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Full Length Research Paper

Adoption of soil conservation practices through knowledge governance: the Mexican experience

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Top-down and centralized soil conservation programs have caused low adoption of sustainable practices. The adoption is a multistage and adaptive process that relies on the management of local knowledge. The results of 61 surveys were analyzed in order to systematize experiences of soil knowledge governance involving social organizations and farmers. Soil knowledge governance was done mainly through the sharing of experiences among farmers. This path resulted both in the strengthening of existing institutions and in the creation of new associative forms and rules. The incentives for farmers to maintain soil conservation practices went beyond the financial ones and reflected the diversity of their views and expectations: eating healthy food, diversifying agricultural production, and improving their social position in the community. The increased adoption of soil conservation practices that resulted from this approach led to the rethink the kind of public policies that would better help soil conservation in Mexico.

Key words: Public policy, soil conservation, soil knowledge governance, sustainable land management.

INTRODUCTION

Soils provide a wide range of ecosystem goods and services, particularly in terms of runoff control, water-holding capacity, ecosystem productivity, carbon sequestration (Amundson et al., 2015), food production (White et al., 2012) and biodiversity preservation (Ibañez et al., 2012); they also play a key role in at least seven of the proposed planetary boundaries (Bouma, 2014).

Soil erosion is a challenging issue not only because it causes yield loss (Montgomery, 2007) and has environmental impacts, but because it is also closely linked to rural poverty (Ruben and Pender, 2004). To address and mitigate this problem, programs have been developed with the help of governmental and non-governmental international funding. These efforts have been made under different premises and different names such as, soil conservation, conservation agriculture, climate-smart agriculture, and sustainable land management, which all express the same concern: implement low-impact agriculture that maintain soil quality.

At first, these programs were characterized by information transfer mechanisms limited to the unilateral transmission of specific technologies to farmers, without incorporating their demands, experiences and expectations (Manuel-Navarrete and Gallopin, 2012), and without considering site-specific biophysical conditions,

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the type of agriculture (irrigated or rain-fed) or livestock production (intensive or extensive), or land extension (Damián and Toledo, 2016). These early programs, thus, tended to have a simplistic view of rural issues. Such top-down, unilateral mechanisms seem to explain why the conservation initiatives undertaken have faced low rates of adoption of practices by farmers (Helin and Haigh, 2002; Andersson and Ken, 2012; Arslan et al., 2014; Nkala et al., 2011; Ward et al., 2018).

Incorporating the knowledge built over decades to centuries into conservation initiatives requires knowledge governance, understood as “a fluid and historical processes of co-evolution between agents, organizations and institutional arrangements, and the knowledge they help to create and reproduce” (Manuel-Navarrete and Gallopin, 2012). The patterns of knowledge governance affect the mainstreaming of sustainability practices and integrate knowledge about their multiple dimensions (such as social, cultural, ecological; van Kerkhoff and Lebel, 2006). Due to the wide variety of ecosystem services performed by soils, no single level of governance can provide incentives for users to safeguard their long-term delivery (Orchard and Stringer, 2016). There is also growing acknowledgement that centralized, top-down mechanisms are inadequate for tackling land degradation as well as ensuring the sustainable use of natural resources more widely (Nagendra and Ostrom, 2012). Experience has shown that there is no “best practice” or innovative policy approach that can be applied to any type of region (Tödling and Tippl, 2005), and that no conservation practice is a panacea that can be adopted everywhere (Hudson, 1987).

General experience from the field and literature indicates that successful, scaled up and durable adoption of new technology requires consideration of both agro-ecological and socioeconomic factors affecting the incentives and constraints to adopt (de Graaff et al., 2008; Soule et al., 2000; Jara-Rojas et al., 2013; Arslan et al., 2014). It is however important to differentiate between the adoption of a new technology, generally done to increase economic profitability, and the adoption of a conservation strategy, which implies transforming the agroecosystem (de Graaff et al., 2008; Jara-Rojas et al., 2013).

In Mexico, soil erosion affects 60% of the land and 48.6% of the agricultural production units; while loss of soil fertility was mentioned as the main obstacle to the development of farming activities (INEGI, 2012). Soil erosion has costly consequences, with an estimated 38.3 to 54.5 dollars per hectare lost in yield and nutrients that have to be replaced by fertilizers (Cotler et al., 2011). The problem of soil erosion in Mexico has been addressed through the creation of public programs promoting technology packages that have not been discussed or agreed with farmers, nor adapted to the large social, environmental and cultural differences of a megadiverse country (Cotler et al., 2013; Turrent et al., 2014; Cotler et al., 2016; Damián and Toledo, 2016).

One of the main challenges to agriculture and livestock production is to create systems that are at the same time productive, resilient and adaptive to climate variability, and water and energy efficient, and this without damaging or polluting the environment (Arnés et al., 2013). In this respect, it is important to recognize that resilient soils are the foundation of resilient agroecosystems (Blanco-Canqui and Francis, 2016). Farmers working in different contexts have developed innovative strategies to improve soil quality and deal with climate variability (Altieri et al., 2015) to help develop adaptive climate-change response strategies (Astier et al., 2012). Such a “knowledge dialog” between generations and within communities has a long tradition throughout Mexico (Moreno-Calles et al., 2013; Toledo, 1990).

Theoretical approach

Concerns about soil dates back several centuries (Rasmussen, 1982) and grew with declining yields, erosion and most of all, drought and deforestation (Showers, 2006). Since the middle of the 20th century, soil conservation programs have followed the guidelines of international organizations, which, under certain ideological assumptions, have understood the soil erosion problem and outlined the steps required to address it (FAO, 1977; Biot et al., 1995; Simonian, 1999; World Bank, 2006; Showers, 2006).

Current governmental approaches promoted and implemented in different countries were classified by Biot et al. (1995) into three major categories based on the paradigms they pose about the causes of land degradation, the role of institutions, the market, the role of science and the peasant behavior, among others characteristics. These three-contested views about degradation are neither strictly sequential in their historical development, nor mutually exclusive (Table 1). However, since the globalization and industrialization of agriculture, pauperization of small farmers, and the loss of agrobiodiversity, several researchers and social movements have proposed new paradigms that take up the knowledge of peasants from many latitudes. These are based on the principles of food sovereignty, agrodiversity, resilience and defense of the territory (Altieri and Nicholls, 2008, Altieri and Toledo, 2011; Gliesmman, 2013; Holt-Gimenez, 2001; Via Campesina, 2013; Turrent et al., 2017; Astier et al., 2012; Astier et al., 2015). These proposals that collect local knowledge are opposed to the classic and neoliberal visions, adopted by the government agencies, in terms of values, where the concepts of efficiency, performance and homogeneity are not shared and in terms of participation, knowledge and the responsibility of small farmers.

In this context, this study sought to systematize

Table 1. Some characteristics of different peasant behavior paradigms.

	Institutional prescription	Peasant behavior	Immediate cause of erosion problems
Classic	Top-down centralized decision making.	Ignorant, irrational, traditional. Lack of participation by land-users in designing and implementing conservation technologies	Mis-management by users. Inadequacies of state bureaucracies charged with soil conservation strategies.
Populist	Bottom-up participation	Virtuous, rational, community-minded. It is required site-specific participatory study.	Mis-management by state, capitalists, big business
Neoliberal	“Market” policies, property rights, resource pricing	Rational egocentric	Poor government policies and bureaucratic rules & regulations. Direct relationships between poverty and land degradation.
Agroecology	Bottom-up recognizing local traditions, rights and knowledge	Peasants as central social actors in the processes of resistance to the neoliberal trade agenda and in the construction of alternatives based on their knowledge	Alliances between transnational industries, food corporations and governments that cause the dispossession of territories to peasants and indigenous peoples

Modified from: Biot et al. (1995).

experiences of soil knowledge governance involving social organizations and farmers or ranchers, with the aim of incorporating soil conservation practices and promoting sustainable land management. Emphasis was placed on: (i) mechanisms for building knowledge governance; (ii) the implementation of sustainable land management according to local socio-environmental conditions; (iii) institutions promoting and adopting soil conservation practices; and (iv) mechanisms for learning and monitoring soil conservation practices**.** The results of this study should lead us to rethink the kind of public policies that would better help soil conservation in Mexico.

MATERIALS AND METHODS

The study was conducted in two phases. The first one consisted in a compilation of case studies from social organizations working on farming issues at the national level, which were analyzed in light of the following criteria:
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(i) A working method based on both ongoing dialog between NGOs and farmers and knowledge governance over 3 to 5 years;
(ii) The incorporation of soil conservation practices and implementation of sustainable land management.

