for livelihood improvement in the region through roselle production on especially the least fertile soils.

4.2 Relation between nutrient uptake and type of nutrient input

The 2006 results revealed that the current farmers' practice to apply only mineral NP leads to a deficient crop nutrient uptake. Maize grain yield increased by more than 45% when K was added (treatment NPK), despite the fact that the P input with NPK was reduced by almost 90% compared to NP. Moreover, there were clear indications that this extra K supply facilitated an increased uptake of N (Table 7).

The influence of the source of nutrients on maize grain yield and total nutrient uptake is most easily examined by comparison of treatments NPK and vermicompost from the 2007 experiments, because they received almost equal quantities of N and K. Tables 4 and 7 shows that NPK always had higher yields and uptake rates of N and P, and sometimes of K than vermicompost. On average, the yield response to vermicompost was only 40% of the yield response to NPK. Even the uptake of P was higher for NPK than for vermicompost, although with vermicompost nearly three times as much P was applied. However, P was certainly not a growth limiting nutrient in these experiments.

Our results demonstrated that variations in harvest index were linked to nutrient treatment as well as to experiments (locations) and experimental year. The highest observed harvest index values were close to 0.5. Applications of NPK as well as V+NPK increased aboveground biomass production, grain yield, and harvest index (Figure 3, Table 4). Several studies exist on the benefits of the integrated use of organic and mineral nutrient sources. These concern a better synchronicity of nutrient release, an enhanced moisture retention, and an improved cation exchange capacity in the long term (Goyal et al., 1992; Akhtar et al., 1999; Kramer et al., 2002; Khaliq et al., 2004; Adediran et al., 2005; Fageria and Baligar, 2005; Tittonel et al., 2008; Maobe et al., 2010). Losses from NPK fertilizers likely were less because these were split-applied in two (2006) or three (2007) portions. However, losses from vermicompost could be reduced by applying low amounts (2.5 Mg DM ha^{-1}), and along with mineral fertilizers (V+NPK) yield improvements were found.

4.3 Relations between nutrient proportions in crop components and yield.

Nutrient mass fractions, maximum and minimum PhE's together with crop nutrient equivalency (CNE) were tools that allowed for identification of the main limiting factors in maize production. Our data revealed that straw K contents at harvest were extremely low and that they were all very close to the minimum value of 4 g kg^{-1} given by Nijhof (1987). Contrary to K, most of the N and P taken up by the plants is remobilized and incorporated into the kernels (Ma et al., 1999). Nevertheless, the mass fractions of N in grain at harvest (10.9 - 12.6 g kg^{-1}) were all just above the minimum value of 9 g kg^{-1} (Nijhof, 1987).

Average K mass fractions in the maize leaf opposite and below the ear at silking were almost 50% lower than the critical value required for achieving a good crop growth rate (Table 5). The CNE approach and the calculations of FN, FP and FK support this result and demonstrate that K was the most limiting nutrient at that growth stage. For maize grain production an adequate content of K during silking is important since most of the K has already been taken up at that time (Khademi et al., 2002). Shortage of K from then on will therefore affect N metabolism (e.g., grain kernel filling) and the overall crop N use efficiency (Jordan-Meille and Pellerin, 2004; Çelik et al., 2010). In 2006, the N:P:K proportions in the aboveground biomass were in general more balanced than in 2007 (Figure 7). This corresponded with higher values of the harvest index (Table 4). Our findings showed that physiological nutrient use efficiency was dependent on the harvest index. Hence, PhE_P-bal, PhE_K-bal, CFP and CFK were no constants (Figures 2 and 4). In other studies using these concepts derived from the QUEFTS model, only maize with a harvest index of 0.4-0.45 was included (Smaling and Janssen, 1993; Setiyono et al., 2010).

The CNE approach for total aboveground biomass developed by Janssen (2011b), and summarized in NPK radar graphs (Figure 7), highlights that for both years there was no balanced nutrition, but the proportions of N and K were improved in most of the NPK (both years) and V+NPK treatments. Here, also the highest aboveground biomass and maize grain yield were found. In all of these cases, the P portion (FP) exceeded the optimum value of 33.3%.

4.4 Physiological nutrient efficiency

The analysis based on maximum and minimum PhE's demonstrated that both N and K were the major yield-limiting factors for maize production in both years. This finding confirmed earlier survey results on 22 fields of 8 farms in the same region (Flores-Sanchez et al., 2011). In 2006, maize grain yield was somewhat, but not significantly

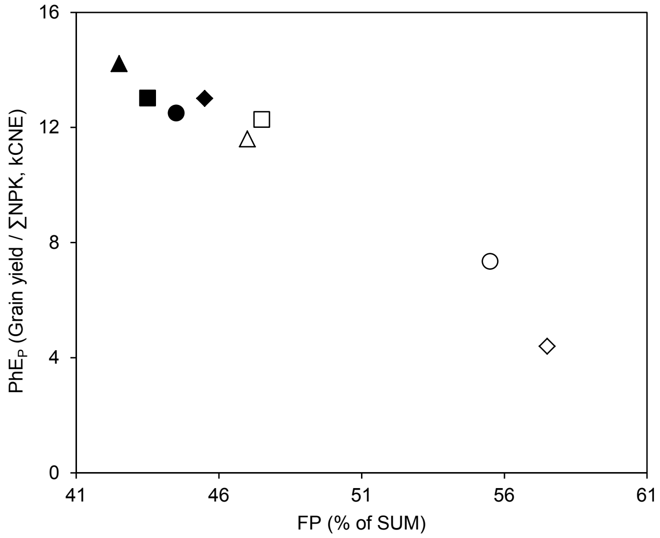

Figure 9. Relationship between the proportion of P (FP) of the sum of N, P and K (expressed in kCNE) in aboveground biomass and physiological nutrient use efficiency (PhE). Legends M-3, MR-2: ○ V, Δ NPK, □ V + NPK, ◊ U; M-2, MR-1: ● V, ▲NPK, ■ V + NPK, ♦ U.

higher with vermicompost than with goat manure (Table 4), although equal amounts of N, P and K were added with both amendments (Table 3). A few studies have indicated that vermicompost owns more favorable properties for crop development than animal manure (Atiyeh, et al., 2000; Loh et al., 2005; Lazcano et al., 2008). Moreover, the mineral N content in animal manure is generally higher, thus leading to higher risks of N leaching (Basso and Ritchie, 2005).

PhE was negatively related to the P portion of the sum of nutrients, expressed in kCNE per ha. (Figure 9; 2007 experiments). Lowest PhE$_P$ was found in experiments M-3 and MR-2, particularly in treatment V and the unfertilized control. Also FP obtained with the various treatments was negatively related to yield. In all points in Figure 9, FP was 42% or higher, so clearly above the optimum of 33.3%. A high FP points to low portions of N and/or K. In all of the experiments, P did not show any sign of deficiency. However, the P soil values in three fields (Table 1) were classified around the critical levels (10-17 mg kg^{-1}) (Dabin, 1980). In the region of our study crop nutrition is characterized by continuous application of P-containing fertilizers, thus P can be accumulated in the soil and become available to plants for a period of many years (Sanchez et al., 1997; Janssen, 1998).

To improve farm management within the area, a few low-cost recommendations can be derived from the current study. Along with mineral fertilizers, organic sources such as vermicompost have to be applied in at least two split applications when given in higher amounts than 2.5 Mg DM ha^{-1} in order to curtail nutrient leaching losses.

This could lead to a build-up of soil fertility in the mid- to long-term (Palm et al., 2001). Under the current conditions of K soil deficiency, crop residues should be considered as a substantial source for recycling K supply (Rosolem et al., 2005).

Finally, it is worth noting that all experiments were carried out under sometimes harsh conditions and faced constraints which were linked to limited organic sources (manure), accessibility to farmer's fields, large variations within fields as well as long distances from villages to research centres and laboratories for sending soil and plant samples. However, given these restrictions our results demonstrated that potential changes in current crop management are feasible as a start for closing the current yield gaps. Further research, including complete factorial experiments, is needed to assess both balanced crop nutrition and nutrient recovery from both mineral and organic fertilizers in greater detail.

5. Conclusion

In this study we highlighted the foremost limiting nutrients for maize production in the Costa Chica region through an evaluation of the current nutrient management practices by carrying out small-scale field experiments during two years. The experiments were set up in farmers' fields representative of the region. They clearly showed that the current use of subsidized packages containing only mineral N and P can be improved upon. Neglecting a sufficient K application led to unbalanced crop nutrition characterized by luxurious P consumption, shortage of K and low grain yields. At silking, K was the most limiting nutrient, and at harvesting both N and K proved to be most limiting for grain production. The concept of the crop nutrient equivalent approach applied to leaves at silking and total crop nutrient uptake at harvest was a helpful tool to assess the most growth-limiting nutrients. Grain yields strongly increased by balanced mineral NPK inputs as well as by combinations of mineral NPK, applied in split doses, and vermicompost in not too high quantities at sowing. These findings suggest that theoretically attainable yields could be achieved if nutrient input recommendations would be fine-tuned towards efficient use of the available resources.

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Chapter 5

Decomposition and N contribution of aboveground residues, root residues and vermicompost in maize-based cropping systems in Southwest Mexico

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Abstract

Depletion of soil fertility is one of the main concerns of the farmers in the Costa Chica, a coastal region in Southwest Mexico. The current trends of reduced fallow and crop residue harvesting exacerbate nutrient cycling unbalances and threaten the sustainability of the common maize production systems. Consequently, farmers are highly dependent on chemical fertilizers. To counteract this situation, it is necessary to supply the soil with organic sources. Field experiments during one rainy season were carried out in two farmers' fields in order to estimate the decomposition rate and N release of three organic materials: aboveground maize and weed residues, belowground plant residues and vermicompost. Decomposition was monitored using the litterbag method, and decomposition patterns were fitted by means of an existing dynamic mono-component mineralization model. Rates of decomposition varied according to the type of organic material. The remaining dry matter proportion of aboveground residues and roots ranged from 30 to 55% after 8 months, whereas more than 80% of their total N contents were released. Besides, only 35% of the vermicompost mass was decomposed after 6.5 months. However, about 65% of its N was mineralized. Therefore, especially vermicompost can be regarded as an attractive amendment for both crop N supply and soil organic matter build-up. At an application rate of 10 Mg ha^{-1} it delivered a substantial soil mineral-N input of about 60 kg ha^{-1} in both fields during the maize growing season. In the longer term this will also lead to an increase in soil pH which was too low on one of the two fields for the realization of a significant maize N uptake from vermicompost.

Keywords: aboveground, residues, root residues, vermicompost, decomposition rate, N release, mineralization model

1. Introduction

In the region of the Costa Chica, Mexico, farming systems are organized in small production units with land holdings ranging from 1.5 to 9 ha. The main crops are maize (*Zea mays* L.) and roselle (*Hibiscus sabdariffa* L.). Soil fertility decline is one of the main concerns of the farmers. Chemical fertilizers constitute the main input for crop nutrition, and only few farmers use animal manure. Besides, manure is usually applied only to the fields close to the homestead. Main sources of organic matter to be returned to the soil are the crop residues which are left at the end of the growing season. However, currently these are mainly grazed by animals roaming the fields unprotected by fences during the dry season. At the beginning of the rainy season some farmers remove the remaining crop residues, a practice known as "rastrojear", and burn them subsequently in order to facilitate farming practices (Flores-Sánchez et al., 2005). Additional inputs of organic materials such as vermicompost are therefore necessary under these poor soil fertility conditions to restore soil organic matter (SOM) and to improve physico-chemical soil properties like soil pH (Flavel and Murphy, 2006). At the same time, these sources of organic material can reduce soil erosion in the region which is a major problem due to the hilly landscape and the intensive rainfall during the growing season.

In the Costa Chica, no information exists on the role of decomposition of and nitrogen (N) release from crop residues that would allow improving the nutrient use efficiency in the smallholders' maize-based cropping systems (c.f. Ibewiro et al., 2000). Here we report experiments carried out on farmers' fields during one growing cycle to evaluate i) the decomposition and N release pattern of aboveground and root residues of maize and weeds, and of vermicompost which attracts increasing attention in the region, and ii) N uptake by maize and weeds from these organic materials and mineralized soil N by means of an N balance.

2. Materials and methods

2.1. Experimental sites

Two on-farm experiments were conducted in two communities of the municipality of Tecoanapa (16°48' N, 99°09'), Guerrero, Mexico during the growing season of 2007. Mean annual temperature was 27°C, and precipitation was 1,822 mm (Figure 1). Soils were classified as Loamy Eutric Regosols (SEMARNAT, 2009; FAO, 2010). Two experimental sites were selected to carry out the study: field JR located in the village of Xalpatlahuac and field IM located in the village of Las Animas. The first field was characterized as fertile on a steep slope with a loamy texture and cattle could roam freely after maize harvest. The second field was flat and less fertile with a loamy-sandy texture and fenced to prevent grazing (Table 1).

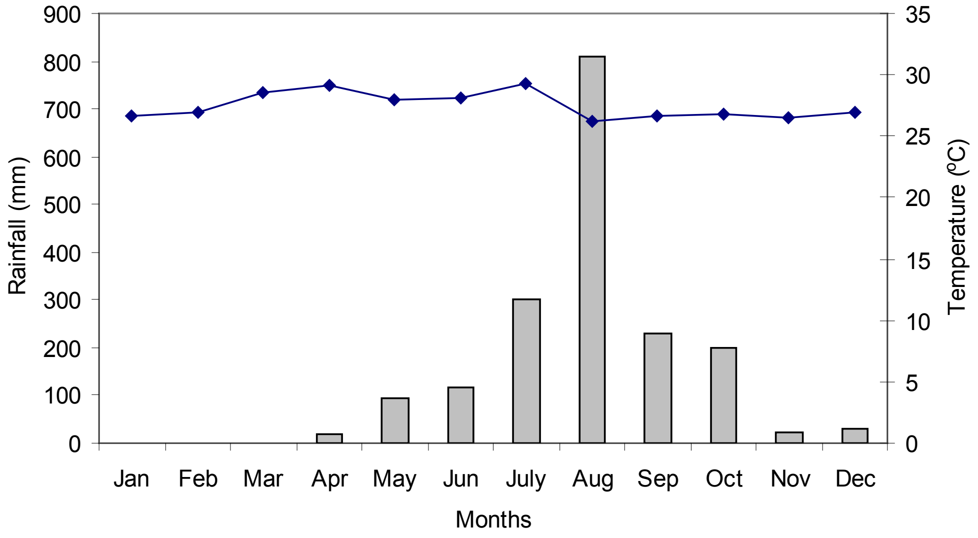

Figure 1. Precipitation and average daily temperature during 2007 for station Ayutla, Guerrero (*Comisión Federal de Electricidad*).

Table 1. General soil properties of the two experimental fields (May 2007).

Field	Exp.	Slope	pH	O.M.	Org. C	Nt	P Bray $^{-1}$	K	Sand	Clay	Silt	Bulk density	Field capacity	Per-manent wilting point
		(%)	(H_2O)	g kg^{-1}			mg kg^{-1}	cmol kg^{-1}	(%)			g cm^{3}	(%)	
IM	M-2	5	4.3	11	6.4	0.4	15	0.30	51	21	28	1.38	14.9	7.4
JR	M-3	21	3.7	13	7.5	0.5	18	0.63	40	23	37	1.44	22.9	8.6

2.2. Experimental procedures

The trial was part of a larger experiment (see Chapter 4) in which maize was grown with different sources of nutrients (vermicompost, chemical fertilization NPK, vermicompost + chemical fertilization NPK) and an unfertilized control. The decomposition and N release was carried out in the 5 m × 5 m unfertilized maize plots. Individual plots comprised five rows of 5 m at a between row spacing of 1 m. The planted maize cultivar was the criollo locally known as Palmeño. Sowing was carried out in the last week of June. Herbicide (1 L ha^{-1}) was sprayed one week before sowing and three weeks after sowing. Maize was harvested in the first week of November. To estimate N balances aboveground biomass of maize and weeds were estimated in plots fertilized with vermicompost and in the unfertilized plot. Maize plants from the central row but excluding border plants were cut at ground level and separated into grains and stover, while weed biomass was sampled in a subarea of 1 m^2 within the central row. Plant material was oven-dried at 70°C for 24 hours to estimate aboveground dry matter production. Maize grains, maize stover and weeds were analyzed for N, P and K. Total N was analyzed using the semi-micro-Kjeldahl procedure (Bremmer, 1965). Total aboveground maize and weed N uptake were used to construct field N balances.

2.3. Sampling of organic materials

Aboveground residues

Aboveground maize crop and weed residues were sampled in April 2007. Five areas of 1 m^2 were randomly selected in each field. Aboveground maize crop residues were separated in stems and leaves, and the proportion of weeds in the sampled material was measured before drying. The plant material was oven-dried at 70°C for 24 hours and total aboveground biomass was estimated (kg DM ha^{-1}).

Root residues

The belowground biomass was estimated in April 2007. Five columns (monoliths) of 0.2 m × 0.2 m × 0.2 m were dug from the field and transferred to the lab. Monoliths were soaked with water, and roots were carefully removed. Roots were oven-dried at 70°C for 48 hours and weighed.

Vermicompost

The vermicompost was produced and provided by the Center of Agricultural Technological Baccalaureate No. 191 located in Tecoanapa, Mexico. The facilities to produce vermicompost consisted of 10 compost beds made of bricks and cement with a slight slope (1-2%). Each bed was enclosed by a wall (1 m × 10 m × 0.5 m). Substrate consisted of a mixture of dry crop residues, grass hay, leaves of trees, and cattle manure (mainly goat manure) in a ratio of 25% dry plant residues and 75% cattle manure. The substrate was carefully mixed and watered in order to start the composting process and covered with straw. After three weeks, about 10 cm of the substrate was put in the compost beds and stocked with about 1000 earthworms (*Eisenia foetida*) per square meter. The substrate was covered with a mesh in order to reduce moisture loss and to protect earthworms from birds. Every two weeks another layer of 10 cm of substrate was applied until a final height of 40 cm height was formed. Water was sprinkled every three days to maintain moisture content and to regulate the body temperature of the earthworms. Three months after starting the procedure the vermicompost was collected and sieved through a 1 cm mesh size. Average moisture content was 40%.

The initial chemical composition of all of the organic materials is presented in Table 2. Total N was analyzed using semi-micro-Kjeldahl procedure (Bremner, 1965). P and K were analyzed by inductively coupled plasma spectrometry (ICP-AES Varian Liberty Series II, Varian Palo Alto, CA, USA) (Alcántar and Sandoval, 1999).

2.4. Litterbag preparation and processing

Decomposition of the organic materials and N release was studied during the rainy season using the litterbag method (Beyaert and Fox, 2008). This method is widely used, and is a valuable tool to estimate decomposition of substrates such as leaf litter and recalcitrant materials (Coleman et al., 2004).

Aboveground residues

Nylon litterbags of 30 cm × 25 cm (2 mm mesh size) were filled with 50 g DM of aboveground crop and weed residues. This mesh size was selected to ensure close contact among the biotic environment (micro- and meso-fauna, bacteria and fungi), the abiotic soil surface and the crop residues in the litterbag (Robertson and Paul, 2000; Bradford et al., 2002). In field JR the bags were randomly placed on the soil during the first week of May, while in field IM this was done in the third week of May; 12 bags were used per location. In field JR, bags were recovered after 6, 17, 26 and 38 weeks, and in field IM after 4, 14, 23 and 34 weeks.

Root residues

The root residues were put in 12 nylon bags of 10 cm × 15 cm (40µm mesh size). The chosen mesh size was small in order to avoid losses from litterbags as well as to prevent exchange with soil particles and debris (i.e. excluding the influence of meso-

Table 2. Initial chemical composition of the organic materials (g kg^{-1} DM) in the two fields.

Material	Field	Nutrient		
		N	P	K
Aboveground residues	IM	9.1	0.2	0.9
	JR	9.4	1.1	2.6
Root residues	IM	10.7	0.4	0.9
	JR	10.9	1.5	4.2
Vermicompost	IM	9.3	2.4	7.9
	JR	9.3	2.4	7.9

fauna), but allowing contact with micro-fauna, bacteria and fungi (Bradford et al., 2002). In each nylon bag 10 g DM of root residues was added and the bags were buried horizontally at a depth of about 10 cm under the soil surface in each field during the first week of July. The bags were retrieved after 8, 17 and 29 weeks for field JR and at 7, 11 and 28 weeks after placement for field IM.

Vermicompost

Vermicompost was added in 12 nylon bags of 10 cm × 15 cm (40µm mesh size) at a rate of 37.5 g DM per bag. The small size of the mesh was selected to avoid loss of material through the mesh. The vermicompost bags were buried horizontally at 10 cm below the soil surface. In field JR, bags were buried during the last week of June, and sampling occurred 5, 13, 16 and 21 weeks after placement. In field IM the bags were placed in the first week of July and sampling took place 4, 11 and 28 weeks after installation.

Analyses

Three replicates of each group of organic materials were randomly harvested at each sampling time. The plant residues were carefully separated from the bags and sprinkled with water to remove adhering soil. The remaining materials were oven-dried in small aluminum containers at 70°C for 48 h, and weighed. Total N in the samples was determined by the semi-micro-Kjeldahl procedure (Bremner, 1965). In case of the aboveground residues, about 25% of the material contained in the bags was taken for the analysis, while in case of roots and vermicompost all of the material contained in the bags was analyzed.

2.5. Modelling material and nitrogen decomposition patterns and statistical analysis

The decomposition patterns of the organic materials were calculated using the mono-component mineralization model developed by Yang and Janssen (2000) in which the organic matter dynamic is treated as a single component over time. The mineralization rate, K (t^{-1}), is calculated as:

$$K=Rt^{-S} \tag{1}$$

Where R (dimension t^{S-1}) represents K at t=1, and S (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time.

The amount of remaining organic material on time t (Y_t), is calculated by:

$$Y_t = Y_o \exp(-Rt^{1-S}) \quad (2)$$

Where Y_o is the initial quantity of the organic material.

The model parameters R and S in Equation 2 were fitted using the non-linear regression procedure in PASW Statistics 17.

Two methods were used to the estimate the potential soil supply of N (SN; kg N ha^{-1}). The first method was proposed by Janssen et al. (1990):

$$SN = fN * 6.8 * C \quad (3)$$

$$fN = 0.25 * (pH-3) \quad (4)$$

Where C represents soil organic carbon (g kg^{-1}), assuming 58% C in SOM, and pH is pH (H_2O); for the calculations a minimum value of 4.5 was assumed.

The second method was taken from Grace et al. (2002) who estimated annual decomposition rate of soil organic N in experiments at El Batán, Mexico to be 1.26%.

The N balance of the two fields was calculated as the difference between the combined N release from soil and organic materials on the one hand and N uptake by maize and weeds on the other.

3. Results

3.1. Parametrization of the mono-component model

The mono-component model was parameterized for the three organic materials in each field (Tables 3 and 4). The parameter values for R and S presented in Table 3 demonstrate major variation in OM decomposition among the materials. However,

Table 3. Fitted parameter values R (±SE) and s (±SE) for OM decomposition of the three groups of organic materials in the two fields according to the mono-component model.

Field	Organic material	R (year s^{-1})	s	r^2 adjusted
IM	Aboveground residues	0.79 (± 0.07)	0.41 (± 0.08)	0.94
	Root residues	1.11 (± 0.26)	0.41 (± 0.18)	0.84
	Vermicompost	0.48 (± 0.03)	0.89 (± 0.03)	0.98
JR	Aboveground residues	2.10 (± 0.39)	0.03 (± 0.19)	0.89
	Root residues	0.83 (± 0.37)	0.86 (± 0)	0.98
	Vermicompost	0.52 (± 0.06)	0.80 (± 0.08)	0.95

Table 4. Fitted parameter values R (±SE) and s (±SE) for N decomposition of the three groups of organic materials in the two fields according to the mono-component model.

Field	Organic material	R (year s^{-1})	s	r^2 adjusted
IM	Aboveground residues	2.53 (± 0.11)	0.33 (± 0.03)	0.99
	Root residues	3.25 (± 0.18)	0 (± 0.04)	0.99
	Vermicompost	1.35 (± 0.02)	0.71 (± 0.01)	0.99
JR	Aboveground residues	2.65 (± 1.48)	0 (± 0.42)	0.80
	Root residues	2.29 (± 0.16)	0.56 (± 0.05)	0.99
	Vermicompost	1.67 (± 0.05)	0.56 (± 0.02)	0.99

differences between fields were only observed for the aboveground plant residues. In case of N disappearance there was hardly any variation among materials and between fields (Table 4). Decomposition patterns were satisfactorily fitted with the model (Figures 2 and 3).

3.2. Decomposition of organic materials

Aboveground residues

The total amounts of aboveground plant residues measured in April 2007 were 2,600 and 1,100 kg DM ha^{-1} in fields IM and JR, respectively (Figure 2A). The proportion of weeds in the collected material was 20 and 17%, respectively. The decomposition rate was greater during the first four months. At the end of this period, 67 and 45% of the initial weight remained in fields IM and JR, respectively (Figure 2D). At the end of the sampling period (36 weeks on average) the residual dry mass had declined to 55 and 30%, respectively.

Root residues

Total root biomass measured in April 2007 was 833 and 500 kg DM ha^{-1} for fields IM and JR, respectively (Figure 2B). The initial root DM decomposition rate differed between fields. The loss of weight during the first two months in field JR was 47%, whereas it was only 20% in field IM. However, at the last sampling date in January 2008 these differences had disappeared, and the remaining root biomass in each field was then just below 50% of the amount applied (Figure 2E).

Vermicompost

An application rate of 10 t DM ha^{-1} of vermicompost was taken as the initial amount to estimate the time patterns of decomposition and N release. Decomposition rates

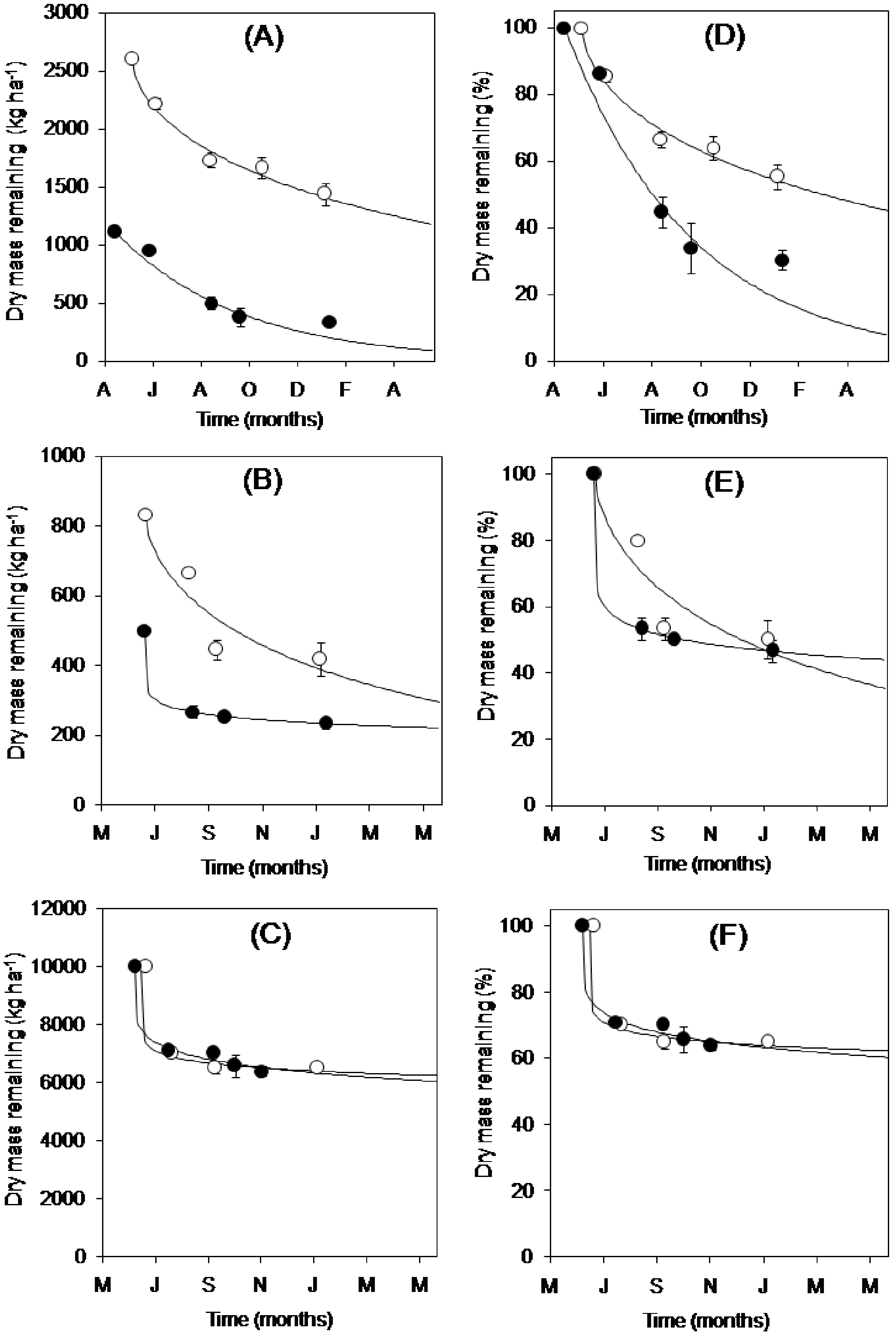

Figure 2. Total DM remaining in litterbags with time expressed in absolute values (kg ha^{-1}) (A, B, C) and as percentages (D, E, F) for the three organic materials in the two fields during the growing season of 2007. (A) and (D) aboveground residues; (B) and (E) root residues; (C) and (F) vermicompost. Open symbols: field IM. Closed symbols: field JR. Solid lines represent the fitted mono-component model. Bars represent standard error of the mean.

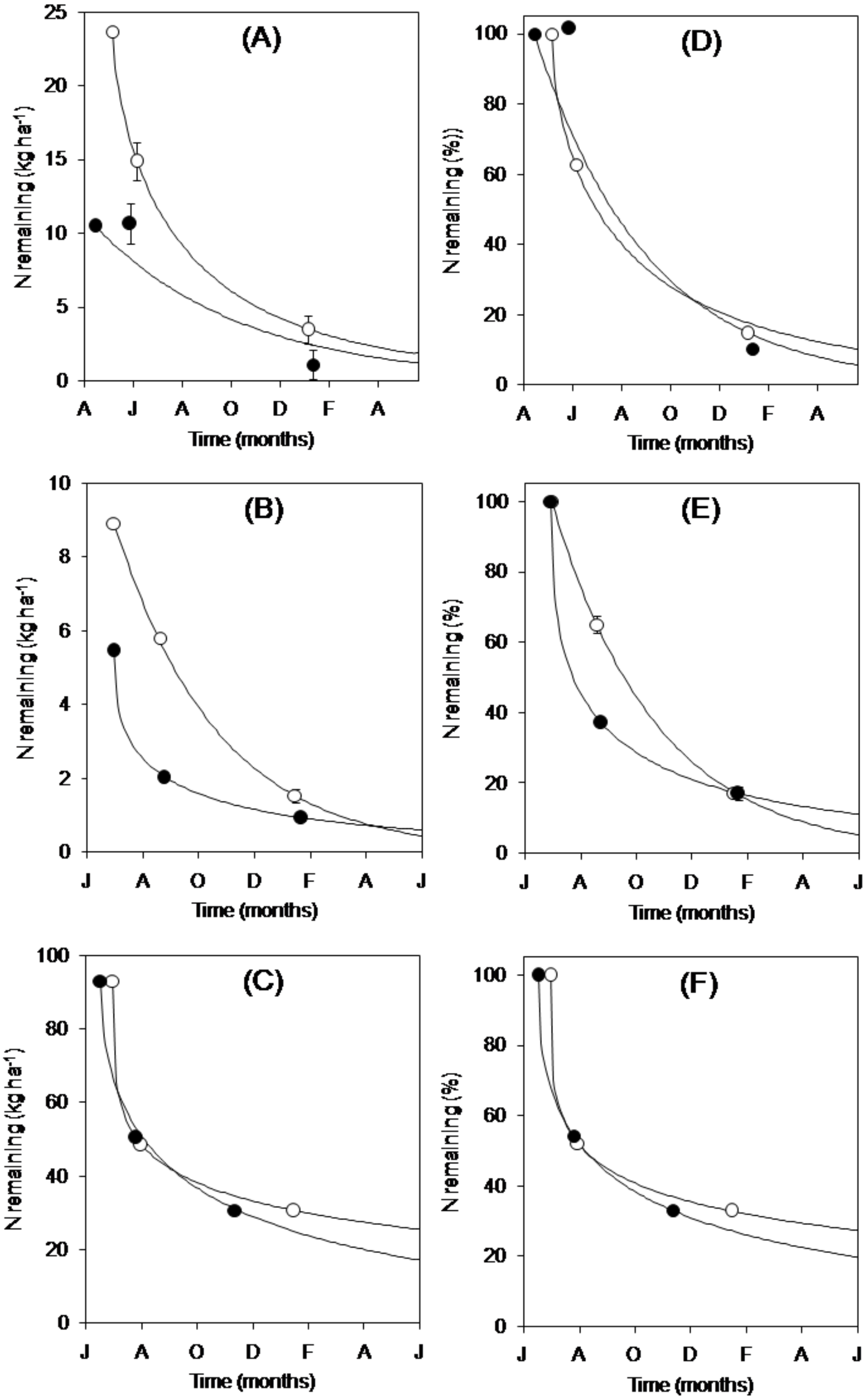

Figure 3. Total N remaining in litterbags with time expressed in absolute amounts (kg ha^{-1}) (A, B, C) and as percentages (D, E, F) for the three organic materials in the two fields during the growing season of 2007. (A) and (D) aboveground residues; (B) and (E) root residues; (C) and (F) vermicompost. Open symbols: field IM. Solid symbols: field JR. Solid lines represent the fitted mono-component model. Bars represent standard error of the mean.

followed the same trend in each field (Figure 2C). Within the first 30 days rapid decomposition was observed and about 30% of the initial amount of vermicompost disappeared from the litterbags. After that period decomposition slowed down and at the end of the measuring period the proportion of vermicompost DM that remained was approximately 64% in each field (Figure 2F).

3.3. Nitrogen decomposition

Aboveground residues

The initial amount of N in aboveground plant residues was 24 N kg ha^{-1} in field IM and 11 kg N ha^{-1} in field JR (Figure 3A). At the end of the study 9 kg N ha^{-1} was released in field JR (89% of total N applied; Figure 3D). In field IM this amount was already released within the first 30 days and at the end of the experiment 20 kg N ha^{-1} had been released (85% of total N applied; Figure 3D).

Root residues

The time patterns of remaining N in the root residues are presented in Figures 3B and 3E. The total amount of N at the beginning of the study was 9 kg N ha^{-1} in field IM, and 5.5 kg N ha^{-1} in field JR. Residual N decreased gradually to 1.5 kg ha^{-1} in field IM and 1 kg ha^{-1} in field JR, equivalent to an N-release of 83% in each field (Figure 3E).

Vermicompost

The application rate of 10 t ha^{-1} of vermicompost corresponded with an initial N amount of 93 kg ha^{-1}. Within the first 30 days the N release was 43 kg N ha^{-1} in field JR and 45 kg N ha^{-1} in field IM (Figure 3C), equivalent to an average fraction released of 47%. At the end of the measurements total N release in each field appeared to be 62 kg N ha^{-1} (67% of total N; Figure 3F).

N balance

The estimated soil N supply differed only slightly between the two methods. Using the procedure proposed by Janssen et al. (1990) the soil N contribution was 16 and 19 kg N ha^{-1} for fields IM and JR, respectively. Following Grace et al. (2002) these levels were with 14 and 18 kg N ha^{-1} about the same. To construct the N balance the former values were used (Table 5). Total N released during the growing season in plots with vermicompost ranged from 91 to 99 kg N ha^{-1} (Table 5). In the fertilized cropping system this N contribution from vermicompost was on average 63% of the total amount of mineralized N. In the unfertilized plots, total N release ranged between 30 and 41 kg ha^{-1}. N contribution from the indigenous organic materials differed greatly

Table 5. N balance of the two fields during the growing season of 2007.

Field	N released (kg N ha-^{1})						N uptake (kg N ha^{-1}) plots with vermicompost			Balance	N uptake (kg N ha^{-1}) unfertilized plots			Balance
	Soil	AR*	RR	V	Total		Maize	Weeds	Total		Maize	Weeds	Total	
IM	16	19	6	58	99[a]	41[b]	48	9	57	42	30	12	42	-1
JR	19	7	4	61	91	30	15	11	26	65	12	12	24	6

*AR: aboveground crop residues; RR: root residues; V: vermicompost

[a] Total N released from soil and the three groups of organic materials

[b] Total N released from soil, and aboveground and root residues

between both fields. In field IM, crop available N in the unfertilized treatment from this source constituted 61%, while in field JR this was a mere 36%. In plots with vermicompost the total N uptake in both fields was widely variable. In field JR, weeds were an important component in terms of competition for N with 42% of the total uptake. N balances in the vermicompost plots were very positive for both fields. There was a surplus of 42 and 65 kg N ha^{-1} for fields IM and JR, respectively. Without vermicompost, field JR had a similar share of N uptake between maize and weeds, while in field IM the maize crop was responsible for 61% of the total N uptake. The N balance in field IM was almost zero, while in field JR there was a calculated surplus of 6 kg N ha^{-1}.

4. Discussion

In two on-farm litterbag experiments aimed to establish the patterns of mass decomposition and N release of three groups of organic materials the mono-component model appeared to be an appropriate fitting tool. The estimated parameter values for the DM degradation of aboveground plant residues and root residues differed widely between the fields of each of the two farms. However, at the end of the experiment there appeared to be no differences any longer in case of the root residues. The slower breakdown of aboveground residues on field IM as compared to JR could not be explained from the weed content in these residues because they were almost the same. However, the total amount of aboveground residues was more than twice as high on this field and the P and K contents were much lower compared to those on field JR. This might indicate that the share of less degradable maize stems was higher on the field of farm IM. Since there were no differences between the decomposition patterns of the applied vermicompost on each field this seems to be a plausible explanation. Vermicompost is well-known for its high content of lignin which is a recalcitrant compound with a great resistance to microbial decomposition. In accordance with this is the observation that almost two-thirds of the vermicompost mass was still present in the litterbags of both fields at the end of the experiment. However, this finding demonstrates its potential as an external source to increase the SOM stock which is one of the most important factors in soil conservation and reclamation (Bernal et al., 1998).

Concerning both the aboveground and belowground residues the overall level of DM decomposition was higher than that of vermicompost. The observed average value of about 50% at maize harvest is in agreement with a number of other experiments carried out over a period of less than one year (Burgess et al., 2002; Mubarak et al., 2002; Fang et al., 2007).

The N release pattern from the organic materials differed little between the two fields. However, about 70% of the vermicompost N was released during the first 30 days on both locations, whereas initial N decomposition was especially lower in case of root residues. According to the N balances, there were great surpluses when all the organic materials were considered together. This was accompanied by a total aboveground N recovery by the maize crop of 0.2 for vermicompost in field IM, while in field JR this was close to 0 (data not shown). These low values can be partly explained through the relatively high share of weeds in the total N uptake, particularly in field JR, but above all they point into the direction of N immobilization and run-off losses. In acidic soils with a pH around 4, like in the current study, nitrification is inhibited (Harmsen and van Schreven, 1955). Under these conditions ammonification is largely carried out by fungi since bacteria show little activity. Therefore, nitrate leaching losses may not be expected to take place and the assimilated N is incorporated in the pool of living soil biomass (Mengel, 1996; Neale et al., 1997; Andrew et al., 2002). As a consequence, soil microorganisms acquire inorganic N before plants, thus greatly reducing the availability of N for maize roots (Durieux, 1993; Calba, 1997; Hodge et al., 2000). These processes all take place in the top layer of the soil profile which was especially in the slopy field JR very vulnerable to run-off losses. Already in July, the first month of the experiment, the 300 mm of rainfall greatly exceeded the evaporative demand of the vegetation. In August the situation was even worse since then a precipitation of 800 mm was recorded.

The initial N release from the aboveground plant residues as well as from the roots proceeded at a slower rate compared to vermicompost. In the unfertilized plots, where only these residues were present, the N balances were more favourable. It was calculated that the N balance in field IM was close to zero. In the more acidic field JR with a lower level of plant-available N, the N uptake by weeds and especially maize was very restricted. This resulted in an extremely low maize grain yield of 300 kg ha^{-1} (Chapter 4) and a positive N balance that was equal to 25% of the total amount of N absorbed by the maize and the weed plants. Other studies demonstrated that N derived from maize residues was more essential for N maintenance than as source of N supply for crop production (e.g. Mubarak et al., 2003).