In the second phase, for the case studies that met these criteria, a survey was conducted, which included both open- and closed-ended questions. The survey was conducted by various means: (i) through a website; (ii) by email; and (iii) on site, for farmers without internet access. The elaboration of the questionnaire followed several steps. First, the questions were elaborated according to the objectives of the research. As the questionnaire was directed towards two different groups: agricultural systems and silvopastoral systems, the specific questions on the systems were differentiated, for which a bibliographic review was made on these systems in diverse socio-environmental conditions of the country. Once the questionnaire was prepared, a group of experts on the subject reviewed it. They improved and validated the questions in terms of clarity and relevance.

Subsequently, the questionnaire was applied to a small but diverse group of 10 farmers, located in different ecological regions. The results obtained from these samples allowed refining of the questions. The questionnaire was accompanied by a text explaining the purpose of the study. Once we have all the questionnaires, they were classified according to the different type of systems, and the answers in each group were compared and analyzed.

The following four main topics were addressed:

(i) Selection of soil conservation practices as the result of a knowledge governance process involving social organizations and farmers;
(ii) The local context (social, institutional and ecological) surrounding the implementation of soil conservation practices;
(iii) New institutions promoting and adopting soil conservation practices; and
(iv) Mechanisms for learning and monitoring soil conservation practices.
The survey allowed information to be collected from both landowners and NGO technicians.

RESULTS

Sixty-one survey responses were obtained from farmers (32), ranchers (12) and technicians (17) working for social organizations. The completed surveys covered 20 out of the 32 Mexican states. Of the 61 case studies, 36 related to agriculture and 25, to livestock production. Slightly more than 30% of the survey responses were from regions with a temperate climate; 27%, from regions with a humid tropical climate; 23%, from regions with a semi-arid climate; 16%, from regions with a dry tropical climate; and 3%, from regions with an arid climate (Figure 1). The agricultural systems were mostly based on maize, which forms the basis of the Mexican diet and has deep cultural roots.

The average age of the farmers and ranchers who implemented soil conservation practices and transformed their systems was 48 years, which is below the Mexican countryside’s average (55 years; INEGI, 2007).

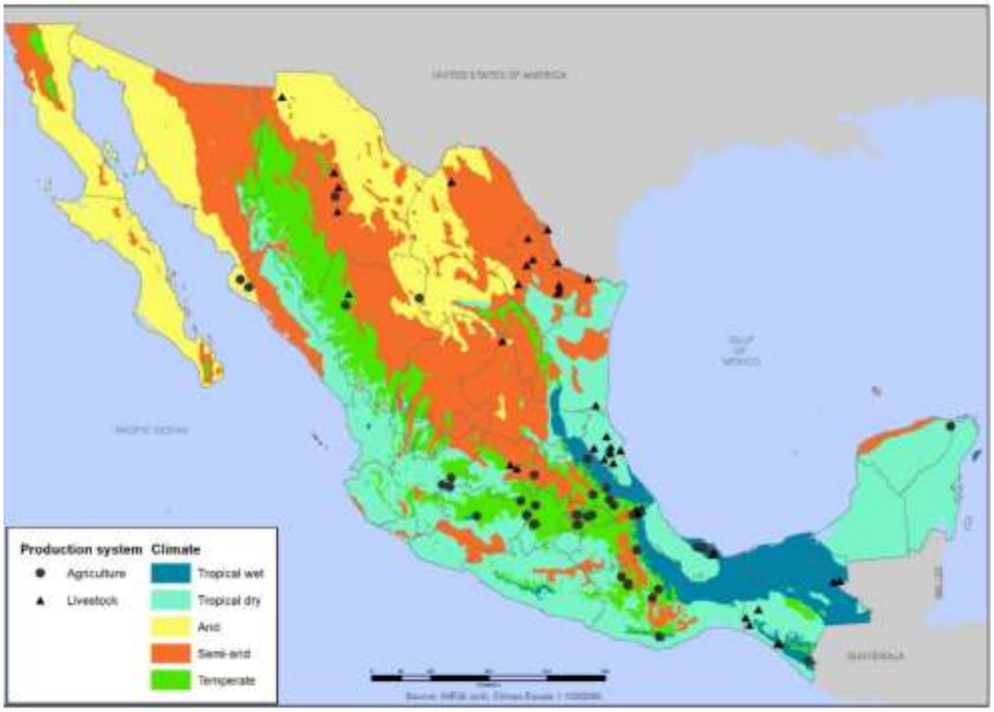

Figure 1. Sites covered by the survey of soil conservation practices and associated production systems and climates in Mexico.

Building of soil knowledge governance

The respondents to the survey reported the presence of 30 social organizations (NGOs), 12 community-led organizations: *ejido* (collective forms of ownership) committees, watershed committees, producer associations, 4 federal government organizations and 4 public academic institutions. These organizations had been working at the different sites for over 5 years, building relationships of trust, dialoguing with the farmers and encouraging them to think about their quality of life and expectations, thus triggering the building of new production systems. Different means were used to raise awareness of soil degradation problems by facilitating discussion and the sharing and appropriation of experiences. The main means used to build knowledge were those that allowed greater proximity between stakeholders (farmers, NGOs and researchers), such as workshops and the sharing of experiences among farmers or “knowledge dialog”.

The main reasons why farmers decided to incorporate soil conservation practices and make substantial changes to how they manage their farm were (in decreasing order of importance): (i) preventing further soil erosion and increasing yield; (ii) increasing soil organic matter content, infiltration and plant diversity; and (iii) creating local jobs. Forty-five percent of the soil conservation practices were designed specifically for each site’s environmental and social conditions by social organizations and farmers. The farmers already knew 24% of these practices; 17% were promoted through subsidies from a government program; and the remaining 14% unknown by the farmers at first, were introduced by the social organizations following a socialization and acceptance process.

The reported soil conservation practices were implemented on agricultural parcels or livestock parcels (Figure 2).

According to the survey responses, the practices most commonly used on the agricultural parcels were agronomic and vegetative practices, combined with mechanical ones. The agronomic practices most commonly used on these systems were crop rotation, the addition of organic matter to the soil, and intercropping (Figure 2). Of the mechanical practices, terracing was the most common. For 19% of the agricultural systems, a single agronomic practice was used; for 68% of them, two or more of these practices were used; and for the remaining 13%, no agronomic practice was used.

On the livestock parcels, the most commonly used practices were living fences, the reduction of animal load, pasture rotation and the planting of trees and shrubs. As with agricultural systems, most (over 75%) of the respondents implemented two or more vegetative practices. The mechanical practices were not implemented as often as the vegetative ones: 39% of the respondents reported that they did not use them. The new soil conservation practices were incorporated

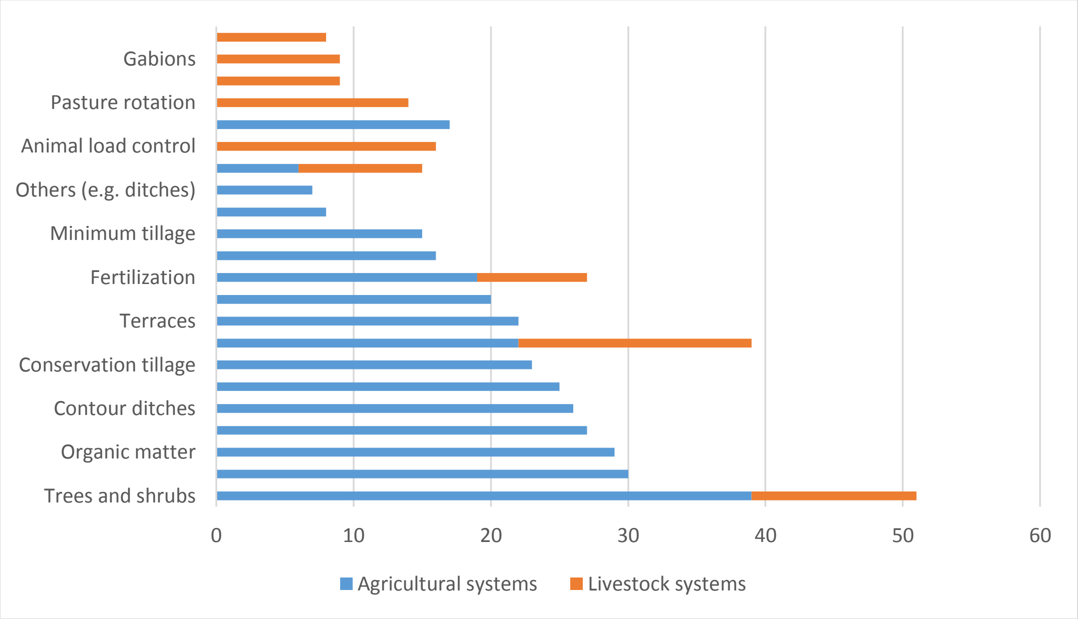

Figure 2. Results of soil conservation practices implemented on agricultural and livestock systems from survey.

gradually and led to radical changes in the whole production systems. Thus, the dialog and consensus built from knowledge governance allowed not only isolated practices to be incorporated, but also conventional systems to be converted into sustainably managed ones.