5. Conclusions

Over one growing season it was observed that the remaining aboveground crop and weed residues presented higher variation in the degree of decomposition (from 30 to 55%) between both fields than roots and vermicompost. This difference was in all probability due to a more stemmy nature of the maize residues in one of the fields. As an average, about 50% of the total residues were decomposed and nearly all of their N was released from the litterbags. The remaining vermicompost appeared to be the least decomposed material. However, due to its much higher N input level the N contribution was higher than from aboveground maize and weed residues and roots together. Vermicompost can therefore be considered as a promising option to increase soil organic matter turnover and improve crop production. However, it is necessary to adjust its application strategy by synchronizing nutrient release with crop demand. Most of the vermicompost N is released during the first weeks of the growing season when there is a great risk that rainfall exceeds evapotranspiration. Further studies are recommended to evaluate decomposition of organic materials and N release patterns for periods longer than one year in order to quantify the system N dynamics in subsequent years. Besides, it is worthwhile to gain more insight in the process of N capture by microorganisms in relation with soil pH and the magnitude of run-off losses.

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Chapter 6

Soil fertility management and maize-livestock interactions as a way out of poverty? Exploration of farm-specific options for a region in Southwest Mexico

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Abstract

Farming systems of the region Costa Chica, Mexico face limitations linked to low yields and soil fertility degradation. Several options of maize-based cropping systems at field level have been proposed to improve current limitations. These options need to be evaluated at farm level in order to evaluate their feasibility in relation to the need for self-sufficiency in food production, for cash and long-term soil fertility and the availability of labour. To explore consequences of changes in current farming systems for 8 typical farms in the region, 4 scenarios were defined; the first two scenarios comprised re-dressing imbalances in current crop nutrition and organic matter (OM), respectively, and the last two scenarios explored high fertilizer input and animal husbandry. The results demonstrated that improvements in family income and OM balance at farm scale were feasible. Farms responded in different ways to the various options depending on available land, current soil quality, current cropping systems and presence of livestock. In the short term, improvements in crop nutrition based on mineral fertilizers increased family income but only had substantial effects on OM balances when fertilizer rates were double the amount currently subsidized. Addition of organic fertilizers resulted in positive effects on OM balance, but with often strong trade-offs with family income due to costs of acquisition, transport and application. Effects on OM balances were more substantial when organic fertilizers were included in crop nutrition strategies. Animals played an important role in increasing OM balances, but had relative little effect on improving family income. The results highlight the need for policies that take into account farm-specific differences in crop and livestock intensification opportunities.

Keywords: maize, farming systems, explorations, crop nutrition

1. Introduction

An important share of the world's food supply is produced on smallholder farms (Herrero et al., 2010).Worldwide there are about 500 million farms with less than 2 ha of land (Wiggins et al., 2010). Many people in rural areas depend directly on productivity on these holdings, which are often located in biophysically marginal production areas. Despite policies to support family-based agriculture in many Latin American countries, persistent lack of productivity leads to rural poverty, resulting in migration of young people to cities and, in the case of Mexico, to the United States.

Maize-based smallholder systems dominate the southern Mexican states of Chiapas, Oaxaca and Guerrero, which constitute the poorest regions of the country, home to about 8 million poor people (CONEVAL, 2010). In Mexico, farm sizes up to 3 ha account for 71% of farms, representing around 5 million ha. These smallholders are mainly maize producers; on 42% of maize land they produce 22% of the national volume of maize (Gómez, 2010). Smallholder maize production systems resemble the traditional milpa systems that date back to ancient civilizations in Mesoamerica, by producing maize with beans and squash in the same field (Zizumbo-Villareal and Colunga-GarcíaMarín, 2010). However, multi-year fallowing after 2-3 year of production as was practiced in the milpa system has been abandoned due to land shortage. Besides, restoration of soil fertility is largely based on fertilizer input and crop residues, which, however, are also eaten by roaming cattle (Kass and Somarriba, 1999; Flores-Sanchez et al., 2011). In the state of Guerrero, subsidy schemes exist to financially support farmers in purchasing fertilizer for up to 2 ha of land. Since 1994 the schemes include a limited choice of artificial fertilizers that provide nitrogen (N) and phosphorus (P) but not potassium (K) or lime. In 2005, the subsidy schemes were reorganized by adjusting rates and types of fertilizers to soil pH and including bio-fertilizers such as *Azospirillum brasilense* and *Glomus intraradices* but K still was not considered as part of the packages (Secretaría de Desarrollo Rural de Guerrero, 2007).

A farm survey in five communities of the Costa Chica, a region of Guerrero along the Pacific coast, outlined the constraints that smallholders in the region face: farm sizes of maximum 5 ha, fields that are often only accessible on foot or horseback, production on steep slopes, soils with low to extremely low levels of organic matter (OM) and fertilizer schemes that lead to low as well as imbalanced nutrient availability. Yields of maize grain varied from 750 kg ha^{-1} to 3,000 kg ha^{-1}, with very little relation to N or P input (Flores-Sanchez et al., 2011). Between-field variation in maize yield was significant and dominated variation between farms and communities. A series of on-farm experiments (Flores-Sanchez et al., 2013; Chapter 4) confirmed the lack of N and K and the relative abundance of P, and indicated that application of vermicompost together with inorganic fertilizers and intercropping with canavalia (*Canavalia brasiliensis* Mart. ex Benth) can contribute to enhanced OM input and increases in soil OM in the longer term. Increase in soil OM is considered as essential for long-term productivity by enhancing water retention, erosion mitigation, and increasing cycling of plant nutrients, all of which increase resilience to predicted higher temperatures and increased precipitation variability in Mesoamerica (Marengo et al., 2012).

Cropping systems that seem promising at field level may be infeasible when considered at farm level where constraints emerge such as self-sufficiency in food production, labour availability or restrictive cash flow. Thus, proposals on alternative crop management need to be combined with assessments at higher levels of organization and considered within the context set by policies (Hyman et al., 2008). Greater soil OM input necessitates availability of OM sources, which may need to be found at farm or even regional levels.

This paper sets out to evaluate at farm level the feasibility of various maize production systems that are proposed at field level. We focused on systems as proposed by the state government, the national extension service and our own research, and evaluated the consequences of applying these alternatives at eight specific farms for which detailed data on resource endowment were available. The farm-level explorations were organized in four incremental scenarios, the first two steps comprising re-dressing current nutrient and OM input imbalances and the latter two exploring high fertilizer input and animal husbandry trajectories.

The aim of this paper is therefore to present and apply a methodology for ex-ante evaluation of alternative maize production strategies to improve farm-level performance in terms of economic, social and environmental objectives. The method is applied to analyse the room for increasing family income and soil OM levels and decreasing labour input for farmers in the Costa Chica based on existing technologies.

2. Materials and methods

2.1. Approach

Using soil and management data from on-farm surveys we parameterized all relevant farm-specific inputs and outputs of current and alternative maize-based cropping systems (MBCS) for eight case study farms in the Costa Chica. The alternative systems were based on on-farm experiments (Flores-Sanchez et al., 2013; Chapter 4) and data from local government and extension sources, and focused on different rates and combinations of fertilizer and OM applications. Emphasis was put on maize production, ignoring production of intercropped species such as bean (*Phaseolus* *vulgaris* L.) and squash (*Cucurbita pepo* L.) that are produced in small amounts for self-consumption or for local marketing. Roselle (*Hibiscus sabdariffa* L.), which is produced in more substantial amounts in the region was included both as mono-culture and intercropped with maize. Canavalia (*Canavalia brasiliensis* Mart. ex Benth) was included as a potential new cropping activity that could enhance soil fertility or provide feed for cattle. Crop response to inorganic fertilizers and resources was predicted using field-specific information as input for the QUEFTS model (Janssen et al., 1990), which had been tested on a local dataset (Flores-Sanchez et al., 2011). The field-level data were integrated at the farm level using the FarmDESIGN model (Groot et al., 2012), which allowed exploration of alternative farm configurations that outperformed the current farms in terms of the objectives family income, labour requirements and OM balance. Exploration of possible farm configurations was organized in four incremental scenarios, the first of which aimed at redressing imbalances in nutrient and OM balances, and the latter investigated fertilizer- and livestock based intensification options. Details of the approach are described in the next sections.

2.2. Case study farms

We selected eight farms from two communities in the municipality Tecoanapa (16°48’ N, 99° 09 W) for which data on resource endowment and productivity (Table 1) were available from previous work (Flores-Sanchez et al. 2011, 2013; Chapters 4 and 5). Mean annual rainfall in the municipality was 1,300 mm concentrated between June and October. Minimum and maximum temperatures varied with altitude, from 12-27^{o}C in the higher areas (900 masl) and 18 to 33^{o}C at less than 300 masl (Presidencia Municipal de Tecoanapa, Gro., and Instituto de Investigación Científica Área Ciencias Naturales-UAG, 2001). Soils, like elsewhere in the Costa Chica region, were of volcanic origin, classified as regosols. In 2010 the population of Tecoanapa comprised 44,079 inhabitants, over 66% of whom were engaged in farming activities (INEGI, 2011). Total agricultural area was about 14,000 ha.

The case study landholdings ranged from 1 - 4.2 ha spread over one to four fields (Table 1) and were managed by households with 4 to 12 family members. The main crops maize and roselle were grown during the rainy season (June to November). Most commonly, maize was intercropped with roselle as well as low densities of squash and beans, although there were fields in which maize and roselle were grown as monocrops. Farmers practiced no-till without mechanization and weeds were controlled by herbicides or by cutting with hand-held implements. Mineral N and P fertilizers were the main inputs for crop nutrition and application rates varied widely among farms. Manure was used only when farmers owned animals. Average maize

Table 1. Resource characteristics and actual production levels of maize and roselle onthe eight case study farms in the communities Las Animas (A1-A4) and Xalpathlahuac (X1-X4). Data from Flores-Sanchez et al. (2011).

Farm	No. family members	Area (ha)	Area per capita	Number of fields	Cropping systems[a]	Fertilizer inputs (kg ha^{-1})[b]		Herbicide (l ha^{-1})	Yields (kg DM ha^{-1})[b]		Number of animals	
						N	P		Maize	Roselle	Cows	Goats
A1	12	3.0	0.3	1	MR	82	0	6	1268	2	0	0
A2	5	4.1	0.8	4	MR	164 -205 (177)	0	2	1284-2431 (1682)	22-145 (64)	12	0
A3	7	3.3	0.5	2	M	82 – 91 (88)	0	4	1470-1958 (1685)	-	14	14
A4	4	4.2	1.1	4	MR, M	89 – 140 (116)	0-27 (15)	2	1522-2509 (2020)	15-247 (126)	7	0
X1	6	2.5	0.4	3	MR, M	121–130 (128)	20–30 (28)	6	1673-2647 (2425)	67	0	0
X2	9	1.0	0.1	1	MR	131	20	5	(2098)[c]	103	0	0
X3	7	3.1	0.4	3	MR	96 – 97 (97)	16–17 (17)	6	1212-2374 (1652)	110-122 (118)	0	0
X4	7	1.3	0.2	2	M, R	12 – 150 (118)	4–13 (11)	4	2122	467	0	0

[a] MR: maize-roselle intercrop, M: maize monocrop, R: roselle monocrop; [b] Field –specific variation; average value between parenthesis, [c] Value between parenthesis corresponds to estimated yield using QUEFTS; actual yield was 661 kg ha^{-1} due to severe attack of *Trichoplusia ni*

grain yield was 1.8 Mg DM ha^{-1}; roselle calyx yield was 135 kg ha^{-1}. Only the harvestable products (maize cobs and roselle calyxes) were removed from the field by the farmers. As most of the fields were not fenced, roaming cattle had free access to crop residues during the dry season.

Livestock resources fell into two broad categories: (1) equines (donkeys, horses, and mules), pigs, poultry (chickens, turkeys), and (2) goats and cows. The first category was used for transport of materials, traction, and/or home consumption, and was occasionally also sold. The second category served primarily as capital and was sold in case of immediate need of cash. Pigs and poultry were kept near the house and fed with household leftovers and grains. During the cropping season equines, goats and cows were fed by means of cut-and-carry forage provided around the farmstead and by grazing in communal fields. In the dry season, animals were grazed in communal fields, own fields or in other farmers' fields.

The land characteristics (Table 2) show that farm fields were located on steep slopes, were prone to light to severe erosion, were slightly to considerably acid, and had low levels of OM and plant macro-nutrients (SEMARNAT – UACH, 2002).

2.3. Field-level re-design

2.3.1. Maize-based production systems

In this section we describe the steps taken to re-design field-level maize cropping systems. Since the objective of the study focused on alternatives to current systems for the short term, we concentrated on existing technologies or technologies that could be mobilized without major research effort.

Design criteria

We used three sources of information to select design criteria, i.e. attributes distinguishing the different alternative production systems (Hengsdijk and van Ittersum, 2003): the state government fertilizer subsidy scheme, the recommendations of the national extension service, and results from our own experiments and surveys. We did not find other sources of information that were locally relevant. The resulting design criteria and the associated variants are listed in Table 3.

The design criteria comprised the origin of fertilization strategies, sources of nutrients, use of canavalia and level of residue retention. Cropping systems were constructed by combining variants of the various criteria. Not all combinations resulted in cropping systems that were parameterized. In particular, information on the effect of combinations of organic and mineral sources of nitrogen is still limited, and information on canavalia only existed from the on-farm experiments. In total 14 maize-based cropping systems (MBCS) were parameterized (Table 4). For each

MBCS all relevant inputs and outputs were defined as described in the next section.

Quantification of outputs and inputs of MBCS

Outputs and inputs of the cropping systems were quantified to be able to evaluate their performance at farm level in the next stage using the FarmDESIGN model. Marketable outputs comprised maize grain and roselle calyx yields. Non-marketable outputs comprised changes in the soil OM balance resulting from application and

Table 2. Land characteristics of the eight case study farms. Ranges refer to variation among fields. Soil erosion was calculated using RUSLE (Renard et al., 1997). Data summarized from Flores-Sanchez et al. (2011).

Farm	Slope (%)	Soil depth (cm)	pH-H_20	SOC	Nt	P-Bray-1 mg kg^{-1}	K-exchangeable cmol kg^{-1}	Potential soil erosion (t ha^{-1} yr^{-1})
				g kg^{-1}				
A1	25	40	5.3	7	0.57	11	0.24	30
A2	19 – 46	50 – 62	5.3 – 6.0	6 – 16	0.36 – 1.37	2 – 21	0.17 – 0.28	5 – 55
A3	20 – 55	55 – 60	5.5 – 6.1	3 – 10	0.29 – 0.83	10 – 15	0.09 – 0.19	20 – 42
A4	30 – 41	40 – 60	5.3 – 5.5	3 – 13	0.30 – 1.11	7 – 27	0.10 – 0.16	28 – 73
X1	21 – 26	49 – 60	4.8 – 5.3	11 – 15	0.95 – 1.26	7 – 12	0.13 – 0.26	12 – 16
X2	25	50	5.1	12	1.01	4	0.19	14
X3	9 – 19	50 – 57	4.9 – 5.1	6 – 11	0.50 – 0.98	22 – 39	0.13 – 0.14	2 – 23
X4	5 – 43	54 – 65	5.2 – 5.7	11 – 12	1.02 – 1.08	5 – 6	0.13 – 0.17	2 – 30

Table 3. Criteria used to design alternative maize-based cropping systems (MBCS) for smallholders in the Costa Chica, Mexico.

Design criterion	Variants and their labels
Origin of the strategy	• Current farm-specific use (Cu) • Current farm-specific use plus K (Cu_{+K}) • Subsidy scheme (S) • Subsidy scheme plus K (S_{+K}) • Agronomic recommendation (R) • On-farm experiments (E)
Source of external nutrients	• Mineral fertilizer (F) • Vermicompost (V) • Combination of mineral fertilizer and vermicompost (FV)
Canavalia	• Not used (c) • Intercropped with maize (C)
Level and destination of residue retention	• 30% of dry matter to soil, 70% to animals (r) • 100% of dry matter to soil (R)

Table 4. Design criteria used to create maize-based cropping systems (MBCS) for smallholder farming systems in the Costa Chica, the abbreviations of the variants, their use in scenarios during exploration and the information sources used in their quantification.

Design criteria						Used in scenario[1]				
Origin of the strategy	Source of external nutrients	Canavalia	Level and destination of residue retention	Abbreviation	Nutrient inputs N-P-K (kg ha^{-1})	S 0	S 1	S 2	S 3	Source
Cu	F	c	r	Cu(Fcr)	Farm-specific	X	X	X	X	Current practice (Flores-Sanchez et al., 2011)
Cu$_{+K}$	F	c	r	Cu$_{+K}$ (Fcr)	Farm-specific, plus K equal to N		X	X	X	Current practice with addition of K
S	F	c	r	S(Fcr)	69-30-00		X	X	X	Government subsidy scheme (Ríos et al., 2009; Secretaría de Desarrollo Rural de Guerrero, 2007)
S$_{+K}$	F	c	r	S$_{+K}$ (Fcr)	69-30-25		X	X	X	Government subsidy scheme (Ríos et al., 2009; Secretaría de Desarrollo Rural de Guerrero, 2007) with addition of K according to Gómez et al. (2007)
R	F	c	r	R(Fcr)	135-39-83				X	Extension service recommendation (Navarro et al., 2002)
E	F	c	r	E(Fcr)	55-5-46			X	X	
E	V	c	r	E(Vcr)	23-6-20			X	X	
E	F-V	c	r	E(F-Vcr)	78-11-66			X	X	
E	F	C	r	E(FCr)	55-5-46			X	X	On-farm trials (Flores-Sánchez et al., 2013 ; Chapter 4)
E	V	C	r	E(VCr)	23-6-20			X	X	
E	F-V	C	r	E(F-VCr)	78-11-66			X	X	
E	F	C	R	E(FCR)	55-5-46			X	X	
E	V	C	R	E(VCR)	23-6-20			X	X	
E	F-V	C	R	E(F-VCR)	78-11-66			X	X	

[1] Scenario S4 comprises the MBCS of S3 and number of animals as decision variables

decomposition of OM. Inputs included seeds of maize, roselle and canavalia, mineral and organic fertilizer, herbicide, and labour. For each field, crop products were characterized in terms of biomass and yield(see below), and N, P, K and ash contents using on-farm measurements (Flores-Sanchez et al., 2011), complemented with information from the literature (Mitra and Shanker, 1957; Burgess et al., 2002; Colunga et al., 2005; Harrington et al., 2006).

Using the design criteria outlined in Table 3 soil fertility strategies were created (Table 4). Farm-specific current fertilizer use (Cu) served as a reference. The simplest change comprised application of K at the same rate as N to compensate for the lack of K in current strategies and in the soils (Flores-Sanchez et al., 2011). Also for the subsidized fertilizer package (69-30-00 kg ha^{-1} N-P-K) an alternative which included 25 kg ha^{-1}K was created based on INIFAP recommendations (Gómez et al., 2007). Finally, a system with a fertilizer rate of 135-39-83 (kg ha^{-1} N-P-K) was included corresponding to the agronomic recommendation (R) for maize – roselle systems (Navarro et al., 2002). Other soil fertility strategies were based on experimental trials (E), which included mineral fertilizers at a rate of 55-5-46, vermicompost at a rate of 2.5 Mg DM ha^{-1}, equivalent to 23-6-20 (kg ha^{-1} N-P-K), and a combination of both equivalent to 78-11-66 (kg ha^{-1} N-P-K).

Maize production levels for each cropping system and each farm were calculated in an input-oriented manner using the model QUEFTS (Janssen et al., 1990), which was evaluated for the region by Flores-Sanchez et al. (2011). The model uses soil chemical properties as inputs, including organic carbon (g kg^{-1}) assuming 58% C in soil OM, total N (g kg^{-1}), P-Bray-1 (mg kg^{-1}) (B.H. Janssen; personal communication), K-exchangeable (cmol kg^{-1}), pH (H_2O) and cropping system-specific rates of fertilizer. The model first calculates crop uptake rates of N, P and K based on the potential supply by the soil, the applied amounts of fertilizer, and an estimated nutrient recovery of applied nutrients. Next, three intermediate yield estimates are made, one for each of the nutrient pairs based on the uptake of N, P and K, taking into account for each nutrient values for maximum accumulation (i.e. the nutrient is not yield-limiting) and maximum dilution (i.e. the nutrient is yield-limiting). In the final step, yield is predicted based on the smaller of the three yield estimates.

Weed management was assumed to be conventional with herbicide applications at maize sowing and three weeks later, resulting in same biomass of weeds as found for current practices (Flores-Sanchez et al., 2011). In all land use activities, roselle yield was assumed to be similar to that found currently on the farms, as roselle was found to show little response to different rates of fertilizer (Chapter 4).