Sustainable land management in a local context

Most agricultural systems were located on *ejido* land (50%) or in communities (28%), and 48% were small-scale, consisting of 1 to 3 ha. They used mainly family labor (52%) or a combination of family and hired labor (33%). In most cases (57%), the production was for self-consumption with the sale of surplus; 19% of the production was only for self-consumption; and 24% was to be sold in local markets. Some of the reported agricultural systems covered more than 20 ha, used exclusively hired labor and had their production sold in both regional and international markets.

The livestock systems were located on *ejido* land (77%) or private land (23%) and varied widely in size, from less than 5 ha to over 100 ha. The smallest parcels used mainly family labor, and their production was for self-consumption only (48%) or self-consumption with the sale of surplus. The parcels over 50 ha large, however, tended to use a combination of family and hired labor, with the products destined for both regional (48%) and international markets (52%). In most cases (70%), the soil conservation practices were applied on degraded soils to restore soil properties and functions; they were thus used as a corrective measure rather than to prevent soil erosion.

Initially, the agricultural systems consisted of rain-fed monocultures (of maize or another cereal) that used agrochemicals and produced low yields, while the livestock systems consisted of extensive productions on moderate to steep slopes, with grazing lands obtained by slash-and-burn. The incorporated soil conservation practices mainly sought to transform the agricultural systems into sustainable managed lands by diversifying crops and adding organic matter to the soil. In many sites, these practices led to the recovery of *milpa*, the traditional polyculture of maize, squash, beans, chili peppers and other edible species.

The original production systems were thus transformed into sustainably managed lands, as shown in Table 1. The agricultural systems were diversified into *milpa* interspersed with fruit trees, maize interspersed with fruit trees, maize grown on terraces with fruit trees, avocado agroforestry systems and conservation tillage systems (maize and soy). As for the livestock systems, they were modified into silvopastoral systems (with species compatible with the climate, humid tropical or dry tropical) or holistic livestock systems.Although the proposed production systems are, in principle, sustainable, the environmental and social conditions of the sites where they were implemented were not always appropriate. A clear example of this is conservation tillage. In the case of small *ejido* lands, it was promoted by government organizations; while in that of large private lands, it was initiated by the owners themselves with the help of producer associations. In the first case, the system was not fully adopted because when it was implemented, the

Table 2. Environmental, social and institutional characteristics of the agricultural and livestock systems converted into sustainable managed lands through soil conservation practices from surveys.

Type of sustainable managed land	Climate	Size of property	Type of labor	Support needs	Destination of production	Land Tenure
Milpa interspersed with fruit trees	Temperate and humid tropical	Small	Family	High demand for training (to design furrows and manage fruit trees)	Self-consumption and sale of surplus	*Ejido*
Maize interspersed with fruit trees	Temperate	Small	Family	Demand for training (to manage fruit trees)	Self-consumption and sale of surplus	*Ejido* and community
Maize grown on terraces with fruit trees	Temperate and semi-arid	Small	Family	Demand for training (to manage fruit trees)	Self-consumption and sale of surplus	*Ejido*
Avocado agroforestry system	Temperate	Small	Family and hired	Producers learned by themselves through observation	Self-consumption and sale of surplus	Private
Conservation tillage system (maize and soy) with irrigation	Temperate	Large	Hired	Long learning process through courses, workshops and the support of other producers	Sale in international markets	Private
Conservation tillage system (maize) without irrigation	Temperate to semi-arid	Small	Family	Support needed to improve the agricultural system (leaving the stubble on the ground) and modify the livestock system accordingly	Self-consumption and sale of surplus	*Ejido*
Silvopastoral system	Humid tropical	Medium	Family and hired	Demand for support to design the new system and manage livestock	Self-consumption and sale of surplus in regional markets	*Ejido* and private
Silvopastoral system	Dry tropical	Medium	Family and hired	Demand for support to design the new system and manage livestock	Self-consumption and sale of surplus in regional markets	*Ejido* and private
Holistic livestock system	Semi-arid to arid	Large	Hired	High demand for support: radical change in the paradigm of livestock production	Sale in regional and international markets	Private

*Small: less than 5 ha; medium: 5-20 ha; large: over 20 ha.

government organizations did not consider the fact that local production systems integrated both agricultural and livestock activities. Stubble being an essential input for feeding the animals, it could not be left on the ground. In the second case, the farmers had no livestock and simply stopped selling the stubble to livestock producers to incorporate it into the soil (Table 2).

New (and old) institutions to promote and implement soil conservation practices

In over 90% of the cases, social organization played an important role in reducing costs, sharing knowledge, expanding networks and contacts, and communicating risks. In the case of *ejido* lands, where many decisions—regarding government programs, the maintenance of water infrastructure and roads, common areas—are made by the *ejido* assembly, joint reflection by

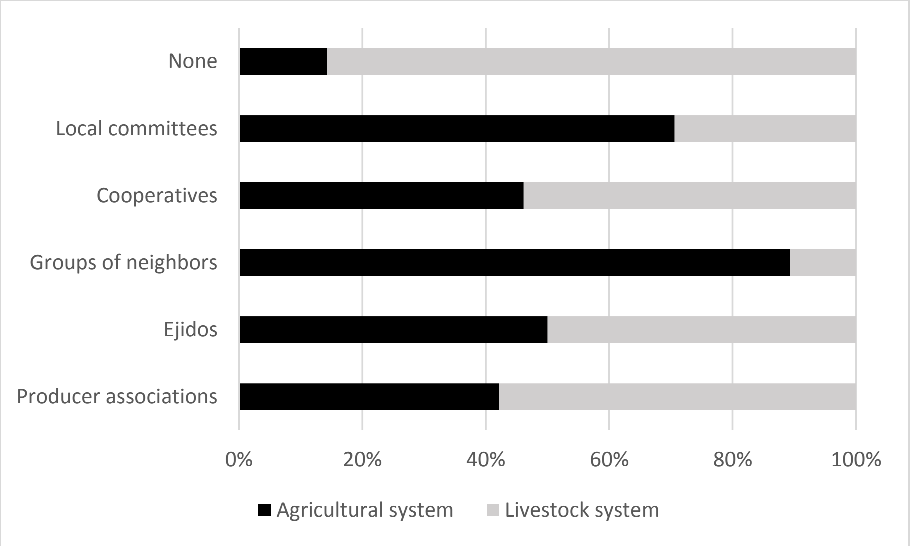

Figure 3. Best social organizations to successfully implement soil conservation practices in agricultural and livestock systems according to the survey.

farmers and NGOs allowed to make commitments to strengthen the *tequio* (community tasks), improve accountability for the resources obtained, and control the animal load in common areas, among other achievements. Thus, the dialog about soil conservation practices resulted in the strengthening of local institutions.

Regarding the agricultural systems, respondents mentioned that the creation of groups of neighbors, producer associations and local committees proved to be useful, as they allowed inputs like compost, *bocashi* (compost activator) and organic pesticides (*bioles, caldos*) to be produced jointly. For the livestock systems, cooperatives helped reduce both the costs of buying livestock inputs and selling prices, thanks to their many members (Figure 3). A small percentage of respondents mentioned that they did not need any social organization. In all these cases, the lands were for private use, with all management decisions made by the owners themselves.

In most cases, a single organization was considered insufficient to accompany the process, as it rarely had all the knowledge required to both design and assess soil conservation practices, or lacked the financial and technological resources to do so. The results show that the presence of different organizations (such as, local, academic, governmental, social, etc) working in conjunction led to a polycentric governance that strengthened the process of adopting these practices.

Mechanisms for learning and monitoring soil conservation practices

Soil conservation practices require extra work. For landowners to take ownership of them, it is thus important that they see tangible results of their implementation. According to the survey, the results of these practices were evaluated by: (i) measuring yield for livestock systems and carrying capacity (evaluating product quality was also mentioned); (ii) participatory monitoring based on local knowledge, to identify sedimentary changes in water bodies; and (iii) technical monitoring (such as, monitoring of the survival of fruit trees, maintenance of mechanical works, monitoring of the proper functioning of furrows).

Three to five years after the implementation of soil conservation practices, more than half of the respondents identified positive changes in their parcels, the main ones being, in decreasing order of importance: (i) reduced soil erosion; (ii) increased yield; (iii) increased soil organic matter, and thus increased infiltration and soil moisture retention; (iv) increased plant diversity; and (v) the creation of local jobs.

The incentives for farmers to maintain soil conservation practices were very diverse. Among the main ones, the following were mentioned: (i) eating healthy food (grown without agrochemicals), particularly in the case of agriculture for self-consumption; (ii) diversifying crops, in order to have products to sell all year round; (iii) reducing soil erosion, which threatened the integrity of their property; and (iv) improving their social position in the community by being seen as innovative people, with the possibility of teaching and seeing their family united around a new project (thus reducing the migration of young people).

Most of the time, soil conservation activities are not incorporated into traditional production systems and, as such, may represent extra work. The respondents to the survey identified different barriers to carrying them out. Among the main ones, they mentioned the lack of money, the lack of acceptance by the other community members, the lack of technical support, and the lack of social organization. These barriers were overcame mainly by organizing themselves with residents of the same community and its surroundings, looking for training opportunities and, in many cases (51%), requesting financial support from the government. The respondents however mentioned that without this funding, they could continue to carry out soil conservation practices, if the landowner actively participates in them and they receive support from civil society organizations.

The lack of acceptance of better practices by other members of the community was reported to be one of the main barriers to propose and implement them. However, 55% of the respondents mentioned that they have replicated the practices on other parcels, resulting in higher yields and noticeable improvements in soil condition and agricultural biodiversity.

DISCUSSION

Historically, Mexico's soil conservation programs have followed the guidelines of international organizations, which, under certain ideological assumptions, have understood the soil erosion problem and outlined the steps required to address it (FAO, 1977; Biot et al., 1995; Simonian, 1999; World Bank, 2006; Showers, 2006). The main weakness of these programs has lied in not considering knowledge governance involving different stakeholders as a critical success factor (Simonian, 1999; World Bank, 2006).

Policy and attitudes regarding soil conservation practices have changed markedly over the course of the past half century (Carlisle, 2016). During this time, various studies have shown that the success of a soil conservation program depends on the adoption of practices, and that this process relies on the management of local knowledge, which better represents the local conditions (Angeon et al., 2014).

The adoption of soil conservation practices is a complex process (de Graaf et al., 2008; Eakin and Wehber, 2009; Manuel-Navarrete and Gallopin, 2012; Angeon et al., 2014). Here, various factors come into play: personal and family factors (such as, attitudes, knowledge, family situation, migration), social factors (such as, technical support, land tenure, migration), physical factors (such as, slope, erosivity and climate variability, soil erodibility), institutional factors and collective action (such as, rules, standards, community work), as well as economic factors (such as, income, debt, outside job).

The diversity of these factors makes it clear that the adoption of such practices is not a linear process. Several studies have also highlighted the importance of understanding the adoption of soil conservation practices as a multistage, adaptive process rather than instantaneous, single-step decision-making (Coughenour, 2003; Carlisle, 2015). Any change in the farmer's situation (like the need to migrate in order to supplement income, or a debt incurred due to health care costs) can set back the implementation of these practices, even if the farmer is convinced of their value. Another factor that can undermine the adoption of soil conservation practices is the inconstancy of regional and national policies regarding priority issues-which tend to change with every change of government—, or a change in NGO priorities and funding. This instability can affect the payment of recurring costs for the purchase of machinery, fixing water infrastructure or training, among others. This illustrates both the strength and the weakness of polycentric governance systems (Orchard and Stringer, 2016) where, on the one hand, the responsibilities and capabilities are distributed among several stakeholders, but on the other, vulnerabilities increase accordingly.

This study shows that an important step towards adopting soil conservation practices was having them designed by several social organizations and farmers through soil knowledge governance, considering the environmental, social, institutional and economic conditions specific to each site. As a result, most of the chosen practices were agronomic and vegetative measures that promote ecological diversity, reduce soil erosion, and add organic matter to the soil, hence improving soil quality (Lal, 2014). Such a preference for this type of practice has been reported for other areas with different environmental and social conditions (Carlisle, 2016). Thus, there seems to be a departure from the current paradigm of government programs for soil conservation, which are often managed by a centralized administration in a top-down manner, without considering environmental and social differences. This may be why mechanical practices like check dams, ditches and stonewalls have dominated so far (Biot et al., 1995; Lapar and Pandey, 1999; Cotler et al., 2013, 2016).

In a context of public policy program, these mechanical, structural measures may have been preferred as "attention grabbers because they are spectacular and conspicuous… however, they are hardly ever adequate on their own" (Liniger and Critchley, 2007). The literature on soil conservation has tended to emphasize the importance of financial incentives in adopting practices (Lapar and Pandey, 1999; De Graaff et al. 2008). Although such incentives are, indeed, important in a poor rural context, they do not meet the diversity of views, concerns and values of this population. This study shows that in the case of agriculture for self-consumption, important incentives also include improving the environment, ecological diversification, playing a leading role in the community, and improving the quality of their food. This contrasts with large regional and international producers, for which “money is the best incentive”. This agrees with various studies that found that “immediate financial benefits were less important to farmers than long-term soil health” and food security (Carlisle, 2016, Damián and Toledo, 2016). Sheeder and Lynne (2011) also concluded, “policy instruments that facilitate expression of (the) shared ethic may be more likely to increase conservation technology adoption rates than policies that stress only financial incentives”. Other experiences on soil conservation behavior (Lockeretz, 1990; Sheeder and Lynne, 2011) have emphasized the multiple motivations that are at play at the time of adopting soil conservation practices.

In Mexico, as in other Latin American countries, decades of intense rural–urban migration have caused the abandonment of agricultural activities, the breakdown of local knowledge, and a weakening of social organization (Anta and Carabias, 2008). Incorporating young people into a process of soil knowledge governance may thus provide them with a means of valorizing their biological and cultural heritage (Maffi, 2001).

In the production systems analyzed, soil knowledge governance focused mainly on the joint implementation of practices and alternative land management, based on the farmers’ knowledge and expectations. The methods for assessing the practices and the system as a whole, however, are to be strengthened. The monitoring of works and evaluation of acceptability would transform soil conservation into a learning process that would gradually increase the confidence of the farmers in its efficiency. Indeed, experience has shown that monitoring and evaluation lead to important changes and modifications in the approaches and technologies used (Liniger and Critchley, 2007). Participatory research could open new channels of communication to develop methods for the participatory monitoring of soils using local indicators and tools. Soil conservation should no longer be seen as an isolated problem, separate from the other environmental issues faced by rural areas. Since rural areas are characterized by different biophysical and social conditions, the goal should not be to build soil conservation programs of a top-down nature, but programs that are flexible, adaptable to local conditions, and built jointly with the farmers through knowledge governance.

Conclusions

Up to now, Mexican government programs for soil conservation have been based on international guidelines and implemented in a top-down manner. Specific technologies have been unilaterally transferred to farmers without incorporating their demands, experiences and expectations, and without adapting the practices to the different environmental, social and institutional conditions (Manuel-Navarrete and Gallopin, 2012). This has led to a very low adoption rate of soil conservation practices.

In recent years, a consensus has emerged that the identification and implementation of soil conservation practices jointly with farmers is key to redesigning new agroecosystems that are both resilient and sustainable (Astier et al., 2012; Stringer et al., 2014; Altieri et al., 2015). In the cases analyzed here, the polycentric governance of soil knowledge allowed agroecological alternatives to be developed jointly with NGOs, academic and government organizations, and farmers. The incentives for farmers to continue to invest time, resources and effort in these agroecosystems reflected the communities’ diversity of views, concerns and values. Small farmers were sensitive to incentives such as eating healthy food (grown without agrochemicals), diversifying their income, reducing soil erosion and improving their social position in the community by being seen as innovative people, with the possibility of teaching and seeing their family united around a new project. Thus, unlike the approach set forth in government policies for soil conservation, the incentives were not limited to financial ones.

Despite several years of working together in a framework of soil knowledge governance, the agroecosystems analyzed remain fragile and vulnerable, notably to changes in the political and economic priorities of the government and NGOs. For this reason, polycentric governance systems should be based on public policies that are flexible, bottom-up and adaptable to different environmental, social and institutional conditions and that incorporate local knowledge. What is required for the upcoming soil conservation programs is both vertical scale-up (institutionalization) and horizontal scale-up (expansion of the practices), with multi-level decision-making and a long-term, flexible funding that will allow a learning process to take place.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Nutrient release pattern from *Leptic Cambisols* as influenced by vermicompost and inorganic fertilizer applications

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An experiment was conducted to determine the effects of vermicompost, inorganic fertilizers and their combinations on release of soil nutrients at different growth stages of wheat. A factorial combination of four levels of inorganic fertilizers (0, 33.33, 66.66, and 100% of the recommended NPK fertilizers) and vermicompost (0, 2, 4 and 6 t ha^{-1}) were laid out in complete randomized design with three replications. Soil was collected before planting and after planting (at tillering, flowering and maturity stages of wheat) from each pot in order to determine dynamics of selected nutrients (NPK). The interaction between vermicompost and chemical fertilizers were not significant for NPK contents of the soil at all growth stages except phosphorus at heading stage. In all cases, highly significant increases in total N, available P and K in the soil were observed due to the increasing rates of main effect vermicompost or inorganic fertilizers during all growing periods. The highest available as well as total contents of NPK in the soil were found at tillering stage. This initial increment at tillering stage for both factors showed a declining trend later at heading and maturity stages. However, the observed decline was in exception for vermicompost applied at 6 t ha^{-},^{1} which maintained highest level of available P and K and 4 t ha^{-1} which continued mineralization of K up to heading stage. In general, application of 6 ton vermicompost per hectare was found proportional with the full dose of the recommended fertilizers in supplying NPK for wheat crop. Therefore, building up the total as well as available NPK to higher levels up to heading stage can bring maximum nutrient uptake and yields of wheat.