A number of fertilization strategies included canavalia as cover crop (Table 4), which was assumed to be sown 4 weeks after sowing maize. Experimental results did not reveal direct effects of canavalia on maize grain yield (Flores-Sanchez et al., 2013), but did demonstrate a substantial reduction of weed biomass. Assuming similar conditions as in the experiments for those MBCS that included canavalia, weed biomass was reduced by 66% compared to current practices. Except for those strategies in which fields were assumed to be fenced resulting in 100% residue retention, 70% of the biomass of crop residues, weeds and canavalia was assumed to be removed by roaming animals (on farms without animals) or fed to the own farm animals (Flores-Sanchez et al., 2011). Input from N_2 fixation by canavalia was set at 6 kg ha^{-1} y^{-1} in a maize – roselle intercrop, and 16 kg ha^{-1} y^{-1} in a maize monocrop, similar to field estimates (Flores-Sanchez et al., unpublished data).

Quantification of labour input was based on current labour use observed on each of the case study farms. A fixed amount (2 labour-days = 16 hours) of additional labour was added to account for the time needed to cover the fertilizer and compost after application to the plant base. This technique was assumed to be a 'best technical means' (van Ittersum and Rabbinge, 1997) to maximize use efficiency by avoiding washing off. Labour was hired outside the farm to deal with labour peaks; the remainder was supplied by the farmer and his family (Table 5). We denote the former as casual labour and the latter as regular labour.

Table 5. Regular and casual labour (hr ha^{-1}) for each MBCS variant and for each farm.

Farm	MBCS					
	Current		All Cu and R variants[1]		All others	
	Regular	Casual	Regular	Casual	Regular	Casual
A1	128	208	144	240	160	256
A2	176	256	200	280	224	288
A3	96	176	112	208	128	224
A4	180	244	196	276	212	292
X1	120	232	136	264	152	280
X2	144	288	152	312	160	336
X3	168	264	192	288	216	296
X4	144	288	171	250	184	274

[1] Variants as described by their labels (Table 3).

For each cropping system production costs were estimated based on quantities and prices of inputs: mineral and organic fertilizers, herbicides, seeds and labour. Cost of inputs per MBCS and variation among farms are presented in Table 6. Prices of crop products (maize grains and roselle calyces) and animal products (meat) were obtained from the databases *Sistema Nacional de Información Agroalimentaria y de Consulta* (SIACON) and *Sistema Nacional de Información e Integración de Mercados* (SNIIM) using data of 2003. Both family and hired labour were valued at 50 MX$ hr^{-1}.

Table 6. Average costs per ha (in Mexican pesos (MX$) for each maize-based cropping system. Ranges are due to differences in amounts used per farm. For abbreviations of the MBCS see Table 4.

MBCS	Casual labour	Regular labour	Fertilizers and herbicides	Seeds[a]	Fences	Total cost
Cu(Fcr)	3961	1580	1189	0	0	6730
Cu_{+k}(Fcr)	4063	1703	2004	0	0	7770
S(Fcr)	4150	1703	1233	0	0	7086
S_{+K}(Fcr)	4063	1703	1502	0	0	7268
R(Fcr)	4078	1703	2304	0	0	8085
E(Fcr)	4063	1703	1023	0	0	6788
E(Vcr)	4063	1703	2812	0	0	8578
E(F-Vcr)	4063	1703	3508	0	0	9274
E(FCr)	4161	1802	1023	350	0	7336
E(VCr)	4161	1802	2812	350	0	9125
E(F-VCr)	4155	1802	3508	350	0	9815
E(FCR)	3442	1838	1092	350	181	6644
E(VCR)	3442	1838	2893	350	181	8444
E(F-VCR)	3442	1838	3570	350	181	9122

[a] Cost of canavalia seed. Farmers used own or exchanged seeds of maize and roselle.

2.3.2. Animal production systems

The design of animal production activities concentrated on goats and cattle, as numbers of horses, donkeys and mules were limited to one or two animals per farm. No detailed information was available on management systems, but based on farmer interviews and experiences in the area we assumed on-farm feeding for two to three months, depending on available feed resources, and roaming outside the farm during the rest of the year. This had implications for nutrient cycles as roaming was assumed not to contribute to the on-farm nutrient or OM cycles.

We distinguished cows, heifers, calves and goats with body weights of 450, 300, 170 and 75 kg, respectively. Marketable outputs comprised meat of culled cows and goats. Calves stayed with the mother and used her milk. Non-marketable outputs comprised changes in the soil OM balance resulting from application and decomposition of manure during the time the animals were on the farm. Animal feed stuffs comprised grain, straw and weeds which were produced within the farm. Feed was characterized by three feed value indicators: dry matter (g kg^{-1}), metabolizable energy (Mcal kg^{-1}) and crude protein content (g kg^{-1}), which were based on published and regional sources (NCR, 1981, NCR, 2001; Douxchamps, 2010; Cortez-Arriola, personal communication). The amount of labour needed for herd and stable management and for general farm management was estimated based on Cortez-Arriola et al. (unpublished data) who collected data on smallholders in West-Michoacán. Parameters such as carcass %, milk protein and fat content, and energy and protein requirements were taken from literature (NRC, 1981; NRC, 2000; Martínez et al., 2010).

2.4. Farm-level analyses: performance of current and possible future farming systems

The performance of current and possible future farming systems was evaluated in terms of family income, OM balance and input of regular (own) labour using the FarmDESIGN model (Groot et al., 2012).The model calculates transfers of dry and OM, C, N, P and K between the farm compartments crops, animals, manure and soil, all based on production ecological relations. Imports, e.g. through fertilizers and exports, e.g. sales or losses are taken into account. The model allows characterization of the current farming system, as well as exploration of future farming systems that perform better in terms of the objectives by varying areas of current and alternative MBCS and numbers of farm animals under a set of user-specified constraints, e.g. related to maximum area and feed balance deviation. Results are expressed as trade-offs among objectives.

The crop component comprised the current and alternative land use systems, i.e. maize and roselle as monocrop, and/or maize – roselle as intercrop, as well as the land use system products, i.e. maize grains, maize residues, roselle calyces, roselle residues, and weeds. Crop products have one or several destinations: application to the soil (crop residues and cut weeds left on the field), feed for animals (crop residues and weeds), home use by the farm family (grains) and selling on the market (grains and calyces).

The animal component included goats and cows. Feed balances and manure produced by animals were calculated for the part of the dry season that the animals were around the homestead. The duration of this on-farm feeding phase was estimated to be 100 days for farm A3, and 130 days for farms A2 and A4, based on information of the farmers and calculations with the model. In the explorations (Scenarios S1-S4, see below) it was assumed that manure produced within the farm was applied to the crops. These amounts were included in the calculation of grain yield per production system, using QUEFTS.

Family income (FI) represents the actual amount of money available to the farm family on an annual basis, calculated as the sum of the margins of crop and animal products minus costs of fertilizers, pesticides, and casual labour. The amount of maize sold equalled the amount of maize produced minus the amount used for self-consumption. Daily per capita consumption of maize was assumed to be 0.5 kg. We compared family income with the 'basic food basket', a local indicator of the minimum amount of money required for self-sufficiency when basic needs are met through the market (CONEVAL, 2012).

The OM balance was calculated by combining four 'sub-balances': root residues, aboveground crop residues, manure and soil OM. Balances were calculated as the difference between annual input and output. Of the maize and weeds residues, 30% biomass was assumed to remain in the field where they were produced, the remainder being taken up by animals. In case of farm-owned animals, the resulting manure was assumed to stay on the farm. If the farm did not own animals, roaming animals were assumed to export the OM from the farm system. Roselle residues were assumed to be not suitable for animal consumption and remained in the field. Similarly, in MBCS with residue retention due to fencing of the fields no export or 100% of residue retention was assumed.

The net contribution of root and aboveground crop residues to the OM balance was quantified as the amount of OM remaining one year after application in the field (Groot at al., 2012). Root biomass was estimated as 15% of total crop biomass (Rodriguez, 1993). After calibration with litterbag experiments in farmers' fields (Chapter 5), the mono-component model of Yang and Janssen (2000) was used to predict the amount of root OM remaining per field after one year.

Estimates of bulk density (1.3 Mg m^{-3}) and annual rate of SOM decomposition (0.5 % $year^{-1}$) were taken from Grace et al. (2002) for no-tillage conditions in long term trials at CIMMYT, central Mexico. This information was used together with field-specific estimates of soil depth to calculate annual soil OM degradation (see Groot et al., 2012).

Erosion was considered a cause of soil OM and plant nutrient losses. Loss rates were calculated using RUSLE estimates of soil loss, multiplied by SOM, N, P or K fractions as established in an earlier farm diagnosis (Flores-Sanchez et al., 2011).

Balances for regular labour were calculated by subtracting farmer-provided own labour input for herd and animal management and for the various activities in each MBCS from the amount of labour available given the size of the farm family, assuming each person to provide 2190 hour per annum.

Exploration of possible future farming systems started from the current farming systems (scenario S0), which for three farms included animals (Table 1), and then proceeded in four incremental steps (Scenarios S1 to S4). Scenario S1 included the MBCS Cu(Fcr), Cu_{+K}(Fcr), S(Fcr), S_{+K}(Fcr),), E(Fcr), E(FCr), and E(FCR)in which plant nutrient provision was improved compared to the current system (Cu(Fcr), Table

4) by relying on imported fertilizers. Canavalia and crop residue retention were included in two MBCS E(FCr), and E(FCR). In Scenario S2 the set of MBCS was further expanded by those designed to enhance soil OM balances (E(Vcr), E(F-Vcr), E(FCr), E(VCr), E(F-VCr), E(FCR), E(VCR), E(F-VCR); see Table 4). In this scenario six MBCS included canavalia, and three with residue retention. Scenarios S1 and S2 thus assumed fine-tuning of current cropping system management by redressing nutrient and OM imbalances without substantially changing production per unit area. Scenarios S3 and S4 assumed incremental intensification of production by allowing the model to select R(Fcr), the MBCS with the highest fertilizer inputs (S3) and associated yields, and to select a herd of goats and/or cows that was fed on the farm during 120 days (S4). In all scenarios, canavalia was included as a monocrop, to evaluate its potential to compete with other land use activities to restore soil functions. Scenario S4 was not run for farms X2 and X4, as their size (1 ha) was assumed to be prohibitive for providing on-farm feed for animals during 120 days. On the farms that owned animals in scenario S0, the number of animals was kept constant in scenarios S1 to S3, and optimized in S4.

The explorations were performed in FarmDESIGN using a genetic algorithm and a fitness function based on Pareto-based ranking and crowing metrics (Groot et al., 2012). Three objectives were addressed simultaneously: maximization of family income, maximization of the OM balance, and minimization of the regular labour balance. For Scenarios S1 to S3 the decision variables included cultivated areas of MBCS. When a farm cultivated roselle either in mixture with maize or as monocrop, these variants were included as well, thus assessing the strength of roselle to compete with other land use activities. For Scenario S4 the number of milking cows, their replacement rate, and the number of goats were added as decision variables. Cultivated areas were set as constraints in S1 to S3, in S4 expanded with constraints on feed intake (dry matter (g kg^{-1}), metabolizable energy (Mcal kg^{-1}) and crude protein (g kg^{-1}) to ensure reasonable feeding patterns.

The results are described in two steps. In the first step each maize-based cropping system (MBCS) is assumed to be deployed on the whole farm and consequences are assessed in terms of family income, OM balance and regular labour balance. This analysis highlights the variation among MBCS per farm and among farms. In the second step, the trade-offs among the objectives for the four scenarios are summarized by triangles which connect current system performance with best performances for each of the objectives. By projecting these in two dimensions triangles are obtained, which show the amount of improvement possible compared to the current farming systems and the severity of the trade-offs among the objectives.

3. Results

3.1. Single MBCS deployed on the whole farm

Compared to the current farm-specific systems the re-designed MBCS resulted in yields that were up to a factor 2 greater (Table 7). Highest yields were mostly associated with the agronomic recommendation R(Fcr), which resulted in yields at or above 3.5 Mg ha^{-1}. Farms responded differently to a particular strategy, reflecting the current differences in soil fertility status of their individual fields. Applying the cropping systems to the entire farm area showed that 6 out of 8 farms remained below the ‘basic food basket’ (Figure 1) indicating that livelihoods would need to rely on barter, remittances or on income from hiring out labour. We define the family income gap as the difference between family income from a maize production technology and the basic food basket. The two farms that achieved family income close to or slightly above the basic food basket included animals (farms A2 and A4). These were also the farms with the largest per capita land area. In contrast, farm A3, which had the largest number of animals (14 cows and 14 goats, Table 1) attained less family income and suffered a larger family income gap. The gap was even larger than that of farms X1 and X3 which did not include cows or goats while having a slightly smaller per capita land area. This suggests that animal husbandry on the land-limited farm A3 did not provide advantages over a purely crop-based strategy.

The subsidies provided through the PROCAMPO program of the Mexican government are linked to farmed hectares and therefore differed among farms. The contribution from PROCAMPO to total family income varied from MX$ 1,030 to 4,300 (white bars in Figure 1).

Table 7. Range of field-specific maize grain yield (kg DM ha^{-1}) for different maize-based cropping systems on eight farms in the communities Las Animas (A1 to A4) and Xalpathlahuac (X1 to X4). Farms A2, A3 and A4 were assumed to also apply on-farm produced manure. Inclusion of canavalia or residue retention did not affect maize yield and is denoted as xx in the MBCS identifiers. For explanation of MBCS see Table 4.

MCBS	Farms							
	A1	A2	A3	A4	X1	X2	X3	X4
Cu(Fcr)	1268	1284 – 2431	1470 – 1958	1522 – 2509	1673 – 2647	2098	1212 – 2374	2122
Cu$_{+K}$(Fcr)	2529	2350 – 4672	2415-3359	3054- 4139	3867-4683	4008	2602-3580	4693
S(Fcr)	2578	2343 - 4350	2356 - 3667	1997 - 3662	2849 - 3988	3249	2112 - 2972	3395
S$_{+K}$(Fcr)	2584	2345 - 4508	2370 - 3700	2022 - 3272	2898 - 4035	3285	2122 - 3030	3586
R(Fcr)	3689	3496 - 5502	3427 - 4704	3093 - 4770	3892 - 5017	4281	3216 - 4052	4567
E(Fxx)	2252	2113 - 3702	2012 - 3226	1719 - 3469	2370 - 3466	2586	1896 - 2892	2931
E(Vxx)	1861	1802 - 3515	1844 - 3117	1388 - 3287	2132 - 3223	2354	1464 - 2524	2710
E(F-Vxx)	2868	2819 - 4312	2690 - 3798	2359 - 4139	2781 - 4021	3176	2529 - 3472	3416

Assuming uptake of a particular MBCS on the entire area of each of the eight farms, trade-offs among family income, OM balance and labour input are shown in Figure 2. Many systems are better than the current system (system A in Figure 2) in both family income and OM balance. Values of family income less than the current are obtained when vermicompost is included without additional fertilizer (systems G, J, M) as additional costs of vermicompost purchase and transportation are not fully compensated by yield increases. Cropping systems E, H, K and N are on the trade-off frontier (Figures 2A and 2D) as they contribute most positively to OM balance and family income. The four systems all rely on fertilizer input, albeit in different amounts (cf. Table 4). Cropping systems H, K and N are associated with 78-11-66 kg ha^{-1} N-P-K input, partly in vermicompost. Cropping system E is associated with 135-39-83 kg ha^{-1} N-P-K input, but does not include an organic source of nutrients. Residue retention and inclusion of canavalia contribute positively to the SOM balance; their effect is about 2/3 of the effect of vermicompost when compared to the fertilizer-only cropping system E (Figures 2A and 2B). System E contributes more than the current system to the SOM balance due to its larger biomass production, which partly stays in the field. Improvements in OM balance demand more labour (Figures 2B and 2E). On farms without animals (farms A1, X1, X2, X3 and X4) increasing crop residue retention substantially increased OM balances (systems L, M and N), but also demanded more labour. The alternative MBCS demanded relatively more labour, but family income was improved (Figures 2C and 2F).

3.2. Explorations based on the four scenarios

Explorations for the eight farms were conducted for scenarios S1 to S4. From the current system (S0) to scenario S3 the number of possible cropping systems increased sequentially, and FarmDESIGN was used to find combinations of areas that optimized farm performance for the three objectives maximize family income, minimize own labour and maximize OM balance, simultaneously. Scenario S4 comprised the set of cropping systems of S3 plus animal husbandry on those farms that did not have animals to start with. Decision variables comprised hectares of cropping activities and, for S4, number of goats and cows and their replacement rate. The results demonstrate that improvements are feasible for family income, OM balance and required family labour as illustrated for farm A3 in Scenario 4 (Figure 3). The relation between labour requirement and the other two objectives was similar for all farms: relatively small differences between best and worst values of labour requirement. As a result, in the rest of this section we concentrate on the trade-off between the other two objectives, which was however calculated including the labour balance objective. The results are shown in Figure 4 and Table 8 for each farm and for each of the four scenarios.

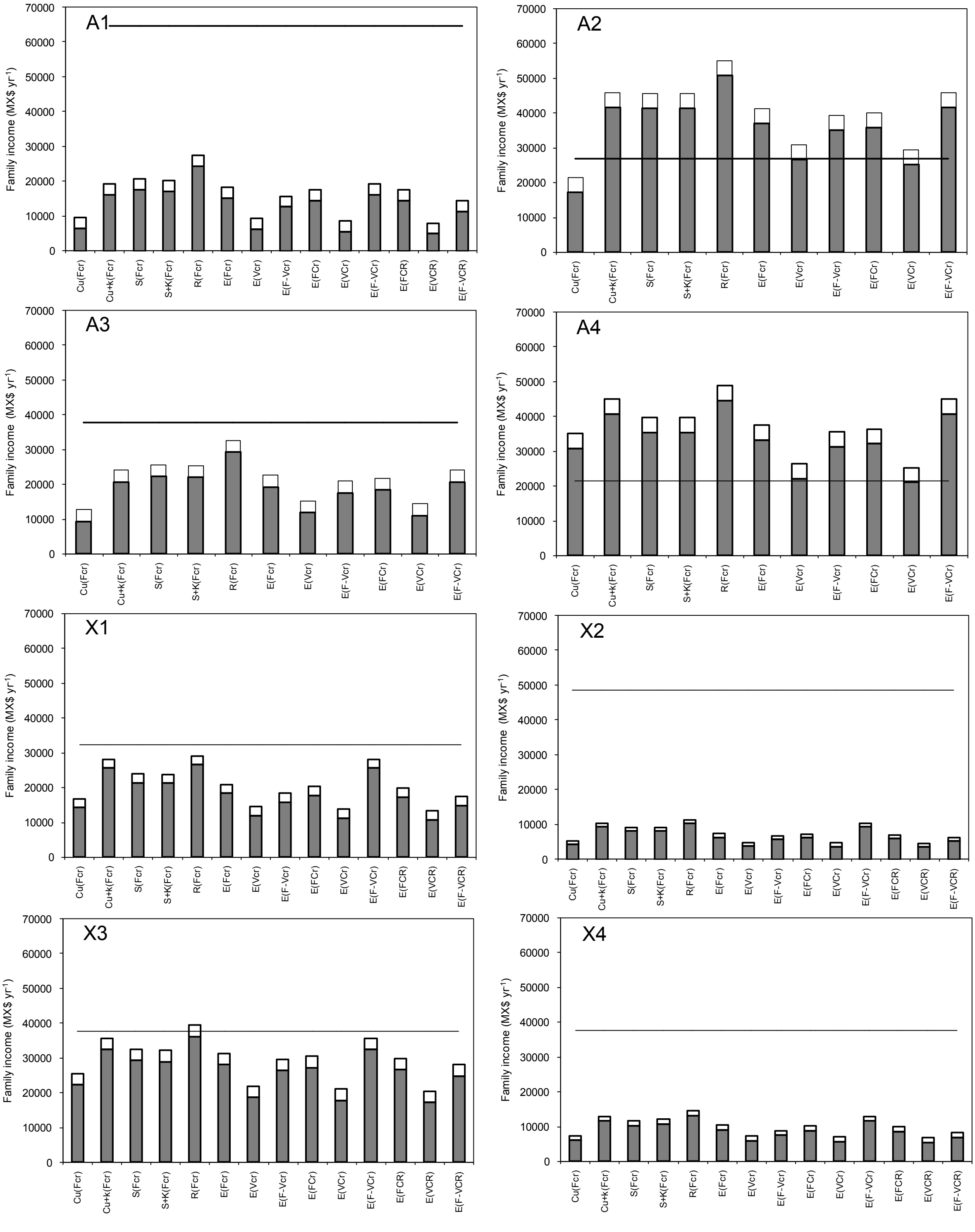

Figure 1. Family income for eight smallholder farms in Costa Chica, Mexico, for different maize-based cropping systems. Grey bars: family income from agriculture. White bars: family income from the PROCAMPO subsidy (MX $1,030 ha^{-1}). The horizontal line represents the basic food basket (CONEVAL, 2012) for the particular farm family. For details on the maize-based cropping systems described in the legend see Table 4.