Key words: Growth stages, mineralization, nutrient availability, nutrient decline.

INTRODUCTION

In Ethiopia, the major constraint to agricultural growth and food self-sufficiency for a long period is the decline in soil fertility. Soil fertility is a manageable soil property and its management is of utmost importance for optimizing crop nutrition on both a short-term and a long-term basis to achieve sustainable crop production (Roy et al., 2006).

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In response to this problem, major efforts have been made to encourage the wider use of inorganic fertilizers. Regardless of a five times increase in fertilizer application in Ethiopia, national cereal yields have only increased 10% since the 1980s (Gete et al., 2010), while relative benefits of chemical fertilizer application have decreased over time.

Even though chemical fertilizers substantially increased the available plant nutrients during the first weeks, losses arising from different factors limit the continual supply of nutrients at critical periods where plants inquire high demand for these nutrients. Reports from Hammermeister et al. (2006) show that chemically fertilized plots declined in NH_4^+ as sampling time continues. On the other hand, available P was high at tillering which declined later at flowering and maturity stages of rice (Lungmuana et al., 2013) compared to organic residues and manures. Loss of ammonium from urea due to leaching and volatilization during two to three weeks after application (Jones et al., 2007), fixation of phosphorus with Al/Fe oxides (Lungmuana et al., 2013) and potassium with interlayer of clay mineralogy (Najafi-ghiri, 2014) were reported after the addition of inorganic fertilizers. Such losses could exhaust the pool and available stock of certain nutrients and brought a question whether they could support plant life until the maturity stage.

However, organic farming systems with the aid of various nutrients of biological origin such as compost and vermicompost were thought to be the answers for the 'food safety and farm security' in future (Sinha et al., 2009). On the other hand, initially low levels and low release of available nutrients from organic amendments at seedling and vegetative stages can restrict uptake of adequate nutrients that might result to poor root and shoot growth of plants. Additionally, the ill effects of farmlands brought about by the application of chemical agricultural inputs for long periods in favor of boosting plant yields (Arancon et al., 2006; Sheoran et al., 2015; Sinha et al., 2009) were at a cost of inherent soil fertility and microbe inhabitants which are supposed to maintain the balance of rhizosphere by natural law.

Furthermore, NPK deficiencies are widespread and external applications are necessary to augment soil supplies for harvesting optimal crop yields while minimizing the depletion of soil nutrient reserves (Roy et al., 2006). In Ethiopia, it was reported that some crops have been suffering from deficiencies of nutrients other than nitrogen and phosphorus (ATA, 2014). This cannot be maintained in agricultural soils of the country where only NP fertilizers are applied unless supplied with organic amendments adequately like vermicasts.

Thus, evaluation of such new technologies when applied solely and/or integrated with the chemical fertilizers might give farmers another alternative to overcome such problems. At the same time, building sustainable and climate smart agriculture with vermicasts can bring a new outlook to organic farming. Therefore, this research was conducted to investigate the effect of sole and combined applications of organic and inorganic fertilizers on the release of NPK at different growth stages of wheat.

MATERIALS AND METHODS

Area description

Soil for pot experiment was taken from farmlands of Mekan area, Enda-Mehoni district, Southern Tigray, Ethiopia. Soils having the same cropping history and soil types were sampled for potting media. According to the pedological map developed for the district, the soil type of the sampling area is Leptic Cambisols (Mitiku et al., 2007). The sampling area was located at 39° 29'18'' up to 39° 33'35'' longitude and 12° 43'28' up to 12° 46'12'' latitude. The pot experiment was carried out at MIT Tissue Culture Micro-Propagation Laboratory's Greenhouse, Mekelle, Ethiopia.

Treatments and experimental design

Vermicompost and chemical fertilizers were used in this experiment as a source of nutrients (NPK). Vermicompost was processed by earthworm *(Eisinea fetida)* using cow manure, *Lanthana camara* leaves and wheat straw. The soil was filled to forty-eight plastic pots having 30 and 20 cm upper and bottom diameters, respectively and 28 cm depth.

A factorial combination of four levels vermicompost and four levels inorganic fertilizers (NPK) was laid out in complete randomized design (CRD) with three replications. The vermicompost levels were consisted of 0, 2, 4 and 6 t ha^{-1} while inorganic fertilizers (NPK) were 0, 33.33, 66.66, and 100% of the recommended NPK rates. All the rates of vermicompost and NPK from inorganic fertilizers were incorporated once irrespective of the treatments and moistened at optimum. The elemental nitrogen (N), phosphorus (P) and potassium (K) was applied in the form of urea, triple superphosphate (TSP), and murate of potash (KCl) respectively. The full doses or recommended rates of NPK fertilizers were the blanket recommendation of 64 kg N ha^{-1} and 46 kg P_2O_5 ha^{-1} which is a common practice for cereal crops throughout the country and 60 kg K_2O ha^{-1} respectively. The amount of Urea, TSP and KCl (g pot^{-1}) was determined by multiplying the recommended fertilizer rates (kg ha^{-1}) and 5 kg soil pot^{-1} and divided by 2000000 kg soil ha^{-1}. Improved wheat variety; Kekaba was used as a test crop and eight seeds of wheat were planted per pot and thinned to 5 after germination to maintain enough space between plants. The moisture level was monitored regularly and maintained with distilled water.

Sampling, laboratory analysis of soils and vermicompost

Prior to planting, one composite soil sample from all soil sampling points and from the processed vermicompost was taken for routine analysis and the result is presented in Table 1. Soil sample was also collected after planting at tillering, flowering and ripening stages of wheat from each pot. The collected soil sample was air-dried, milled using pistil and mortar, sieved to pass through 2 mm diameter mesh sieve, stored and tagged in plastic bags. Then, particle size distribution, pH, EC, CEC, %OC, total N, available P, exchangeable K analyses was carried out for vermicompost and soil samples before planting and Total N (mg kg^{-1}), Av.P (ppm) and Av.K (ppm) for the successive periodic soil samples to investigate

Table 1. Initial characteristics of the soil and vermicompost used for pot experiment.

Parameter measured	Sample source	
	Soil	Vermicompost
pH	7.48	6.78
EC (ms m^{-1})	0.05	2.77
CEC (cmol(+) kg^{-1})	30.6	-
% OC	0.98	11.37
% OM	1.68	19.60
Total N (mg Kg^{-1})	600	14100
% Total P	-	0.78
Av P (ppm)	9.26	-
% Total K	-	1.02
Exc.K (cmol(+) kg^{-1})	0.34	-
% Clay	45	-
% Silt	27	-
%Sand	28	-
Textural Class	Sandy clay loam	-
Moisture content (%)	-	38

the dynamics of nutrients from the above treatments. Soil texture was determined by the hydrometer method (Bouyoucos, 1962).

Soil pH and EC was determined using a pH meter from 1:2.5 soil:water ratio suspension as described in Rhoades (1982) and using EC meter from 1:5 soil water saturation extract (Jakson, 1967) respectively. The determination of soil organic carbon was based on the Walkley-Black chromic acid wet oxidation method (Walkley and Black, 1934). The Kjeldhal process (digestion, distillation and titration) as outlined by Bremner et al. (1982) was followed to determine the total nitrogen. Olsen Method (Bicarbonate extractable P) was used to extract and determine available phosphorus, using 0.5 M NaHCO at adjusted pH 8.5 (Olsen et al., 1954). Determination of CEC at pH 7 was carried out with Ammonium Acetate method as described by Chapman (1965). The amount of exchangeable cations (K) in the extract was determined by flame photometer according to Gupta (2000). Available K was determined by extracting from the sample with Morgan's solution as outlined by Sahlemedhin and Taye (2000).

RESULTS AND DISCUSSION

Selected physicochemical properties of the soil and vermicompost

The textural class of the soil used for the pot experiment was sandy clay loam. According to the rating made by Tekalign (1991), the soil reaction (pH) was moderately alkaline and the organic amendment (vermicompost) was neutral. Similarly, the total organic carbon (%) and organic matter (%) of the soil was found low, whereas it was very high for vermicompost.