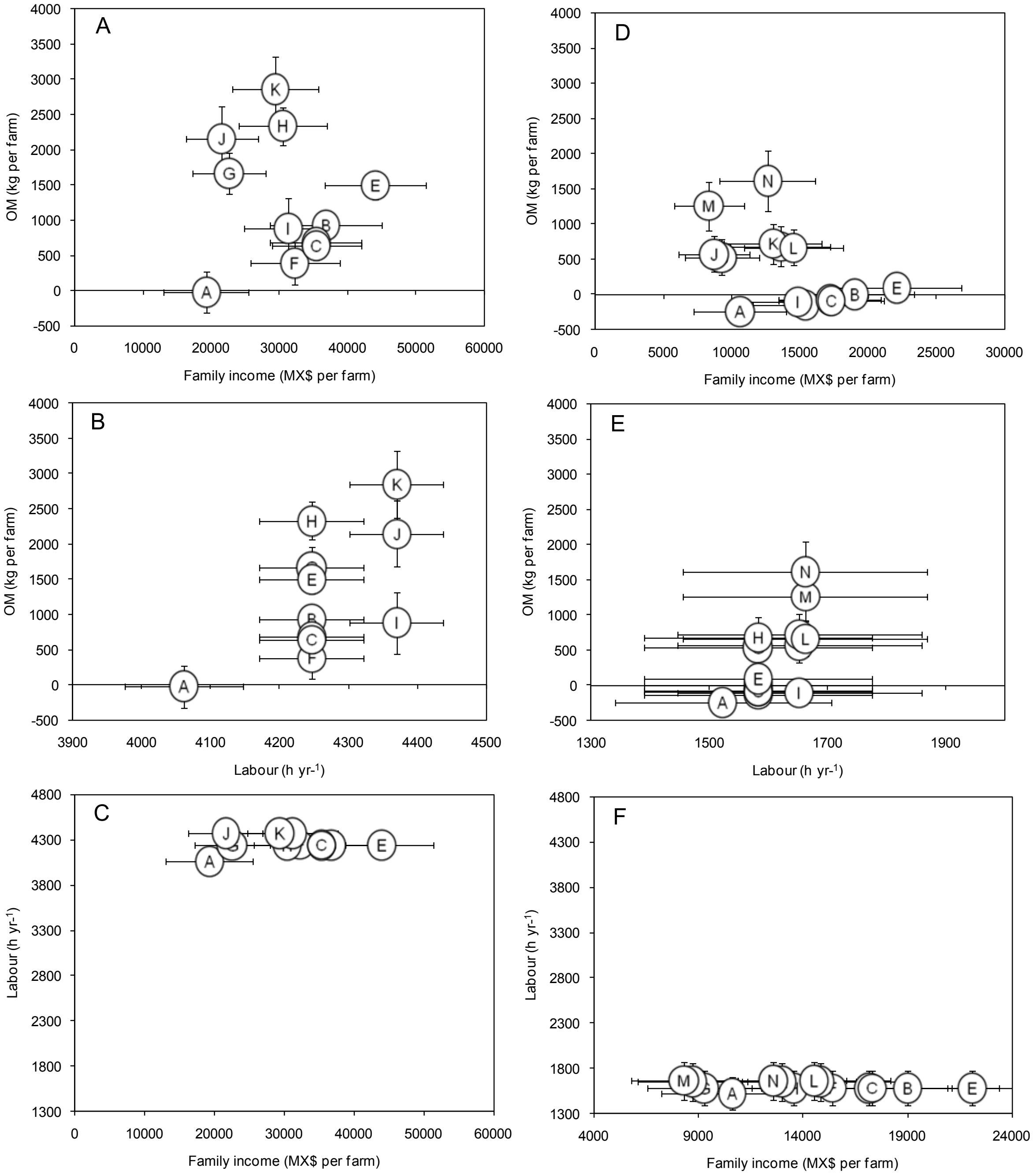

Figure 2. Trade-offs among family income, regular labour requirements and OM balance assuming that eight smallholder farms dedicate their entire cropping area to a single maize-based cropping system (MBCS). Results are expressed as averages across farms. Bars indicate standard errors. Panels on the left concern farms with animals, farms on the right without animals. MBCS codes: A: Cu(Fcr), B: Cu$_{+K}$(Fcr), C: S(Fcr), D: S$_{+K}$(Fcr), E: R(Fcr), F: E(Fcr), G: E(Vcr), H: E(F-Vcr), I: E(FCr), J: E(VCr), K: E(F-VCr), L: E(FCR); M: E(VCR), N: E(F-VCR). For details on the maize-based cropping systems described in the legend see Table 4.

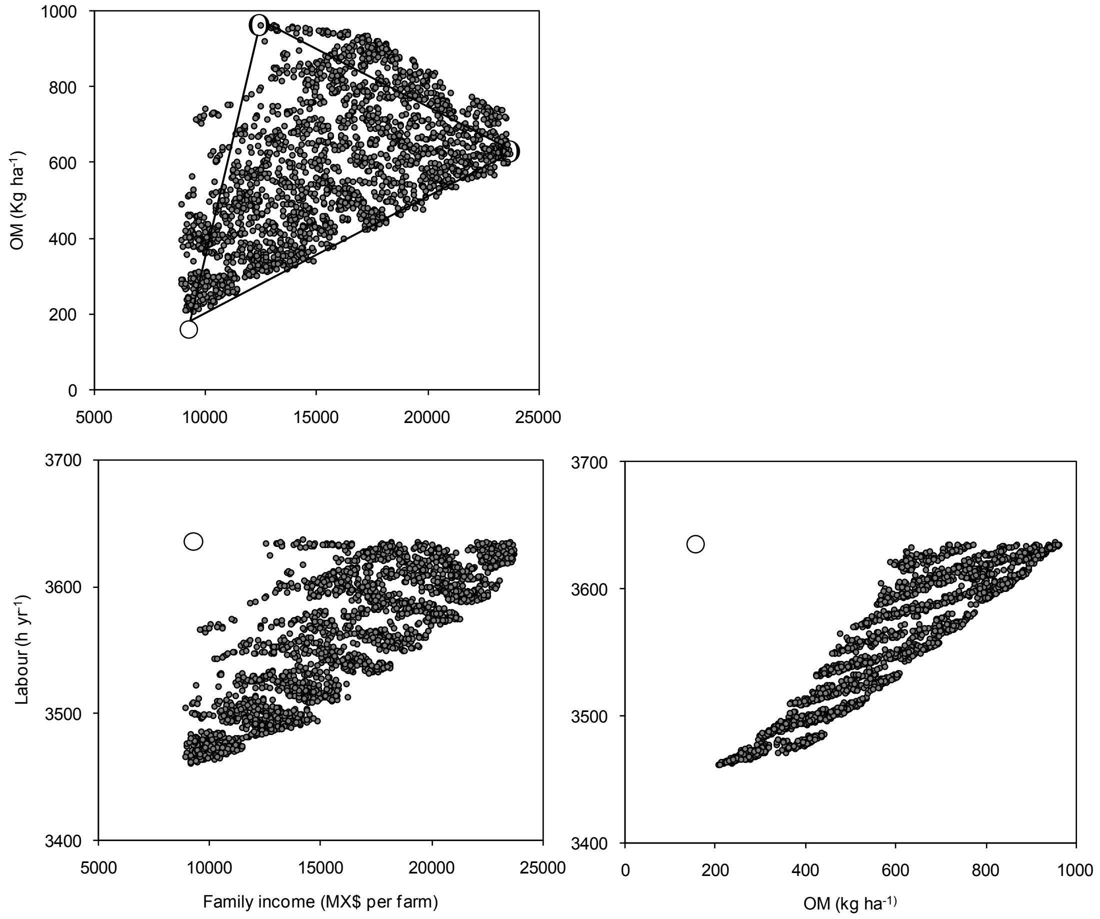

Figure 3. Illustration of the trade-offs among family income, regular labour input and OM balance on farm A3 for explorations based on Scenario 4. The open circle corresponds to current MBCS. Closed circles represent alternative farming systems. The triangle in the top panel illustrates the procedure used to arrive at Figure 4.

For Scenario S1, maximum family income was mostly associated with the current fertilizer strategy plus K (Table 8). On two farms, MBCS based on subsidized rates of fertilizer were selected, and on the farm with the largest number of animals (A3) canavalia was grown on 40% of the area. To maximize OM balance, on some farms MBCS with current or subsidized rates of fertilizer rates dominated, always with a supplementation of K. On other farms moderate fertilizer rates were combined with canavalia and residue retention (E(FCR)). For Scenario S2 the inclusion of vermicompost was selected among the options that maximized OM balances. To maximize family income the land use systems selected were similar to those for S1. For Scenario S3 the R(Fcr) option that included the largest fertilizer rates resulting in the largest maize biomass and yield was selected on all farms to maximize family income. Large biomass and hence residue production by R(Fcr) also made it the option

Table 8. Major MBCS and numbers of animals selected to maximize family income or organic matter balance (OM) under four intensification scenarios. For explanation of abbreviations of the MBCS see Table 4.

Farms	Characteristics	Current S0	Scenario S1		Scenario S2		Scenario S3		Scenario S4	
			Family Income	OM	Family Income	OM	Family Income	OM	Family Income	OM
A1	MBCS (ha)	Cu(Fcr)	S_{+K}(Fcr)* (100)	S_{+K}(Fcr) (100)	S_{+K}(Fcr) (100)	E(F-Vcr) (92)	R(Fcr) (100)	R(Fcr) (100)	R(Fcr) (66) Can (34)	R(Fcr) (62) Can (38)
	Animals	0	0	0	0	0	0	0	13	15
A2	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	Cu_{+k}(Fcr) (99)	E(F-Vcr) (61) S_{+K}(Fcr) (17) Cu_{+k}(Fcr) (17)	E(F-Vcr) (60) E(F-VCr) (38)	R(Fcr) (55) E(F-Vcr) (38)	E(F-Vcr) (53) E(F-VCr) (47)	R(Fcr) (95)	E(F-VCr) (85)
	Animals	12	12	12	12	12	12	12	0	25
A3	MBCS	Cu(Fcr)	S (Fcr) (45) Can (39) S_{+K}(Fcr) (15)	S_{+K}(Fcr) (57) S(Fcr) (33)	S_{+K}(Fcr) (44) S(Fcr) (31)	E(F-Vcr) (85) Can (14)	R(Fcr) (67) Can (33)	E(F-Vcr) (87) Can (13)	R(Fcr) (81) Can (13)	E(F-Vcr) (59) E(F-VCr) (39)
	Animals	28	28	28	28	28	28	28	22	21
A4	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	E(FCr) (85) Cu_{+k}(Fcr) (15)	E(F-VCr) (100)	E(F-VCr) (100)	R(Fcr) (100)	E(F-VCr) (100)	R(Fcr) (93)	E(F-VCr) (100)
	Animals		7	7	7	7	7	7	0	0
X1	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	E(FCR) (100)	Cu_{+k}(Fcr) (100)	E(F-VCR) (100)	R(Fcr) (100)	E(F-VCR) (100)	R(Fcr) (100)	R(Fcr) (100)
	Animals		0	0	0	0	0	0	7	7
X2	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	E(FCR) (100)	Cu_{+k}(Fcr) (100)	E(F-VCR) (100)	R(Fcr) (100)	E(F-VCR) (100)		
	Animals		0	0	0	0	0	0		
X3	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	E(FCR) (100)	Cu_{+k}(Fcr) (100)	E(F-VCR) (100)	R(Fcr) (100)	E(F-VCR) (100)	R(Fcr) (100)	E(F-Vcr) (73) R(Fcr) (13) Can (13)
	Animals	0	0	0	0	0	0	0	0	16
X4	MBCS	Cu(Fcr)	Cu_{+k}(Fcr) (100)	Cu_{+k}(Fcr) (100)	Cu_{+k}(Fcr) (100)	E(F-VCR) (58) E(F-VCr) (33)	R(Fcr) (100)	R(Fcr) (100)		
	Animals	0	0	0	0	0	0	0		

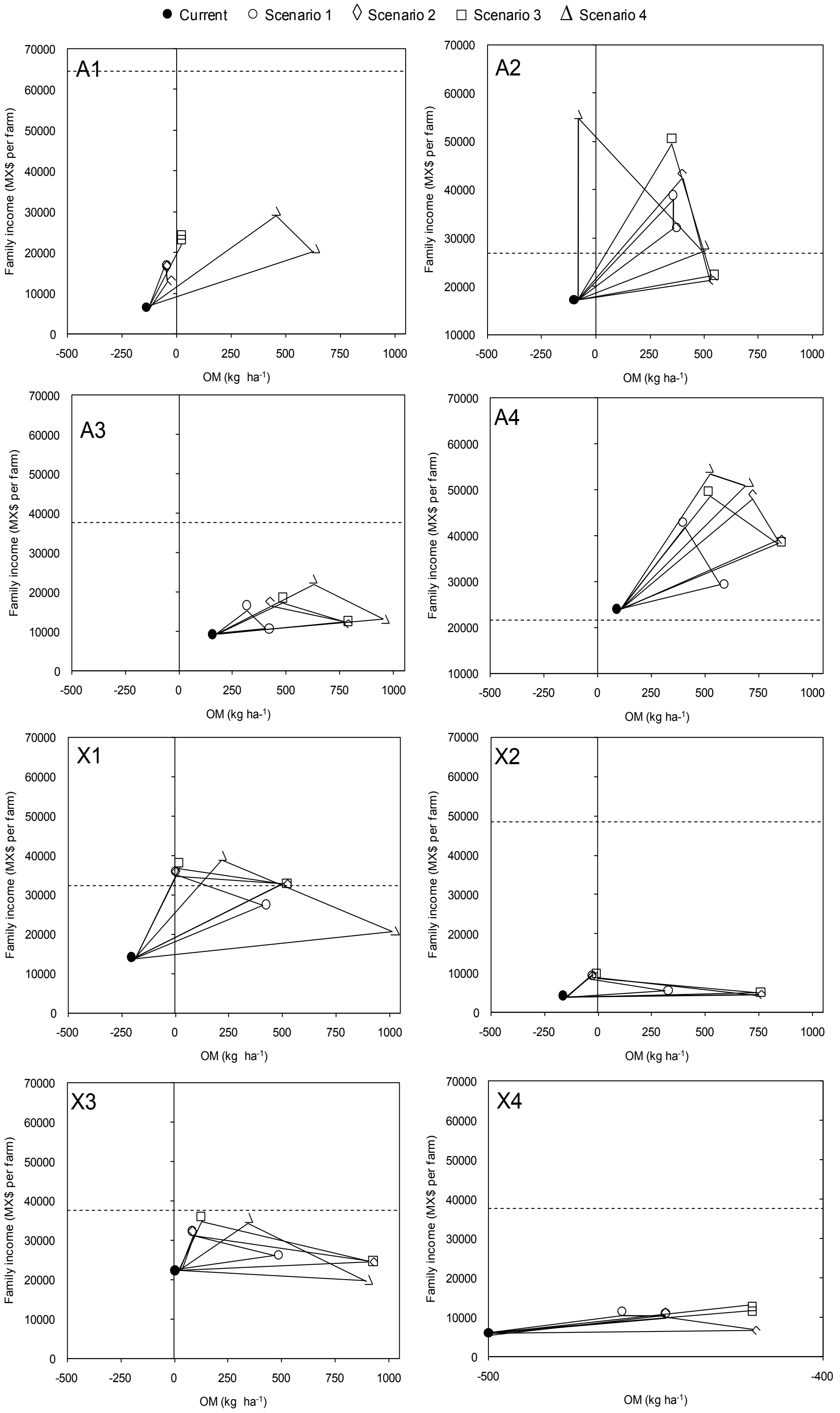

Figure 4. Relationship between family income and OM balance for the exploration of four scenarios on eight farms. The horizontal dotted line represents the basic food basket (CONEVAL, 2012) for the total farm family.

that maximized OM balance on two of the eight farms. On the other farms maximizing OM balance required MBCS relying on canavalia and/or vermicompost. Optimization of number of animals in Scenario S4 maintained R(Fcr) as the best MBCS to maximize family income. Only on half of the farms animal husbandry was a means to increase family income. However, animal husbandry together with the application of vermicompost with or without canavalia (E(F-VCr) and E(F-Vcr)) were important to maximize OM balances (Table 8).

Trade-off triangles were constructed for the objectives family income and OM balance by linearly connecting the current farming system with those that exhibited best performance in each of the objectives, as illustrated in Figure 3. The trade-off triangles (Figure 4) show that as the number and type of land use options increases from scenario S0 to S4, the trade-off frontier shifts outward. Both family income and OM balance can be improved, although with large differences among the farms, as revealed by the size of the triangles. The triangles are not congruent, indicating that the trade-offs between the objectives change when progressing through the scenarios. For some scenarios and farms narrow triangles were found (e.g. farm A1, scenario S3; farm X4, scenario S3) indicating that trade-offs were replaced by (a few) optimal solution(s).

4. Discussion

This study set out to study options for improving socio-economic performance and resource use of smallholder livelihoods in the Costa Chica by bringing together information on alternative maize-based cropping systems and animal husbandry in a context of actual farms. The study addressed socio-economic performance in terms of family income and use of regular labour, and evaluated resource use in terms of changes in the soil OM balance.

4.1. Opportunities for improving family income, OM balance and labour balance

Results for the eight farms from two communities representative of the Costa Chica (Flores-Sanchez et al., 2011) showed the need to increase family income, which on most farms was found to be considerably smaller than the minimum needed to sustain the family members, i.e. the basic food basket. Results also showed that considerable improvements were possible by intensification of maize production (Figures 2 and 4). Roselle is one of the main sources of income; however, its cultivation demands high labour input, making it an expensive crop to grow. Therefore, improvements in maize production appeared to be more attractive.

Whether increases to the level of the basic food basket were feasible was dependent on per capita land area (PCLA). For six out of eight farms the PCLA was too small even at the highest farm productivities calculated in scenario S4. Only farms A2 and A4 (PCLAs 0.8 and 1.05 ha, respectively (Table 1)) reached family income above the livelihood threshold for the current farm systems. Calculations for scenario S4 showed that also farm X1 (PCLA 0.42 ha) could attain the threshold and farm X3 (PCLA 0.44 ha) could come close to it, but with trade-offs with the OM balance. Worldwide, PCLA was 0.21 ha in 2007 (Foresight, 2011).

Current maize systems on all farms were associated with negative annual OM balances, whilst SOC levels in the area are already generally low. We found SOC levels of 3 to 16 g kg^{-1}. Similarly, Navarro et al. (2002) reported values from 2 to 30 g kg^{-1} for the same region; others found a range from 6 to 27 g kg^{-1} (Presidencia Municipal de Tecoanapa, Gro., and Instituto de Investigación Científica Área Ciencias Naturales-UAG, 2001). This high level of soil degradation affects the potential supply of N, P and K (Janssen et al., 1990; Mulder, 2000). As a result, the attainable yield predictions with QUEFTS varied greatly - up to 100% - across fields at similar rates of fertilizer input (Table 7). To increase long-term productivity and input use efficiency on these sandy soils, addition of OM sources should be an integral component of any restoration strategy or policy (Mann et al., 2002; Lal, 2005; Chivenge et al., 2007). In such strategies the existing variation among fields should be taken into account, e.g. by allocating greater amounts of organic inputs to fields that are more degraded. In the explorations increases in annual OM balances were achieved in various ways. Firstly, producing a larger amount of biomass by increasing inorganic fertilizer application resulted in greater yields as well as larger amounts of residues. The results of scenario S3 compared to S2 indicated that the net effect on annual OM balance was usually limited as 70% of the residues were assumed to be removed by roaming animals (Fig. 4). Secondly, use of vermicompost contributed directly to the OM balance, but required important labour and monetary expenditure (Tables 5 and 6). Finally, residue retention by fencing fields and use of canavalia as cover crop contributed positively to OM balances, while requiring less input than vermicompost. The higher costs of maintaining OM inputs caused the trade-off between annual OM balance and family income (Figure 4).