The cation exchange capacity (CEC) of the soil was found to be high as outlined by Hazelton and Murphy (2007). There was medium total nitrogen (%) content on the soil and very high on the vermicompost which was used as potting media according to the rating made by Berhanu (1980) and Tekalign (1991). The total and available phosphorus content of the vermicompost and the soil was rated as very high (Murphy, 1968) and medium (Cottenie, 1980) respectively. Moreover, the total and exchangeable amounts of potassium on the vermicompost and the soil were also found to be medium (FAO, 2006), respectively.

Total nitrogen (mg kg^{-1}) content of the soil at different growth stages

The interaction between vermicompost and inorganic fertilizers was not significant for nitrogen content of the soil at all growth stages, but there were highly significant main effects ($P \leq 0.0001$). In all cases, a highly significant increase in total N of the soil was observed due to the increasing rates of vermicompost or inorganic fertilizers during all growing periods. These results were in agreement with the findings of Thakare and Wake (2015).

Out of all growth stages, the highest total N of the soil was measured at tillering stage for both main effects. At this stage, the total N was 738, 1137, 1495, 1909 mg kg^{-1} for the pots that received 0, 2, 4 and 6 t VC ha^{-1} (Figure 1) and 979, 1196, 1425, and 1679 mg kg^{-1} for the pots that received 0, 33.33, 66.67 and 100% of the recommended doses of NPK, respectively (Figure 2). However, the total N (mg kg^{-1}) content for both main effects showed a declining trend from tillering to heading and maturity stages for all treatments. In that order, it declined by 23, 19, 21 and 23% for the rates of main effect vermicompost and about 30, 21, 17 and 21% for the rates of main effect inorganic fertilizers (NPK) during heading stage.

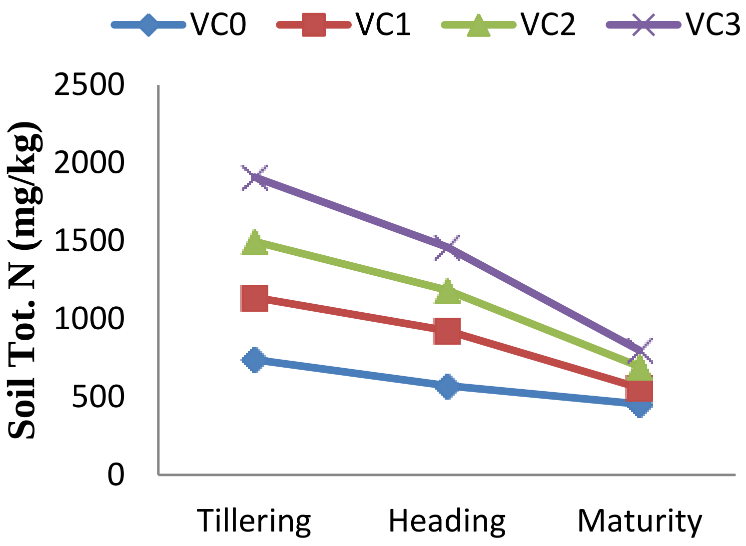

Figure 1. Total Nitrogen (mg kg^{-1}) content of the soil at different growth stages of wheat as influenced by application of different vermicompost levels.

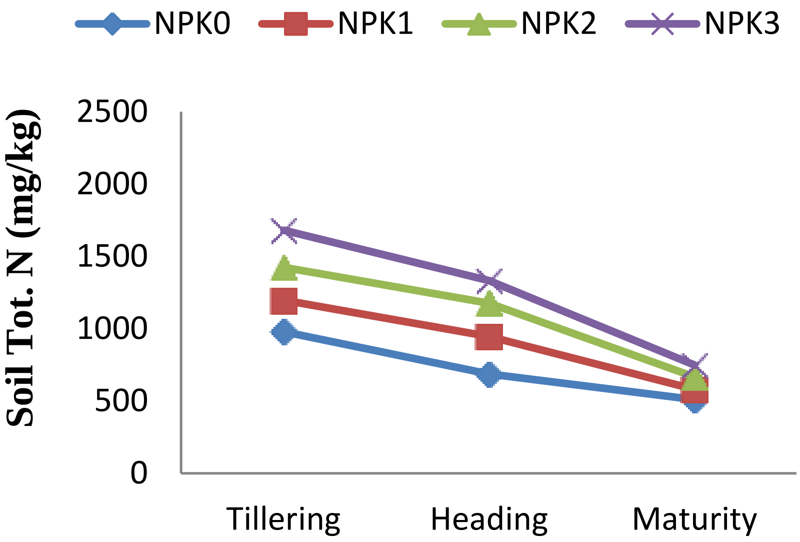

Figure 2. Total Nitrogen (mg kg^{-1}) content of the soil at different growth stages of wheat as influenced by application of different chemical fertilizer level.

Accordingly, about 39, 51, 54 and 58% of the total N measured at tillering from pots that received 0, 2, 4 and 6 t VC ha^{-1} (Figure 1), respectively were declined at maturity stage of the crop. Similarly, the declines for pots treated with 0, 33.33, 66.67 and 100% of the recommended doses of NPK from inorganic fertilizers at this stage were 48, 51, 53 and 56%, respectively. This trend has also been reported by Hammermeister et al. (2006), who reported lower soil N mineral content in the final analysis compared to the initial analysis for several treatments, suggesting loss of N with time. Similarly, Nathiya and Sanjivkumar (2015) have also found higher available nitrogen content on vegetative and flowering stage of groundnut than at postharvest stage, indicating that plants derive nutrients from soil for their growth and development leading to the depletion of soil nutrients at the late growth stages. The decline in mineralized nitrogen with time might be related to the decrease in the labile organic matter (Tirol-Padre et al., 2007).

The temporal distribution of the total nitrogen content for the main effect chemical fertilizer had the same trend with vermicompost. The total nitrogen content was

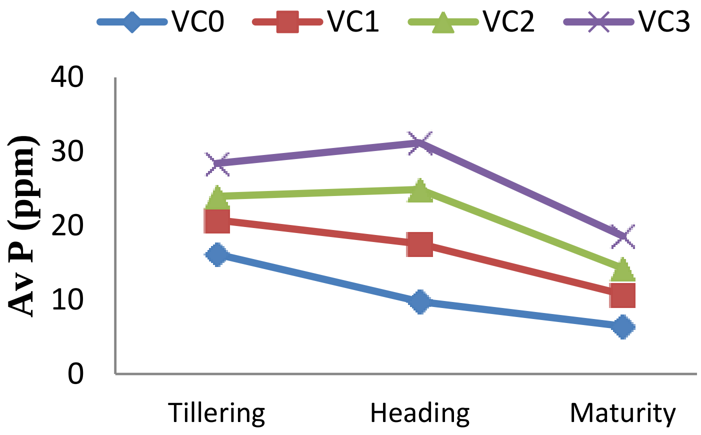

Figure 3. Phosphorus release pattern in the soil at different growth stages of wheat as influenced by application of different vermicompost levels.

increased with application levels of inorganic fertilizers at all growth stages and reached its maximum at tillering, which sharply declined at heading and maturity stages (Figure 2). Such initial increasing trend in available N after application of high rates of N from chemical fertilizer has also been reported, which later declined significantly with sampling time from tillering to heading and maturity stages of spring wheat (Lu et al., 2010).

The extent of decline in total nitrogen content from all treatment levels except the control pots was higher after heading stage of wheat for both treatment levels. At the same time, this decline was increased as the application rate of vermicompost and chemical fertilizers increased. Similar results have been reported by Lu et al*.* (2010) who measured an excessive N loss due to application of high N rate. In this experiment, elevated reduction with application of high N levels could be explained due to the observed higher uptake of nitrogen. Studies from Mehta et al*.* (1963) indicated higher nutrient uptake at the later stages of wheat, which could serve as an exception to the decline in the total N content of the soil solution. On the other hand, immobilization of nutrients explained by increases in the microbial biomass in the soils treated with vermicomposts could decline N contents of the soil and such increase in microbial biomass were greater in soils receiving higher rates of vermicompost applications (Arancon et al., 2006).

It was observed that, the average decline in nitrogen content from the experiment was relatively higher in chemically fertilized pots than for vermicompost treatments. Moreover, the relative higher amounts of total nitrogen measured at all growth stages with application of highest doses of vermicompost (6 t ha^{-1}) compared to other vermicompost and chemical fertilizer levels might be due to the higher level of initial organic carbon content (11.4%) of the vermicompost (Table 1). Similar conclusion had been made from previous studies, which verified that changes in the organic carbon content brought about changes in the total nitrogen content of the soil (Angelova et al., 2013; Tirol-Padre et al., 2007). This investigation also showed a strong positive correlation between the total organic carbon content and the total nitrogen content with value of correlation coefficient as high as 0.97 (Angelova et al., 2013). Angelova et al*.* (2013) have also indicated that the considerable amount of humic acid present in vermicompost could serve as a binding site to NH_4^+, which could prevent the possible losses through leaching and volatilization.