Calculations for scenario S4 showed that increasing animal numbers always served to maintain greater balances of OM. However, maximum family income strategies did not always include animals, indicating the relatively important direct costs for labour and feed associated with them.

Labour requirements increased roughly linearly with family income. Even though a large number of family members were available for working on the farm, according to the farmers casual labour was hired to deal with peaks in field work. A more in-depth analysis is needed to reveal whether this does not concern reciprocal labour, where families work on each other's farms and sow, weed, and harvest together based on monetary remuneration. If that is the case the fraction of family labour in the total labour requirement would be used to a much greater degree than the on average 31% we found.

4.2. Land-use scenarios for the short and the middle term

The land use scenarios S1 and S2 were set up to reveal the importance of redressing imbalances in current nutrient and OM application within the opportunities offered by government subsidy schemes for fertilizers (to a maximum of 2 ha) and by local vermicomposting facilities. For family income maximization in scenarios S1 and S2 fertilizer rates always included K application, indicating the farm economic benefit of a more balanced but also more costly crop nutrition. According to these results, purchasing K at market rates in addition to purchasing subsidized N and P fertilizer would be beneficial to family income (Table 8).

Compared to scenario S1 maximization of OM balance in S2 relied strongly on vermicompost. Vermicompost production and transport costs were taken into account, assuming a maximum application rate of 2.5 ton ha^{-1}. At this rate, total regional vermicomposting capacity may be insufficient to produce the amounts needed to provide for the entire 14,000 ha of agricultural area. For instance, the composting facility in Tecoanapa produced 35 ton in 2006, 1 per mil of the total regional requirement. Government support would thus need to address not only fertilizer purchasing subsidies but also local initiatives to recycle household waste and produce vermicompost.

For scenario S1 and particularly for S2 the land use activities for family income and OM balance are quite distinct. To strike a balance between the two objectives thus requires a mix of fertilizer application that includes K and inputs of external OM, the costs of which fit within the financial constraints of individual farms.

Scenarios S3 and S4 represented more drastic changes, including high fertilizer inputs largely without subsidies and the option to have goats or cattle. Under the S3 scenario family income was maximized for all farms by applying the high fertilizer MBCS on a substantial fraction of the farm area. However, this MBCS did not prove the best for increasing soil OM balance, where MBCS were selected that included vermicompost, canavalia and residue retention through fencing (Table 8). Current subsidies for purchasing fertilizers provided by the State and municipal Governments amount to 600 million Mexican pesos and constitute the major agronomic support instrument. This policy has been criticized for its unilateral focus on fertilizers at the cost of stimulating the development of human and other rural support resources

(Mendez, 2012). A major challenge for policy will be to balance support for short-term gains in yields through fertilizer subsidies and support for long-term benefits from soil improvement.

In scenario S4 animals were excluded from the maximum family income solutions on those farms where feeding the animals (partly with maize grains) and selling the meat was less profitable than selling maize. The fact that on some farms animals were selected, and on others none indicates the delicate farm-specific balance between costs and returns. Goats were never selected as part of the optimal systems, although farms in the region often have considerable numbers of goats. It is known that animals in smallholder systems constitute a source of savings for subsistence needs. Animals can be kept as an insurance against eventualities, and provide an instrument of liquidity and consumption smoothing (McDermott et al., 1999; Randolph et al., 2007; Thornton, 2010). On the farms that had animals to start with (A2, A3 and A4) the contribution of the animal component to family income was only 16%, emphasizing that it is not the immediate cash contribution that makes animal husbandry important for smallholders. Similar to our findings, a study conducted in different countries demonstrated that income from livestock was 12% on average (Pica-Ciamarra et al., 2011). To avoid undesired side-effects of policies that support or not animal husbandry, information is needed to understand the trade-offs that farmers strike between costs of maintaining the animals and benefits provided by animals.

On all farms, cattle became part of the optimal system when maximizing OM balances due to enhanced recycling of residues on the farm rather than exporting residues with roaming cattle. As a result, farms with cattle had positive OM balances. Manure is a valuable resource for improving SOM balances and sustaining crop production (Randolph et al., 2007; McDermott et al., 2010; Pica-Ciamarra et al., 2011). We assumed that all manure produced during the on-farm period was applied on the farm fields assuming N losses during storage of approximately 30% (Groot et al., 2012). Better loss estimates requires information on the ways in which farmers collect, store and apply the manure (Rufino et al., 2006).

4.3. Policy implications

For subsistence farmers in Mexico, maize accounts for 70% of calories and 60% of proteins (Hellin et al., 2012). All eight farms were able to meet the level of self-sufficiency. However, family income from farming was insufficient to meet basic family needs even after re-design of the farms for five out of eight farms and the only option open to these families is to complement their farm income with off-farm employment (García-Barrios and García-Barrios, 1990; Hellin et al., 2012). These results took into account the federal support by the programs PROCAMPO (Program for Assistance in Agriculture) and *Oportunidades* (a program to alleviate poverty), and the fertilizer subsidy program from the state of Guerrero. These results are consistent with reports about the persistence of poverty and the high degree of marginalization in the region (CONEVAL, 2010).

The results suggest that the technological options that are currently available may be insufficient to enable farm families meeting the basic food basket. Diversification of options both on- and off-farm is needed to allow farmers to select activities that are suitable to their constraints and objectives, and policies aimed at regional development are needed. Key element of such rural policies should be agricultural extension and training of smallholders to understand the agro-ecological processes they manage and to promote land use activities that both provide increased returns in the short run as well as rendering the system resilient to changes in prices of inputs and to increased variability in weather as predicted for Mesoamerica (IPCC, 2007). Such ecological intensification can improve the resource base and the living standard of smallholders (McDermott et al., 2010; Hellin, 2012). Recently, the Federal Government and CIMMYT announced the implementation of *Modernización Sustentable de la Agricultura Tradicional* (MASAGRO, the Sustainable Modernization of Traditional Agriculture) targeted at smallholders. The program is aimed at increasing maize production in rainfed areas through improving agronomic practices, and the use of improved maize varieties (González-Rojas et al., 2011; Hellin et al., 2012). It will be very important to take into account that maize landraces or *criollos* are preferred over hybrids by the rural families due to better taste, ease of shelling cobs, time needed for cooking, better quality of *tortillas* storage time, and so on (Hellin et al., 2012). Thus, problems cannot be solved only including varieties. A key issue to be taken into account is the restoration of the resource base given the high degree of soil degradation in smallholder systems (Flores-Sanchez et al., 2011; OEIDRUS, 2011).

4.4. Conclusions

Model-based explorations for 8 real farms in the Costa Chica, Mexico demonstrated that farm family income can be increased and OM balances enhanced, without drastically changing labour input. Variation in response among the 8 farms highlighted the need for farm- and field-specific nutrient management strategies. Notwithstanding the progress possible, most of the farms did not reach a minimum living standard as specified by the basic food basket due to low productivity in combination with low per capita land availability. Policies to alleviate poverty should therefore take a multifaceted regional development approach that also develops off-farm economic options, rather than focus on fertilizer subsidies as is currently the case. Policy support for the regeneration of the degraded soils through OM-based technologies will be necessary as short term benefits favour purely fertilizer-based land use systems. Such support should address logistics as well as development of farmer and scientific knowledge.

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Chapter 7

General discussion

1. Introduction

Exploration of ecological intensification options for smallholder farming systems requires knowledge of agro-ecological processes, and understanding of socio-economic and socio-cultural relationships, including policies (Pretty et al., 2003; Pretty, 2008; Hyman et al., 2008; Giller et al., 2011). In this thesis, a diverse set of approaches was applied to characterize the prevailing farming systems, identify major constraints and evaluate alternative cropping systems. The previous chapters of this thesis indicated that livelihoods of smallholders in the Costa Chica, southwest Mexico are negatively impacted by low yields of the major staple crop maize and few cash-crop alternatives that allow market access. These results confirm the perceptions of farmers (Chapter 2). More detailed analyses of maize production pointed out constraints related to the quality of the predominantly sandy soils, including low plant nutrient concentrations despite sometimes high fertilizer rates, low soil organic matter levels and low soil pH. Among the causes of soil quality decline the study found continuous cropping of maize, sometimes intercropped with roselle with little return of organic matter to the soil, unbalanced external inputs strongly driven by government fertilizer programs that until recently did not take into account soil pH or crop macro-nutrient demand, and limited attention for erosion reduction on slopes of up to 40% (Chapter 2). On-farm experiments with legume intercrops during two years indicated that particularly *Canavalia brasiliensis* Mart. ex Benth could provide weed suppression without affecting maize yield negatively, and be acceptable to the farmers (Chapter 3). On-farm experiments with inorganic and organic plant nutrient sources showed that N and K constitute the main limiting nutrients for maize, while for P luxury consumption was found. Roselle was found to be well-adapted to the acid soils and was most limited by N (Chapter 4). Bringing the data, including those on organic matter decomposition (Chapter 5), together in an exploration of farm-specific development opportunities (Chapter 6) revealed that improvements of farm productivity and organic matter balances are feasible. Results also pointed out that because of family size agricultural productivity on many farms will remain insufficient to cover a reference minimum food basket for the farm family unless larger areas can be cultivated and/or other sources of income can be developed. Based on these results, design of farming systems that enable meeting productivity and resource conservation goals is work in progress. The results also indicate that in addition to re-considering on-farm practices, the fertilizer policy framework requires attention to better target the needs of the farmers and their agro-ecosystems.

In this chapter we will review the methods used in Chapters 2 to 6, and discuss results in relation to the implications for the maize-based farming systems in the Costa

Chica and for policies that target their productivity. The chapter concludes with recommendations for the research and policy agendas.

2. Strengths and weaknesses of approaches

Regional workshops and farm surveys provided empirical information on the way production ecological methods at the field level should be targeted to analyse key limitations in the production and management systems and to explore options for improving farm livelihoods. These methods have a wider applicability, and contribute to better understanding and focusing development-related research interventions in similar eco-regions. Participatory rural appraisals allowed gathering qualitative data, identifying together with farmers the key problems and their possible solutions. By involving farmers in the process of collecting information the communities developed a sense of the variation in points of view and in perceived problems. A limitation of the approach was that a group of farmers or leaders could dominate discussions during the workshops, leaving out less outspoken farmers. Making sure that stakeholders can contribute equally and safely to the process has been identified as an important factor for successful innovation (Clark et al., 2011), and developing facilitation skills of agronomists for this purpose is therefore pertinent. Checking results of the group meetings during farm visits, as we did in this study, was a means to allow input from less outspoken farmers.

By engaging with farmers, experimental options such as the integration of legumes in maize cropping and the use of organic and inorganic fertilizer combinations were exposed to assessment of operational feasibility by the farmers. In particular this resulted in termination of the mucuna treatment which was seen by farmers as interfering with maize harvesting due to the lush and erect growth of the mucuna vine. The results are thus more realistic in terms of management practices, constraints faced by farmers, and environmental variability (Drinkwater, 2002).

Difficulties associated with on-farm experiments were logistic; fields were often far from the villages and could only be reached by foot or on horseback, collection facilities for compost in the villages were poorly developed and no facilities existed in the area for analysing plant and soil samples. The on-farm experiments showed only the short-term effects of changes in intercrop and fertilizer management. Experimentation over longer time periods is needed to evaluate canavalia under different weather conditions and to assess the efficacy of the suggested split application of both organic and inorganic fertilizers.

The use of empirical data provided by the on-farm experiments allowed exploring scenarios using modelling. A major limitation was that in contrast with cropping system data, data on livestock systems were virtually non-existent. We resorted to using standard values from literature and agricultural expertise. The explorations at farm level thus constitute quantitative hypotheses for further validation and evaluation focused on livestock management, crop residue retention and nutrient inputs.

Because of the demand on human and financial resources associated with surveys and on-farm experimentation in the region, the full set of approaches in this thesis is not suitable for scaling out. Given the large number of farmers and the variation in production conditions, any program aimed at change will need to stimulate experimenting by the farmers themselves (Latta and O'Leary, 2003). The detailed survey results (Chapter 2) showed that variation at the level of fields exceeded variation at the level of farms or villages. The on-field experiments demonstrated that under similar treatments results varied widely due to soil variability. In view of the limited amount of soil information available, investments in mapping soil variability are needed to support locally specified soil fertility recommendations. Research could focus on those locations that enable the most wide-scale extrapolation, as well as on outlier situations to test solutions under extreme conditions.

3. Options for ecological land-use intensification

OM management

In current farming systems, crop residues are the main organic sources of nutrients. Around 70% of produced biomass remains in the field as residue after harvest (Chapter 2). Decomposition of residues during the subsequent dry period is limited by lack of water. At the start of the next wet season residues can help to cover the soil and mitigate the effect of heavy rains, and contribute to the soil organic matter pool. However, amounts may decline significantly due to grazing by animals (mainly cattle) that roam the (unfenced) fields. In addition to organic matter, nutrients are exported from the fields in this way, although the extent remains to be established (Chapter 2). Fields that are located further away from the farmers' homes are more likely to lose their residues by roaming animals. This tension between residues for soil fertility and feed for animals frequently occurs in smallholder systems and has long-term consequences for soil fertility and crop production (Tittonell et al., 2009; Rufino et al., 2010). According to our data obtained with litterbags, on average 60% of the biomass of plant residues that was available at the start of the rainy season was decomposed during the growing season (Chapter 5). This resulted in a contribution to the system of approximately 20 kg N ha^{-1} by 2.5 ton ha^{-1} aboveground and root residues associated with current maize production levels. In case of vermicompost, 35% of the dry matter initially present was decomposed during the growing season, contributing around 60 kg N ha^{-1} per 10 t ha^{-1} applied.

Soil pH management

The use of mineral fertilizers is currently the main means to maintain crop production (Chapter 2). Given the acidic nature of the soils of the State of Guerrero (OEIDRUS, 2011), the widespread use of ammonium sulfate along with low crop residue retention stimulated soil degradation (Ríos et al., 2009a). In 2005, the Fertilizer Subsidy Program was reorganized to promote choice of fertilizer type according to soil pH and the use of bio-fertilizers. However, current acidity and low levels of organic matter can affect the effectiveness of bio-fertilizers, particularly *Azospirillum brasilense*. Thus, specific means of increasing low soil pH are needed. Liming would be a straightforward solution, but may be impractical given the poor accessibility of most fields. Amassing organic sources and using these as inputs would also result in pH increases (Avery, 1995; Doran et al., 1996; Chikowo et al., 2010) but may face similar constraints particularly due to relatively low nutrient concentrations as we found for vermicompost (Chapter 4). Transportation and application to the fields of lime or compost implies a greater demand for labour which can be a serious constraint given the current rates of migration of young farm workers to wealthier parts of the country and to the USA.

Organic fertilizer management

Our findings (Chapter 4) revealed that the application of small amounts of vermicompost (e.g. 2.5 t ha^{-1}) combined with reduced amounts of mineral fertilizers allowed to obtain maize grain yields comparable to plots receiving only mineral fertilizers, with an increase in nutrient uptake and nutrient use efficiency. These results underscore the importance of combining mineral and organic fertilizers in maize-based cropping systems. The integration of these components would be a promising option for farmers to increase crop production and in the long term also improve soil properties (Mann et al., 2002; Adediran et al., 2005; Lal, 2005; Chivenge et al., 2007).

In March of 2008, peasant organizations in Guerrero requested a transition of the fertilizer program to integrate organic fertilizers given the strong deterioration of the soils and the reliance on mineral fertilizers as the only external source of plant nutrients (http://movimientos.org/show_text.php3?key=12083). In September of 2011, the Rural Development Ministry[a] recognized the need to include organic fertilizers in

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[a] http://angro.com.mx/noticias/2011/09/se-instalaran-81-plantas-productoras-de-abono-organico-para-produccion-en-maiz-en-guerrero-seder/

the subsidized fertilizer package. To obtain the necessary amounts the Ministry proposed the establishment of compost facilities in each municipality. In the Costa Chica region, the municipality of Tecoanapa pioneered vermicomposting. In 2002, the municipality invested in the construction of a 240m^2 vermicomposting facility, which was supplied with organic material from municipal organic waste, crop residues and manure. The vermicomposting facility produced 35 ton of vermicompost annually. In the municipality 7,548 ha of maize are cultivated (Secretaría de Desarrollo Rural de Guerrero, 2007). If vermicompost is applied at a rate of 2.5 t ha^{-1}, 18,870 t would be needed. Based on estimated annual production of manure in the municipality (including cows, sheep, goats, pigs and poultry) (SAGARPA, 2007; Secretaría de Desarrollo Rural, 2007) and assuming that all manure is used as organic source for vermicomposting (Nagavallemma et al., 2006), around 16,840 ton of vermicompost could be produced. These rough calculations suggest that currently collected organic resources are insufficient to meet even a modest demand for organic fertilizers at the municipality level. More detailed studies are needed on the availability of sources of organic matter in the cities and the feasibility of composting these.

K management

Our on-field evaluations along with model-based calculations demonstrated important inefficiencies in nutrient management and supported the concerns of low soil fertility and low yields (Chapter 2). The inherent soil properties and farming practices coupled with unbalanced fertilization and excessive rainfall events lead to uptake levels of N and K by maize and roselle which were relatively low compared to their input levels. Our diagnosis presented in Chapter 2 (Table 3) revealed that in 67% of the studied farmers' fields exchangeable K was below the critical level of 0.30 cmol kg^{-1}soil (Cox and Barnes, 2002). However, by applying the concept of crop nutrient equivalent it was found that even when soil exchangeable K was equal to or above this level, K was still the most growth-limiting nutrient at the maize silking stage, and at final harvest both K and N were limiting for grain production (Chapter 4). In all probability, this has to do with the fact that K is susceptible to leaching in case of heavy rainfall events.

A small trial in one farmer's field was set up during the growing season of 2012 in order to test once more the effect of K fertilization within the current crop nutrition practices. The field was the same as in the experiment carried out in the village of Las Animas in the year 2007 (Chapter 4). Two treatments were tested: 1) current fertilization (Cu), which corresponded to the farmer's practice of applying 205 kg N ha^{-1}, and 2) fertilization Cu+K, by applying in addition 205 kg K ha^{-1}. Contrary to 2007, the used maize variety was a hybrid. Sowing was carried out on July 9th. In both treatments the fertilizer applications were split into two parts: half of the N and K was applied after sowing in the third week of July, and the remaining N and K was applied in the first week of September. All crop management activities were carried out by the farmer. The inclusion of K fertilizer increased maize grain yield from 4530 to 5210 kg DM ha^{-1}, which was just not significant ($P = 0.06$). In this field, soil exchangeable K was equal to the critical level of 0.30 cmol kg^{-1}. Together with an unusual period of dry weather in the month of July around and after sowing which reduced K leaching losses, this might have caused the relatively small maize yield response to the application of K. The trend found in this small experiment indicated that it is worthwhile to set up experiments across locations in order to obtain more consistent results.

Weed management

The use of herbicides, particularly paraquat, has become the main practice to control weeds. Lack of technical knowledge is wide-spread, and may explain the frequently found over-use of this input (Chapter 2). Inclusion of the legumes mucuna and canavalia into maize and maize - roselle systems demonstrated substantial weed biomass reduction without competition effects on maize (Chapter 3). Thus intercropping with legumes may contribute to a long-term sustainable weed management strategy (Skóra Neto, 1993; Akobundu et al., 2000; Favero et al., 2001; Lawson et al., 2007).

Animal husbandry

Productivity of animal husbandry was found to be low, and contributed only modestly to annual family income. Nevertheless, products such as manure constitute an important input for maintaining soil organic matter balances, and (less so) as source of nutrients for the crops (Chapter 6). The main output of animal production is not very clear; meat, milk or both, since the animals are seen as a source of savings. Livestock in smallholders is a means of security for the family in time of crisis (Randolph et al., 2007). There is a lack of knowledge on the number of animals that can be fed with the forage and crop residues produced annually, which leads to reliance on external inputs to meet the feed requirements (Chapter 6). Thus, it is necessary to define carrying capacity and animal stocking rates (Martínez-Sánchez, 2003; Vázquez et al., 2009) to promote more sustainable livestock systems. During the dry season the lack of enough good quality feed for animals is one of the main limiting factors in animal intake and performance (Van Soest, 1994; Detmann et al., 2009). Canavalia stays green during the dry season and can thus serve as a source of protein-rich animal feed (Douxchamps et al., 2008; Martens et al., 2008). At the same time it provides soil cover at the beginning of the rainy season. Clearly, this dual purpose may lead to trade-offs as the use of canavalia for feeding animals results in reducing amounts of biomass to be used as soil cover. Our on-farm experiments demonstrated that the integration of legumes into existing cropping systems presented promising short-term effects. Longer-term potential positive effects like improvement of physical and chemical soil fertility remain to be investigated.

Farmers need to be trained in methods to manage and conserve feeds such as silage and hay. Another way to overcome the dry season feed gap is developing agrosilvicultural systems, which are a potential option in the region given the existing tree diversity. Species such as *Leucaena lecucocephala* (Lam.) de Wit, *Brosimum alicastrum* Sw. subsp. *Alicastrum* C.C. Berg, *Gliricidia sepium* (Jacq.) Steudel, *Acacia farnesiana* (L.) Willd., *Prosopis laevigata* (H. B. ex Willd.) Johnst. M.C., *Pithecellobium dulce* (Roxb.) Benththan, *Bursera simaruba* (L.) Sarg., among others (Navarro et al., 2012), can be used in these systems. They constitute a good source of protein. Together with alternative feed management, it is important to address animal health and reproduction management, which are currently based on trial and error without using information existing elsewhere in Mexico. Dissemination of information, and extension regarding health, reproductive management and nutrition can be an effective means to improve livestock systems (McDermott et al., 1999).

Whole-farm options

Within the current resource constraints, which concern particularly area of land, crop productivity is an important determinant of performance (Chapter 6). Opportunities for improvement of crop productivity at farm level varied among farmers and were strongly linked to farm size, cropping systems and integration of livestock. On all farms the volume of maize produced met the need for home consumption for the entire year. There was a surplus of grains which can be seen as a source of income when sold on the market. For African smallholder crop-livestock systems it has been demonstrated that uptake of mineral fertilizers and re-configuration of land use activities are strategies that can improve nutrient recycling within the farm and increase productivity (Tittonell et al., 2009; Rufino et al., 2010).

Farms with less than 0.8 ha land per capita did not reach the minimum income needed to cover the basic family food basket (Chapter 6; Scenario 4). On these farms increases in agricultural production will be useful to provide a resilient food base, but it will remain necessary to complement agricultural income with off-farm activities to cover the needs of the household.

The use of mineral fertilizer, including K, was an option that allowed maximizing family income, and had more opportunities to satisfy family economic needs (Chapter 6). In the model the highest rate of mineral fertilizers resulted in the greatest increase in family income. The same strategy, however, was not the most effective to increase organic matter balances. In addition, it would make farms vulnerable to price fluctuations as it requires fertilizer rates beyond current subsidy schemes. The best option for increasing OM was combining vermicompost, canavalia and increased residue retention, but family income was reduced due to the relatively high cost for including vermicompost and canavalia. Increasing crop residue retention may be an easier route for obtaining positive OM balances, at relatively low cost. Furthermore, the inclusion of K in current subsidy schemes offers an opportunity to enhance family income in the short term, and provides a biological and economic starting point to improve soil properties in the longer term.

On farms with animals the inclusion of canavalia may constitute forage of good quality (Sridhar and Seena, 2006) and potentially could allow feeding animals for longer periods than in the current situation (Chapter 2). Consequently, more manure could be produced within the farm, resulting in a greater increase in OM input than on farms without animals. Major trade-offs are linked to family income, because canavalia is a crop that does not offer immediate income to the family and requires more labour. In view of the shortage of suitable land and to avoid competition for land that is designated to cultivate maize and/or roselle, it is more convenient to intercrop canavalia with the main crops.

4. Implications for the research and policy agendas

Research

In Costa Chica, agronomic research has been largely absent, which has perpetuated the low maize yields and low resource use efficiencies. Our study provides a starting point for reversing the spiral of unsustainability and demonstrates several opportunities for further research: a) factorial experiments to assess balanced crop nutrition and nutrient recovery from both mineral and organic fertilizers; b) evaluation of combinations of inorganic and organic sources of fertilizer according to the soil properties; c) longer-term effects of legumes, crop residues and vermicompost on succeeding crops, erosion, and weed dynamics; d) agronomic evaluation of canavalia during the dry season and its potential as source of forage; e) alternative sources of feed such as canavalia, shrubs and trees; f) assessment of combinations of strategies at farm level in the computer and by co-innovation. Thus there is ample opportunity for evaluations and define action-oriented research. The challenge for this research agenda is to include the existing agro-ecological heterogeneity.

Around the world smallholders operate under major agroecological variation and a common concern is soil degradation. Technological innovations need to be focused on improving soil quality. Our results, similar to experiences elsewhere in Latin America and in Africa demonstrate that integrated nutrient management, multifunctional crops and management of crops residues are feasible options to improve current soil degradation (Snapp et al., 1998; Erenstein, 2003; Doré et al., 2011; Altieri et al., 2012; Tittonell and Giller, 2012). Contrary to cropping systems, livestock systems are less developed and demand special attention to explore scenarios to promote sustainable intensification (McDermott et al., 2010). Specific attention is needed for research in support of policies that address productivity and resource base conservation. It needs an effective interface between research demands and their dissemination among the users (Collinson, 2001).

Policy

Improving soil fertility management is one of the main issues that should be included in the policy agenda for Costa Chica due to the relationship between soil fertility and crop production. Our results show that it is urgent to reorient current fertilizer packages towards integrated nutrient management solutions, which include K and organic sources of nutrients. Access to extension services is a second key issue. Technical advice has been largely absent since the introduction and adoption of the fertilizer packages, which has doubtlessly contributed to their low use efficiencies (cf. Chapter 2). It is essential to include in the agenda training programs aimed at self-learning by farmers, at the efficient use of inputs, and at alternative cropping systems. A co-innovation approach as recently developed elsewhere in Latin America (Rossing et al., 2010) can be used as a guiding principle. The technical advice in the short term could be focused on improving fertilizer practices and promoting efficient use of N-P-K by integration of inorganic and organic fertilizers.

Opportunities arise from changes in policy since the start of this study. An ongoing rural development program that started in 2006 is *Guerrero sin hambre* (Guerrero without hunger), which aims to support low-income families, thus alleviating poverty and improving crop productivity. The program promotes development of farmer capacities as a basis for achieving food security (Toledo et al., 2009). One of the main components is providing training to farmers. The program proposed the dissemination of technological innovations, comprising improved varieties (hybrids and landraces), mineral fertilizers adjusted to local soil properties, production and use of organic fertilizers, bio-fertilizers, and green manures, biological control of pest and diseases, and post-harvest management, among others. Importantly, technical support and training in production techniques, marketing and on-farm management were included (Toledo et al., 2009). According to a review report of the State Ministry, technical support and training to farmers were the factors that were responsible for maize grain yield increases by 14% among the beneficiaries (Yúnez-Naudeet al., 2009). In 2010 the program supported 31,000 beneficiaries.

The reliance on external inputs, such as chemical fertilizers and herbicides, and low product prices increase farmers' vulnerability to market volatility. Due to the unfavourable market prices for the cash crops, it has become harder to obtain a proper income from the farm. Farmers are forced to sell their produce locally because of the difficulties of transporting produce to higher-paying markets further away. Low prices at local markets that do not even cover production costs are common. These socio-economic conditions have promoted migration since the families' cash needs can no longer be satisfied from farm income alone. Many young men leave the communities in search of paid employment to finance basic household expenses. Our results demonstrate that improvements in smallholder livelihood conditions are possible by interventions at the levels of field and farm. Experiences in Latin America and Africa have demonstrated improvements in alternative crop management strategies to overcome current situations, but major limitations are the diffusion and implementation of technological innovations (Altieri et al., 2012). The challenge in the Costa Chica as elsewhere is now to develop a policy agenda aimed at creating effective conditions to promote and disseminate these agro-ecological innovations as part of an integral program of sustainable rural development that responds to the many constraints faced by smallholders (Pretty, 2008; Herrerro et al., 2010; McDermott et al., 2010; Altieri et al., 2012; Tittonell and Giller, 2012). In parallel to improving the production situation, attention needs to be focused on the other major concern of the farmers, the marketing of products. To develop this innovation agenda, active participation among the different actors is necessary: farmers, researchers and policy makers.

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Summary

The region of Costa Chica is a hilly area of approximately 8,500 km^2 located in the state of Guerrero in the Southwest portion of Mexico. Climate is sub humid tropical, with 1,300 mm of precipitation on average, and minimum and maximum temperatures of 15 and 30^{o}C at mid altitudes. Soils are of volcanic origin and classified as regosols. Farming systems are organized in smallholder units. The dominant cropping system is based on maize (*Zea mays* L.) either as monocrop or intercropped with roselle (*Hibiscus sabdariffa* L.). Continuous cropping, crop nutrition based on external inputs, and lack of attention for replenishment of organic matter stocks have caused depletion of soil fertility and low crop yields. This has resulted in a spiral of unsustainability. Five communities were identified in which farmers were interested in technological innovations to improve soil fertility and increase yields. The present research was aimed to evaluate alternative cropping systems by means of an interactive process between farmers and researchers in order to increase productivity by improving the resource base. The methodology comprised the integration of three methods: 1) Diagnosis of current farming systems. A set of on-farm methods together with model-based calculations were applied to identify the main constraints limiting farm productivity, to quantify nutrient flows and to help to target interventions; 2) On-farm experiments within the local context. This component was focused on the exploration and evaluation of promising alternative cropping systems for maize and maize-roselle production. On-farm experimentation was based on multifunctional cropping systems and integrated nutrient management; and 3) Integration of results at the whole farm level. This phase comprised the identification and development of model-based scenarios to evaluate solutions for the problems identified in the diagnosis phase. The exploration was supported by the empirical results generated by the on-farm experiments, field data from farmers´ surveys and a whole-farm model.

The results of the diagnosis (Chapter 2) demonstrated that current nutrient management of crops has promoted nutritional imbalances resulting in N- and K-limited production conditions, and consequently low yields of maize and roselle and low resource use efficiencies. Using the RUSLE equation, crop production on moderate to steep slopes was estimated to result in considerable losses of soil and organic matter (OM). Low production levels, lack of specific animal fodder production and strong dependence of animal grazing on communal lands limited recycling of nutrients through manure. In combination with low prices for the roselle cash crop, farmers are caught in a vicious cycle of cash shortage and resource decline. The production- ecological findings complemented farmers´ opinions by providing more insight in the background and extent of livelihood constraints.

To address the identified on-farm constraints, researcher-guided and farmer-

managed experiments were established in two communities in the region, targeted at (1) the prospects of intercropping maize and maize-roselle mixtures with the legumes *Canavalia brasiliensis* Mart. ex Benth and *Mucuna pruriens* L. *var. utilis* (Wall ex Wight) Burk for improving nutrient uptake and weed suppression (Chapter 3), and (2) development of alternative fertilizer strategies (Chapter 4). Experiments were established on rather acid soils during the 2006 and 2007 growing seasons using randomized split-plot designs with three replicates. Maize monocrops and maize–roselle intercrops grown with different sources of nutrients (vermicompost, goat manure, mineral NPK, and vermicompost + restricted mineral NPK) were intercropped with the two legume species, sown four to six weeks after maize. The on-farm experiments demonstrated positive effects of the integration of legumes into the maize and maize – roselle systems already in the short-term. The results showed that sowing of the legumes four weeks after maize was enough to avoid competition and negative effects on yield. The inclusion of legumes caused a reduction of the weed biomass by 24 to 55%. Total residual aboveground biomass returned to the soil increased up to 36% due to the inclusion of legumes. Total N uptake of the intercropped systems was 13 to 36 kg ha^{-1} higher than without legumes. In addition to fixing N from the atmosphere, the legumes acted as a “catch” crop, retaining additionally 23 kg N ha^{-1} and 11 kg K ha^{-1} compared to the no-legume treatment, thus preventing N and K leaching. With its prostrate growth habit and adaptation to poor soil conditions, canavalia demonstrated agronomic advantages in comparison to the more common mucuna that has a climbing nature.

A second set of experiments investigated the usefulness of alternative fertilizer strategies, which would not only replenish plant nutrients but also contribute to soil organic matter accumulation (Chapter 4). Different sources of nutrients (vermicompost, goat manure, mineral NP, mineral NPK and vermicompost + restricted mineral NPK) were tested in maize monocrops and maize-roselle intercrops in farmers' fields using randomized split-plot designs with three replicates. Data were evaluated in terms of economic yield, nutrient use efficiency, and leaf and crop NPK ratio. In 2006, at the same level of N input, NPK increased maize grain yield with 45% compared to NP. In 2007, at a rate of 95-10-80 kg NPK per ha, maize grain yield was around 3,500 kg ha^{-1}, about twice the level under current farming practice.

In both years, N and K appeared the most limiting nutrients, whereas clear evidence was found for luxury consumption of P. Current fertilizer practices that supply only N and P lead to unbalanced nutrient availability. Inclusion of K in current subsidized fertilizer packages can offer improvements in grain yields. Combined use of mineral and organic fertilizers applied in split doses can reduce leaching losses of nutrients and improve in the long-term soil organic matter levels.

The third on-farm experiment was carried out during one rainy season and aimed to estimate the decomposition rate and N release pattern of three organic materials: aboveground plant residues, root residues and vermicompost (Chapter 5). Decomposition was monitored using the litter bag method, and the decomposition pattern was reconstructed by fitting a dynamic mono-component mineralization model. Rates of decomposition varied according to type of organic material. Amounts of dry matter of aboveground residues and roots remaining at the end of the rainy season ranged from 30 to 55%, and more than 80% of total N had been released. Of the vermicompost only 35% was decomposed but with more than 65% of the N released. An application of 10 Mg ha^{-1} resulted in a release of 62 kg N ha^{-1} during the rainy season. Thus, vermicompost may be an important means for SOM build-up and crop N supply.

A whole-farm model was used to evaluate the feasibility of the tested maize-based cropping systems, and other systems that have been proposed, in relation to the need for self-sufficiency in food production, the need for cash and long-term soil fertility and the availability of family labour (Chapter 6). The results demonstrated that family income can be increased and OM balances may be improved. Farms responded in different ways to the various cropping options due to available land, current quality of their resource-base, current cropping systems and presence of livestock. In the short term, improvements in crop nutrition based on mineral fertilizers increased family income but only had substantial effects on OM balances when fertilizer rates were double the amount currently subsidized. Addition of organic fertilizers as vermicompost resulted in positive effects on OM balance, but with often strong trade-offs with family income due to costs of acquisition, transport and application. Animals played an important role in increasing OM balances, but had relatively little effect on improving family income.The results suggest that the technological options that are currently available may be insufficient to enable farm families meeting the ‘basic food basket’, a local indicator of the minimum amount of money required for self-sufficiency when basic needs are met through the market. Diversification of options both on- and off-farm is needed to allow farmers to select activities that are suitable to their constraints and objectives.

Research and training programs are largely lacking in the region. Our study demonstrated that there is room to promote intensification towards sustainable farming systems (Chapter 7). Current subsidy schemes need to be redesigned toward soil fertility strategies that address both crop nutrition and soil organic matter stocks, and are supported by training programs. In such strategies the agro-ecological heterogeneity can be taken into account by stimulating the development of field- and farm specific alternative crop management practices. In addition, creating regional off-farm sources of income will be needed to allow families to achieve a minimum income without the need to become illegal migrants in North America. This requires the active participation of farmers, researchers and policy makers.

Samenvatting

De Costa Chica regio is een bergachtig gebied van ongeveer 8500 km^2 gelegen in de staat Guerrero in het Zuid-Westelijke deel van Mexico. Er heerst een subtropisch vochtig klimaat met een gemiddelde jaarlijkse neerslag van 1.300 mm welke vrijwel geheel tussen juni en oktober valt. De gemiddelde jaarlijkse minimum en maximum temperaturen rond 700 m boven zeeniveau bedragen respectievelijk ongeveer 15 en 30 ^{o}C. De bodems zijn van vulkanische oorsprong en worden geclassificeerd als regosols. Landbouwsystemen zijn georganiseerd in kleinschalige eenheden. Het overheersende teeltsysteem is gebaseerd op maïs (*Zea mays* L.), hetzij als monocultuur of als mengteelt met roselle (*Hibiscus sabdariffa* L.). Continuteelt, gewasvoeding op basis van externe inputs en gebrek aan aandacht voor het op peil houden van de bodem organische stof hebben geleid tot uitputting van de bodemvruchtbaarheid en lage gewasopbrengsten in de Costa Chica regio. Dit heeft geresulteerd in een spiraal van onduurzaamheid. Vijf landbouwgemeenschappen werden geïdentificeerd waar boeren geïnteresseerd waren in technologische innovaties om de bodemvruchtbaarheid en de gewasopbrengsten te verbeteren.

Het onderzoek beschreven in dit proefschrift was gericht op alternatieve teeltsystemen om de productiviteit te verhogen door met name een verbeterde inzet van hulpbronnen. Dit werd gedaan op basis van interactieve processen tussen boeren en onderzoekers. De methodiek bestond uit een combinatie van drie methoden: 1) Diagnose van de huidige teeltsystemen. Waarnemingen op bedrijven werden gecombineerd met modelmatige berekeningen om de belangrijkste beperkingen voor verhoging van de gewasproductiviteit te identificeren, de nutriëntenstromen te kwantificeren en interventies te formuleren; 2) Bedrijfsspecifieke experimenten binnen de lokale context. Deze component was gericht op verkenning en evaluatie van veelbelovende alternatieve, multifunctionele teeltsystemen gebaseerd op geïntegreerd nutriënten-beheer voor maïs en maïs-roselle, en 3) Integratie van de resultaten op het gehele bedrijfsniveau. Deze laatste stap bestond uit identificatie en ontwikkeling van modelmatige scenario's om oplossingsrichtingen te evalueren voor de problemen welke in de diagnosefase waren vastgesteld. De verkenningen werden ondersteund door gegevens en empirische resultaten welke in enquêtes onder de boeren, in de bedrijfsspecifieke experimenten en met een bedrijfssysteemmodel waren verkregen. De resultaten van de diagnose toonden aan dat het huidige nutriëntenmanagement onevenwichtigheden in de gewasvoeding heeft veroorzaakt, met N-en K-gelimiteerde productie-omstandigheden als gevolg (Hoofdstuk 2). Hierdoor zijn de opbrengsten van maïs en roselle relatief laag en is er een lage gebruiksefficiëntie van de ingezette hulpbronnen, met name kunstmest-N. Met behulp van het RUSLE model werd berekend dat gewasteelt op matige tot steile hellingen resulteert in aanzienlijke

afspoelingsverliezen van grond en organisch materiaal. Geringe beschikbaarheid van maisresten, gebrek aan specifieke voederproductie voor landbouwhuisdieren en sterke afhankelijkheid van gemeenschappelijke gronden voor beweiding beperkt herbenutting van plantenvoedingsstoffen via dierlijke mest. In combinatie met de lage prijzen voor de roselle zijn de boeren gevangen in een vicieuze cirkel van een tekort aan geld en een achteruitgang van productieomstandigheden. De productie-ecologische bevindingen vormden een aanvulling op de mening van de boeren doordat ze meer inzicht gaven in de achtergrond en omvang van de problematiek.

Om de vastgestelde productiebeperkingen op de bedrijven te kunnen verbeteren werden gedurende twee jaar binnen twee landbouwgemeenschappen in de regio veldexperimenten uitgevoerd welke door boeren werden beheerd. Deze waren gericht op (1) de perspectieven van de vlinderbloemigen *Canavalia brasiliensis* Mart. ex Benth en *Mucuna pruriens* L. *var. utilis* (Wall ex Wight) voor verbetering van de opname van plantnutriënten en van onkruidonderdrukking in de teelt van maïs en maïs-roselle (Hoofdstuk 3), en (2) de ontwikkeling van alternatieve bemestings-strategieën (Hoofdstuk 4). Hiertoe werden gerandomiseerde split-plot experimenten in drie herhalingen aangelegd op tamelijk zure gronden tijdens de groeiseizoenen 2006 en 2007. De vlinderbloemigen werden vier tot zes weken na het hoofdgewas in rijen tussen de maïs en maïs-roselle gezaaid. De experimentele behandelingen bestonden uit vier mestvarianten (vermicompost, geitenmest, minerale NPK en vermicompost + minerale NPK). Het zaaien van de vlinderbloemigen vier weken na de maïs bleek een voldoende lange periode te zijn om negatieve effecten op de maïsopbrengst te voorkomen. De experimenten lieten al in het eerste jaar positieve effecten zien van de geïntegreerde teelt met vlinderbloemigen. De vlinderbloemigen verminderden de biomassa aan onkruiden met 24-55% en de totale bovengrondse gewas N-opname nam toe met 13 tot 36 kg ha^{-1}. Bovendien werd de totale N-vastlegging in de gewasresten, welke naar de bodem werd teruggevoerd, met maximaal 36% verhoogd. Naast verhoging van de import van N door biologische fixatie van atmosferische luchtstikstof, fungeerden de vlinderbloemigen ook als vanggewas voor N en K in het doorgaans zeer natte groeiseizoen. Hierdoor kon de N en K uitspoeling gemiddeld met respectievelijk 23 en 11 kg ha^{-1} beperkt worden. De liggende groeiwijze en goede aanpassing aan slechte bodemomstandigheden maakte canavalia agronomisch interessanter dan mucuna, welke een klimplant is.