Phosphorus release pattern at different growth stages

Application of vermicompost and chemical fertilizers affected the availability of phosphorus in the soil. All the experimental pots treated with vermicompost and inorganic fertilizers released higher amounts of available P over the control and the availability significantly increased at all growth stages ($p \leq 0.0001$), as the application rate increases. Application of 2, 4 and 6 t ha^{-1} vermicompost gave an advantage of 28, 48 and 76% available P, respectively, over the control at tillering stages of wheat. The increase in available P due to vermicompost was in agreement with the findings of Angelova et al*.* (2013) and Tharmaraj et al*.* (2010). Generally, application of a considerable amount of total phosphorus (0.78% P in VC) (Table 1) with highest doses of vermicompost, could attribute to the elevated increase in available phosphorus irrespective of the treatment levels. After the initial increment in available phosphorus at tillering, a decline was observed at heading stage except for the higher doses of vermicompost (4 and 6 t ha^{-1}) (Figure 3). The available phosphorus content for the rates of main effect vermicompost was then decreased at

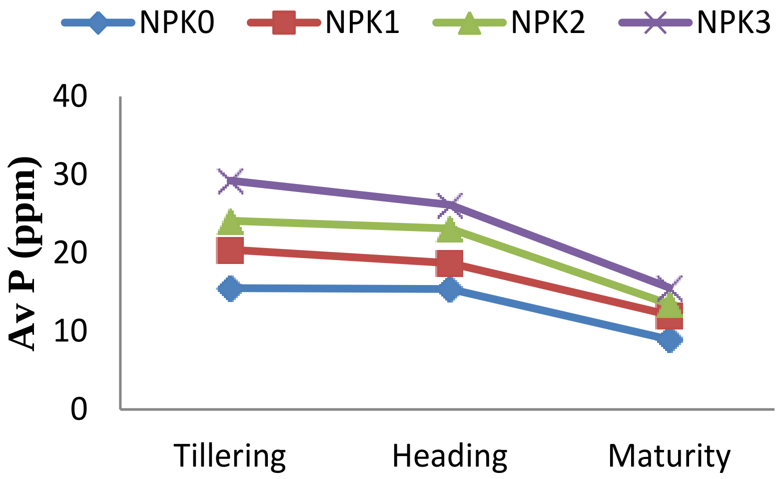

Figure 4. Phosphorus release pattern in the soil at different growth stages of wheat as influenced by application of chemical fertilizers.

maturity stage by average of 43%.

These higher doses of vermicompost continue the release of available phosphorus at tillering, maintain highest level up to heading, and then decreased at maturity by satisfying the P demand of wheat (Figure 3). Such increase on available P at mid stages of crops (mainly at vegetative and flowering) were reported by Lungmuana et al*.* (2013), Malik et al*.* (2013) and Nathiya and Sanjivkumar (2015). The increase in available phosphorus at mid stage of wheat growth might be due to the continuous breakdown of organic matter and solubilization of phosphate minerals by soil microorganisms. According to Arancon et al*.* (2006), the increased amounts of orthophosphates in the soil from the vermicompost-treated plots could be explained by the significant correlations between the microbial biomass N and orthophosphates, indicating that release of P was due largely to the activity of soil microorganisms.

On the other hand, application of 33.33, 66.67 and 100% NPK showed 32, 56 and 89% increments on available P contents, respectively, over the control at tillering stage (Figure 4). Unlike vermicompost, chemical fertilizers slightly decreased at heading stage and sharply reduced in available P at maturity stages. On average, a decline of 44% on available P was observed for the main effect inorganic fertilizers, at maturity. However, pots treated with highest doses of chemical fertilizers (100% NPK) have relatively higher phosphorus content (29.23 ppm) at tillering stage than vermicompost treated pots, whereas at maturity the application of highest-level vermicompost has resulted in higher available P (18.60 ppm) than did the other treatments.

The readily soluble P applied as chemical fertilizers might be exposed to P-fixation reactions in the soil, which might result in periodic decline of available P (Lungmuana et al*.*, 2013). The decline of nutrients might also be due to the adverse effects of chemical fertilizers on beneficial soil microorganisms and soil chemistry, which would hamper the mineralization and solubilization of P from the soil.

Potassium (K) release pattern at different growth stages

The interaction of the different levels of vermicompost and NPK fertilizer was non-significant on the release of available potassium at all growth stages. However, there were marked differences due to fertilization with either main effect on vermicompost or inorganic fertilizers. The availability of K (ppm) at all growth stages notably increased ($p \leq 0.0001$) as the application rates of vermicompost and inorganic fertilizer increased (Figures 5 and 6). The maximum available K values for the main effect of vermicompost were 386.92, 402.42 and 288.17 ppm for pots treated with 6 t ha^{-1}, while the minimum were 289.58, 254.83 and 208.17 ppm for the control treatment at tillering, heading and maturity stages of wheat, respectively. Many studies have reported that a significantly higher values of available K was obtained after the introduction of vermicompost (Angelova et al. 2013; Pankajam and Davi, 2009; Tharmaraj et al*.*, 2010). This increase might be due to the application of a considerable amount of available K found in the earthworm processed organic matter (1.02%) (Table 1) and its solubilizing effect may result in release of available K from the soil.

The highest available K values for the chemical fertilizer applied at 100% of the recommended NPK were 407.92, 384.58 and 306.17 ppm at tillering, heading and maturity, respectively, while the respective lowest available K values of 258.50, 261.83 and 204.50 ppm

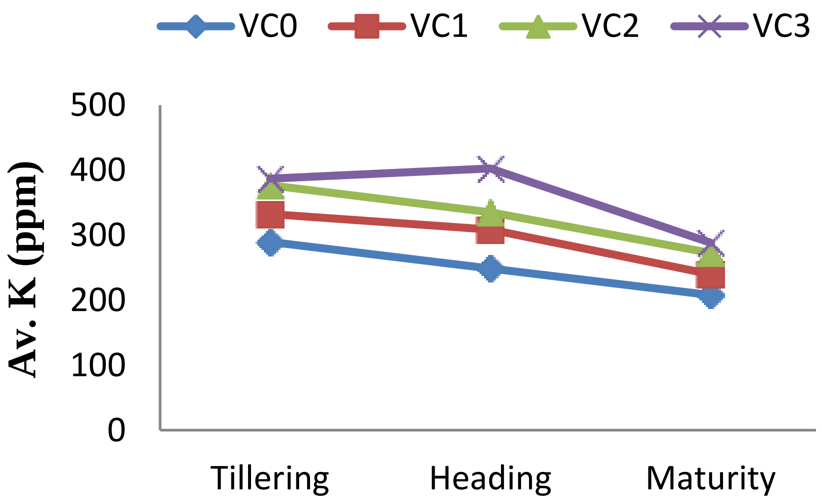

Figure 5. Potassium release pattern in the soil at different growth stages of wheat as influenced by application of vermicompost.

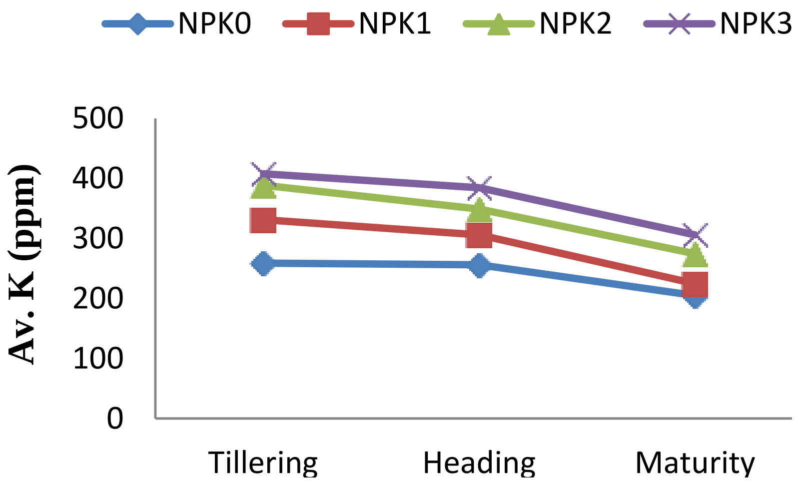

Figure 6. Potassium release pattern in the soil at different growth stages of wheat as influenced by application of chemical fertilizer.

were recorded for the control pots. However, there were no significant difference in available K between 66.67 and 100% NPK at tillering; and between 4 and 6 t VC ha^{-1} at tillering and maturity stages of wheat. The application of vermicompost at 2, 4 and 6 t ha^{-1} increased availability of potassium by 15, 30 and 34% over the control, respectively, at tillering stage. However, declines in available K were recorded at heading and maturity stages of wheat. This decline in available potassium was in exception for pots treated with 6 t ha^{-1}, which continue mineralization of K up to heading and then declined at maturity (Figure 5). This indicates that application of vermicompost at higher rates (6 t ha^{-1}) maintains relatively high amount of available potassium up to heading stage. In line with this, Nathiya and Sanjivkumar (2015) have also found higher exchangeable K level at flowering stage than at reproductive and postharvest stages of groundnut.