In een tweede reeks van experimenten werd de bruikbaarheid van alternatieve bemestingsstrategieën onderzocht, welke ook kunnen bijdragen aan de toename van de bodem organische stof (Hoofdstuk 4). Binnen het in Hoofdstuk 3 beschreven veldexperiment op praktijkbedrijven met de twee vlinderbloemigen werden vier mestvarianten (vermicompost, geitenmest, minerale NP, minerale NPK en vermicompost + minerale NPK) getest in maïs monoculturen en maïs-roselle mengsels. De gegevens werden geëvalueerd op basis van korrelopbrengst van maïs, nutriëntengebruiksefficiëntie, en verhoudingen van NPK in blad en gewas. De resultaten in 2006 lieten zien dat, bij dezelfde stikstofgift, bemesting met minerale NPK de maïskorrel-opbrengst verhoogde met 45% ten opzichte van alleen minerale NP. In 2007 werd met een gift van 95-10-80 kg NPK per ha een maïskorrelopbrengst van 3500 kg ha^{-1} bereikt, ongeveer het dubbele van de opbrengst in de gangbare praktijk waar geen K-bemesting wordt toegepast.

In beide jaren bleken N en vooral K de meest beperkende nutriënten te zijn, terwijl duidelijke aanwijzingen werden gevonden voor overmatige opname van P. De huidige gesubsidieerde kunstmeststoffen met alleen N en P leiden tot dus een onevenwichtige bemesting en lage maïsopbrengsten. Opname van K in het subsidieerde pakket kan tot aanzienlijke opbrengstverbeteringen leiden. Tevens verdient het aanbeveling zowel de minerale als de organische meststoffen in gedeelde giften toe te dienen om de uitspoeling van met name N en K te verminderen.

In een derde experiment werd gedurende één regenseizoen gekeken naar de afbraaksnelheid van en het patroon van beschikbaar komen van minerale N uit drie verschillende organische materialen: bovengrondse gewasresten van mais, wortelresten van mais en vermicompost (Hoofdstuk 5). Hiervoor werd gebruikt gemaakt van de nylon-zakjesmethode en de patronen in de tijd werden gefit met een bestaand mono-component mineralisatiemodel. De afbraakpatronen en het beschikbaar komen van minerale N verschilden sterk tussen de drie soorten organische materialen. De fractie overgebleven drogestof aan het eind van het regenseizoen varieerde tussen 30% voor de bovengrondse gewasresten en 55% voor de wortelresten, terwijl in beide gevallen meer dan 80% van de organische N uit de zakjes was verdwenen. Van de vermicompost werd slechts 35% van de drogestof afgebroken, terwijl iets meer dan 65% van de organische N gemineraliseerd werd. Voor een gift van 10 Mg vermicompost per ha kwam dit overeen met 62 kg N_{min} ha^{-1}. Vermicompost kan dus zowel een belangrijke bijdrage leveren aan de opbouw van bodem organische stof als aan de beschikbaarheid van minerale N.

Met behulp van een bestaand statisch landbouwbedrijfsmodel werd de haalbaarheid van de geteste maïs-productiesystemen geëvalueerd in relatie tot de noodzaak van zelfvoorziening in voedselproductie, de behoefte aan geld, de lange termijn bodemvruchtbaarheid en de beschikbaarheid van eigen arbeid (Hoofdstuk 6). De resultaten toonden aan dat het gezinsinkomen behoorlijk kan worden verhoogd en de bodem organische stof balans sterk kan worden verbeterd. Landbouwbedrijven reageerden op verschillende manieren op de uiteenlopende teeltopties, afhankelijk van de beschikbare oppervlakte grond, de huidige kwaliteit van de bodem, de huidige teeltsystemen en de aanwezigheid van vee. Verbeteringen in gewasvoeding op basis van minerale meststoffen lieten het gezinsinkomen stijgen, maar dit had alleen een belangrijk effect op de bodem organische stof balans als de kunstmestgiften het dubbele waren van de hoeveelheden welke momenteel gesubsidieerd worden.

Toediening van organische meststoffen zoals vermicompost resulteerde in positieve effecten op de bodem organische stof balans, maar dit ging vaak gepaard met negatieve gevolgen voor het gezinsinkomen vanwege de kosten die gemoeid zijn met aanschaf, transport en toediening ervan. Landbouwhuisdieren speelden een belangrijke rol in de verbetering van de bodem organische stof balans, maar hadden een relatief gering effect op verbetering van het gezinsinkomen. De resultaten suggereren dat de huidige beschikbare technologische opties ontoereikend zijn om boerenfamilies in staat stellen een 'basic food basket' te verwerven, de lokale indicator voor de minimale hoeveelheid geld die nodig is voor zelfvoorziening wanneer aan de basisbehoeften wordt voldaan via de markt. Diversificatie van opties is nodig, zowel op als buiten het bedrijf, zodat de landbouwers activiteiten kunnen selecteren welke passen bij hun doelstellingen en beperkingen.

Onderzoeks- en opleidingsprogramma's ontbreken grotendeels in de regio. Onze studie toonde aan dat er ruimte is voor het bevorderen van intensivering en ontwikkeling in de richting van meer duurzame landbouwsystemen (Hoofdstuk 7). Daartoe zouden de huidige subsidieregelingen moeten worden aangepast om zowel de gewasvoeding te optimaliseren als de bodem organische stof opbouw te stimuleren. Een dergelijke aanpassing moet worden ondersteund door opleidingsprogramma’s voor boeren. Hierbij dient rekening gehouden te worden met de aanwezige agro-ecologische heterogeniteit door het ontwikkelen van perceels- en bedrijfs-specifieke teeltpakketten. Daarnaast zal het ontwikkelen van bronnen van inkomsten buiten de boerderij nodig zijn om gezinnen een minimum inkomen te laten verwerven zonder de noodzaak tot illegale migratie naar Noord-Amerika. Een dergelijke ontwikkeling vereist actieve samenwerking tussen boeren, onderzoekers en beleidsmakers.

Resumen

La región Costa Chica es un área montañosa con una extensión aproximada de 8,500 km^2, ubicada en el estado de Guerrero en la porción sur-oeste de México. Tiene un clima tropical sub-húmedo, con una precipitación promedio de 1,300 mm, y con temperaturas mínimas y máximas de 15 y 30^{O}C en altitudes intermedias. Los suelos son de origen volcánico, clasificados como regosoles. Los sistemas de producción agrícola se caracterizan por ser pequeñas unidades. El maíz (*Zea mays* L.) es el sistema de cultivo dominante sembrado en monocultivo o intercalado con jamaica (*Hibiscus sabdariffa* L.). El continuo cultivo de la tierra, la nutrición de cultivos basada en fertilizantes, y la falta de restitución de materia orgánica han causado el agotamiento de la fertilidad del suelo y la reducción de los rendimientos. Esto ha resultado un espiral de insostenibilidad. Cinco comunidades fueron identificadas, en donde agricultores expresaron su interés en innovaciones tecnológicas orientadas al mejoramiento de la fertilidad del suelo e incremento de los rendimientos. La presente investigación tuvo como objetivo evaluar sistemas de cultivo alternativos a través de un proceso interactivo entre agricultores e investigadores con el fin de incrementar la productividad a través del mejoramiento de sus recursos. La metodología comprendió la integración de tres métodos: 1) Diagnostico del estado actual de los sistemas de producción agropecuarios. Un conjunto de métodos de análisis de sistemas agrícolas y modelación se aplicaron para identificar las principales limitantes de la productividad agrícola, cuantificar el flujo de nutrientes, y reorientar posibles intervenciones para su mejoramiento; 2) Experimentos en parcelas de agricultores dentro del contexto local. Este componente se centro en la exploración y evaluación de sistemas de manejo alternativo para la producción de maíz y jamaica. La experimentación se fundamento en el enfoque de sistemas de cultivo multifuncionales y manejo integrado de nutrientes; y 3) Integración de resultados a nivel sistema de producción. Esta fase comprendió la identificación y desarrollo de escenarios alternativos para evaluar soluciones a la problemática identificada en el diagnostico. Las exploraciones fueron apoyadas por los resultados empíricos generados en la experimentación en parcelas de agricultores, datos de las encuestas a agricultores y modelos integrales a nivel sistemas de producción.

Los resultados del diagnostico (Capitulo 2) demostraron que el manejo de la nutrición de cultivos ha promovido un desequilibrio nutrimental, siendo N y K factores limitantes, consecuentemente bajos rendimientos de maíz, y una baja eficiencia en el uso de los insumos. El uso de la EUPS demostró que el cultivo en moderadas y fuertes pendientes resulta en una considerable pérdida de suelo y materia orgánica. Los bajos niveles de producción, la falta de forraje y la alta dependencia de

tierras comunales para el pastoreo limitan el reciclaje de estiércol. Junto con los bajos precios de la jamaica, los agricultores están inmersos en un círculo vicioso de escases de recursos económicos y de deterioro de los recursos. Los resultados obtenidos y la opinión de los agricultores, proporcionaron una visión clara de la situación actual de los sistemas de producción y, los posibles alcances de las limitaciones de los sistemas agrarios.

Para resolver las limitantes identificadas, se establecieron experimentos en parcelas de agricultores de dos comunidades de la región enfocados a (1) perspectivas de la intercalación de las leguminosas *Canavalia brasiliensis* Mart. ex Benth. y *Mucuna pruriens var. utilis* (Wall ex Wight) Burk en los sistemas de cultivo de maíz y maíz-jamaica con el objetivo de mejorar la absorción de nutrientes y la supresión de malezas (Capitulo 3), y (2) desarrollo de estrategias alternativas de fertilización (Capitulo 4) . Los experimentos se establecieron en suelos ácidos durante los ciclos de cultivo de 2006 y 2007 bajo un diseño completamente aleatorio con arreglo en parcelas divididas con tres repeticiones. El maíz en monocultivo y maíz - jamaica intercalados bajo diferentes fuentes de nutrientes (vermicomposta, estiércol de cabra, fertilización mineral con NPK y vermicompost + NPK) fueron intercalados con las dos especies de leguminosas, sembradas cuatro y seis semanas después del maíz. Los experimentos demostraron que la integración de leguminosas en los sistemas de cultivo de maíz y maíz-jamaica presentó efectos positivos en un corto plazo. Los resultados mostraron que la siembra de leguminosas cuatro semanas después del maíz fue suficiente para evitar competencia y efectos negativos en el rendimiento. La inclusión de leguminosas causo una reducción en la biomasa de malezas entre 24 y 55%. La biomasa aérea se incremento hasta en un 36% debido a la inclusión de leguminosas. La absorción total de N en el sistema intercalado con leguminosas se incrementó entre 13 y 36 kg ha^{-1} comparado con los sistemas de cultivo sin leguminosas. Las leguminosas además de ser fijadoras de N, actuaron y como cultivo de “captura”, reteniendo 23 kg N ha^{-1} y 11 kg N ha^{-1} comparado con los tratamientos sin leguminosas, evitando de este modo la lixiviación de N y K. Debido a su hábito de crecimiento postrado y su adaptación a suelos pobres, canavalia demostró ventajas agronómicas comparada con mucuna

En un segundo grupo de experimentos se investigaron estrategias alternativas de fertilización, para restaurar nutrientes vegetales y contribuir a la acumulación de materia orgánica (Capitulo 4). Diferentes fuentes de nutrientes (vermicomposta, estiércol de cabra, fertilización mineral con NP y NPK y vermicomposta + NPK) fueron evaluados en monocultivo de maíz y en la intercalación maíz-jamaica bajo un diseño completamente al azar con arreglo en parcelas divididas con tres repeticiones. Las variables evaluadas fueron rendimiento económico, eficiencia del uso de nutrientes, relaciones de NPK a la floración y cosecha. En 2006, al mismo nivel de N, la fertilización con NPK incremento el rendimiento de grano de maíz en un 45% comparado con fertilización NP. En 2007, la aplicación de fertilizantes a una dosis de 95-10-80 NPK por ha, promovió un rendimiento de maíz alrededor de 3,500 kg ha^{-1}.

En ambos años, N y K fueron los nutrientes más limitantes, y se encontraron claras evidencias de consumo de lujo de P. Las actuales prácticas de fertilización que incluyen solo la aplicación de N y P promueven una desequilibrada nutrición. La inclusión de K en los actuales subsidios de fertilizantes puede ofrecer mejoras en el rendimiento de grano. La aplicación combinada de fertilizantes y abonos orgánicos en dosis fraccionadas puede reducir perdidas de nutrientes por lixiviación y mejorar a largo plazo los niveles de materia orgánica del suelo.

El tercer experimento en parcelas de agricultores fue llevado a cabo durante un ciclo de cultivo con la finalidad de estimar la tasa de descomposición y la liberación de N de tres materiales orgánicos: residuos aéreos de cultivos, raíces de residuos, y vermicomposta (Capitulo 5). La descomposición fue monitoreada mediante el método de “bolsas de residuos”, y el patrón de descomposición fue calculado mediante el modelo de mineralización mono-componente. Los resultados demostraron que las tasas de descomposición variaron según el tipo de material orgánico. El remanente de materia seca de residuos y raíces vario de 30% a 55%, y más del 80% del N total fue liberado durante la temporada de lluvias. En la vermicomposta, solo el 35% se descompuso y más del 65% del N fue liberado. La aplicación de 10 t ha^{-1} contribuyo con un aporte de nitrógeno de 62 kg N ha^{-1}. La vermicomposta puede ser un importante medio para la restitución de MOS y aporte de N.

Un modelo integral a nivel sistema de producción se utilizó para evaluar la viabilidad de los sistemas de cultivo de maíz examinados y otros sistemas que se han propuesto, relacionados a la autosuficiencia alimentaria, la necesidad de dinero en efectivo, la fertilidad del suelo a largo plazo y la disponibilidad de mano de obra familiar (capítulo 6). Los resultados demostraron que los ingresos familiares se pueden incrementar y los balances de materia orgánica pueden ser mejorados

La aplicación de abonos orgánicos como vermicomposta produjo efectos positivos en el balance de MO, pero a menudo con desventajas en los ingresos familiares debido a los costos de su adquisición, transporte y aplicación. Los animales desempeñan un papel importante en el aumento de los balances de MO, pero tuvieron relativamente poco efecto en el incremento de los ingresos. Los resultados sugieren que las actuales opciones tecnológicas son insuficientes para satisfacer la 'canasta básica de alimentos', un indicador local de la cantidad mínima de dinero necesario para la auto-suficiencia alimentaria cuando las necesidades básicas son cubiertas a través del mercado. La diversificación de opciones agrícolas y no agrícolas es necesaria para que los agricultores puedan optar por las actividades más convenientes acordes a sus limitaciones y objetivos.

La investigación y programas de capacitación son ampliamente escasos en la región. Nuestro estudio demostró que hay oportunidades para promover la intensificación hacia sistemas agrícolas sostenibles (Capítulo 7). El actual esquema de subsidios necesita ser rediseñado hacia estrategias de manejo de la fertilidad de los suelos que mejoren la nutrición de los cultivos y su contenido de materia orgánica, y apoyados con programas de capacitación. Estas estrategias deben tomar en cuenta la heterogeneidad agroecológica que promuevan el desarrollo de prácticas alternativas a nivel parcela y sistema de producción. Además, en la región es necesaria la creación de fuentes de ingresos no agrícolas para que las familias puedan obtener ingresos mínimos necesarios y evitar la inmigración ilegal hacia los Estados Unidos. Esto requiere la participación activa de agricultores, investigadores y políticos.

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Curriculum vitae

Diego Flores Sánchez was born on August 9th, 1969 in Mexico City. In 1988, he began his studies at the National Autonomous University of Mexico (UNAM). After obtaining his degree of Agronomy Engineer in 1993, he completed a 10 months Research Fellowship at Colegio de Postgraduados, Mexico. From 1994 to 1997 he worked as assistant researcher at the Rural Development Centre of Colegio de Postgraduados. He was involved in research projects - sustainable use of treated water in Hidalgo, regeneration and conservation of volcanic soils of Latin America - as well as in agricultural and regional development in Vega de Metztitlan.

From 1998 to 1999 he obtained a scholarship from The National Council of Science and Technology (CONACYT) to study for an MSc degree at Colegio de Postgraduados, specializing in Agro-ecology. In his MSc thesis he studied the use and management of maize biodiversity in the Texcoco river watershed.

After receiving the MSc degree in 2000 he rejoined Colegio de Postgraduados as a researcher with research and teaching responsibilities in agro-ecology and agro-ecological cropping systems. In that period he was involved in research projects on agro-ecological reconversion of traditional farming systems in Costa Chica, agro-ecological systems and evaluation of local species in Texcoco, sustainable water management in the State of Mexico, and characterization of farmers to target alternative development options in Ajacuba, Hidalgo.

In 2005, he was awarded a scholarship from The National Council of Science and Technology (CONACYT) for PhD studies at Wageningen University within the Plant Sciences Department of the C.T. de Wit Graduate School PE&RC. He also received a grant from the International Foundation for Science (IFS) under the project S/3601-1, which financed the field work of this doctoral thesis research. His PhD study "*Exploration of agro-ecological options for improving maize-based farming systems in Costa Chica, Guerrero, Mexico*" is reported in this thesis.

After finishing the bulk of his PhD thesis in 2011 he was involved on a part-time basis in regional development projects in Oaxaca and Guanajuato, Mexico, and joined a company that supports research project acquisition.

List of publications

Campos, M.L., Flores, S.D., 2013. Sustratos orgánicos como alternativa para la producción de albahaca (*Ocimum Selloi* Benth). Revista Mexicana de Ciencias Agrícolas 5: 1055−1061.

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Navarro, H., Pérez, A., Flores, D., 2004. Productividad del tepetate con sistemas rotacionales. Terra Latinoamericana, México, 22: 71−79.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Systems modelling and farming systems design (2005)
- Approaches for sustainable development (2005)
- Survey methodologies (2005)
- Nutrient management approaches (2006-2007-2008)

Writing of project proposal (4.5 ECTS)

- Reinventing agro-ecological self-reliance in traditional farming systems in Costa Chica, Guerrero, Mexico

Post-graduate courses (2.4 ECTS)

- Current issues concerning sustainable organic production: ecological and human context; BFS/PE&RC (2005)
- International course of agroecology; Universidad de Antioquia, Colombia (2007)
- Introduction to R; PE&RC (2009)

Laboratory training and working visits (0.9 ECTS)

- Statistical analysis of surveys at farming systems level; Universidad Autonoma de Guerrero (2007)

Deficiency, refresh, brush-up courses (3.3 ECTS)

- Analysis and design of farming systems (2005)
- Systems analysis, simulation and system management (2005)
- Master Class: governance, democracy and multi-stakeholder processes; from theoretical questions to practical implications (2006)

Competence strengthening / skills courses (3.6 ECTS)

- Time planning and project management; PE&RC, WGC/CENTA (2006)
- Scientific papers and criteria for academic arbitration; ANUIES-Mexico (2009)
- Working with Endnote X2; WUR Library (2009)
- Scientific publishing; WGS (2009)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Weekend (2005)
- PE&RC Day: earth science and application using imaging spectroscopy (2008)
- How to write a world-class article; Wageningen UR Library (2010)

Discussion groups / local seminars / other scientific meetings (6 ECTS)

- Agricultural production systems in temperate regions (2005/2006)
- Research presentation series at Colegio de Postgraduados, Universidad Nacional Autonoma de Mexico, Universidad Autonoma Chapingo (2007/2008)

International symposia, workshops and conferences (4.4 ECTS)

- 7th European IFSA Symposium New visions for rural areas: changing European farming systems for a better future; Wageningen, the Netherlands (2006)
- I Congreso Latinoamericano de Agroecologia; Medellin, Colombia (2007)

Supervision of 2 MSc students (144 days)

- Farming systems diagnosis: first steps for the redesign of nutrient and residue management in traditional farming systems in Guerrero State, Mexico
- Prospects of organic fertilizers (compost, manure) and intercropped legumes (*Mucuna pruriens* and *Canavalia ensiformis*) for sustainable maize production in Costa Chica, Guerrero, Mexico