Moreover, application of potassium from chemical fertilizer had also contributed available K to the soil solution. Applications of graded NPK showed successive increments, respectively, in available potassium contents, over the control, at tillering stage. However, the increase in available potassium due to the application of graded levels of vermicompost reached its maximum at tillering stage, which declined slightly at heading and sharply at maturity stages (Figure 5). This reduction at heading stage may possibly be due to the uptake by straw and grain of wheat after tillering stage. Unlike vermicompost, there were no additional organic matters on chemically fertilized pots, which let wheat to be deprived only from the added nutrients and that might have resulted to the excessive decrease in available forms of potassium as the crop growth excels. Likewise, K was also correlated significantly with the availability of total organic matter (Angelova et al*.,* 2013).

Conclusion

In general, application of inorganic fertilizers as well as vermicompost at low levels have a limited capacity in supplying NPK, which might not line up with the trend of wheat nutrient uptake. As there was no addition of Nitrogen sources after the basal application, a reduction of its total amount from all treatments were evidenced throughout the growing season. However, unlike chemical fertilizers, the higher rates of vermicompost showed a continues mineralization trend on available P and K up to heading stages of wheat, which was probably due to the activity of microorganisms along with the presence of organic matter.

Consequently, vermicompost at a rate of 6 t ha^{-1} seems to have an equivalent release of nutrients with the recommended doses of NPK from inorganic sources. Out of all growth stages, the availability of nutrients (NPK) at tillering and heading seems to have a strong positive correlation with the uptake and yields of wheat. Hence, any soil fertility management practices that can augment the availability of nutrients after these growth stages might not have a significant contribution to the uptake as well as to the yields of wheat.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Soil moisture variability effects on maize crop performance along a toposequence of a terraced vertisol in Machakos, Kenya

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Recurrent droughts are often associated with crop failure and therefore food insecurity especially in semi-arid areas of Kenya. A study was conducted in Machakos County in the long rain and short rain seasons of 2014 to determine the effect of soil moisture variability on crop performances and yields along the toposequence of a terraced vertisol. The crops were grown as either sole maize, sole beans or maize-bean intercrop. An experiment was laid in a randomized complete block design (RCBD) and each treatment replicated three times. Data collected included maize height and leaf area index at 9th leaf and tassel stage, maize and bean yield and soil moisture content. The results showed significant variations ($p<0.05$) in soil moisture content, maize height, above ground maize biomass yield and maize and bean grain yield at different slope positions. The lower slope position recorded significantly ($p<0.05$) higher mean soil moisture content (20.6%) compared to the middle (16.1%) and upper (16.3%) slope positions. The lower slope position recorded significantly ($p<0.05$) higher mean biomass yield of 4.94 ton/ha compared to the middle and upper (4.30 and 4.12 ton/ha, respectively). Results of this study indicate that terracing has an effect on soil moisture content variability and that farmers can benefit from low-cost technology using soil and water conservation structures to increase yields.

Key words: Soil moisture variability, terrace embankment, slope position, toposequence, vertisols, crop yields.

INTRODUCTION

Water resources continue to decline steadily because of population growth and expected climate change as a result of global warming (Handia et al., 2003). Various studies (Qiu et al., 2001; Dercon et al., 2003; Zougmore et al., 2004) have reported that soil moisture content is mainly dependent on soil water recharge by rains and other alternate sources like irrigation. Increasing the efficiency of soil water use is an important target to achieve future food security in Kenya particularly in semi-arid areas exposed to drought. On sloppy non-terraced lands, less water infiltrates into the soil and is mostly lost as runoff due to fast velocity. This is primarily due to the fact that surface water, as well as sub-surface water, runs from high to low levels of elevation on sloping land. The

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Table 1. Chemical and physical properties of Machakos study area.

Soil property	Value	Soil property	Value
pH (water)	7.20	Sand %	28.20
pH ($CaCl_2$)	6.30	Silt %	20.50
Total N %	0.05	Clay %	51.30
Exch. Ca %	29.90	Textural class	Clay
CEC	39.90	Cracks	2-3 cm
Bulk density g/cm^3	1.50	-	-

CEC: Cation exchange capacity.

principle of terracing is to reduce runoff and soil loss and contribute to increased soil moisture content through improved infiltration. Soil water management practice through terracing conserves soil moisture for sustainable crop production in the semi-arid areas. Various studies to compare the effectiveness of terraced and non-terraced farms have shown that terraced farms as more efficient in terms of rainfall catchment and recorded high yields compared to non-terraced farms (Damene et al., 2012; Goto et al., 2012). Ramos and Casssanova (2006) compared to soil moisture content on terraced and non-terraced fields and reported more soil moisture content on terraced fields compared to non-terraced fields. The availability of soil moisture differs from position to position in the toposequence of the semi-arid environment (Homma et al., 2001). Various studies (Homma et al., 2004; Samson et al., 2004; Sunday et al., 2011; Ruto et al., 2017) have reported that in the toposequence of terraced lands high positions along the toposequence recorded lower available soil moisture content compared to the middle and lower slope positions. This study aimed at evaluating the role of vertisol to spatial soil moisture distribution along a toposequence of a terraced field. Vertisols are composed of 2:1 montomorillonitic mineral that expands when water is absorbed and shrink when soil moisture content decreases. Vertisol offer opportunities for better crop production in the semi-arid areas with erratic and variable rainfall compared with other soil types due to their high moisture holding capacity which allow crops to survive for longer drought periods. There is little information on toposequential soil moisture variation on a terraced vertisol in relation to rainfed crop production for semi-arid areas. The objective of this study was to investigate the effects of toposequence positions on water losses and productivity in maize cropping systems in semi-arid Machakos County.

MATERIALS AND METHODS

Study site description

The experiment was carried out in Kathekakai location in Central division in Machakos County (Figure 1). It is on latitude 0° 45’ and1° 31’ south, longitude 36° 45’ and 37°45’east and 1500 m above mean sea level. The average annual rainfall is 400 mm and average annual maximum and minimum are, respectively 36.9 and 22.7°C; the long-term average rainfall 540 mm which is bimodally distributed in two seasons, which are divided by distinct dry season. Long rains are low in amount and poorly distributed are expected in mid-March to June while the short rains fall from October to December. The study area has clay soils that are generally deep with less than 2% organic matter, high in clay content, high in the water holding capacity (Table 1). The clay soils of study site are situated in a gently sloping area (2.3-1.8% slope along the toposequence) unlike in many other parts of the world where most vertisols are either found in valley bottoms or low lying flat areas.

Experimental design and layout

The experiment was laid out during long rain season (March-May 2014) and short rain season (October 2014-January 2015) in a randomized complete block design (RCBD). The treatments comprised 3 cropping patterns (sole maize, sole beans, and maize-bean intercrop) each replicated three times (Table 2). The land was cultivated with an ox plough. Maize (Duma hybrid variety) and beans (Rose coco: GLP 2) were planted as sole crops and intercrops as shown in the experimental layout. Maize was planted at a spacing of 75 × 30 cm in pure stands while beans were planted at a spacing of 45 × 15 cm. In all experimental plots, nitrogen was applied at 50 kg N ha^{-1} (Di-ammonium Phosphate 18:46:0) at planting to maize and additional 50 kg N ha^{-1} when maize was four weeks after planting. All plots were hand weeded as practiced by the farmers during the cropping periods.

Data collection on soil moisture variability

Soil samples were collected using a soil auger for gravimetric moisture analysis at depth of 0-30 and 30-60 cm at both 9th leaf stage and tassel formation stages from the U=upper, M=middle and L=lower slope positions when crops started to show signs of moisture stress. Soil moisture content was determined by the gravimetric method (Hess, 1971). Soil samples were first weighed to record the weight of wet soil samples. The soil samples were then oven dried at 105°C in an electric oven for 24 h and then re-weighed to determine soil moisture content on a dry basis as follows:

$$\text{Moisture content \%} = \frac{\text{wt of wet sample} - \text{wt of oven dry sample}}{\text{Wt of oven dry sample}} \text{x } 100 \quad (1)$$

where wt = soil sample weight in grams.

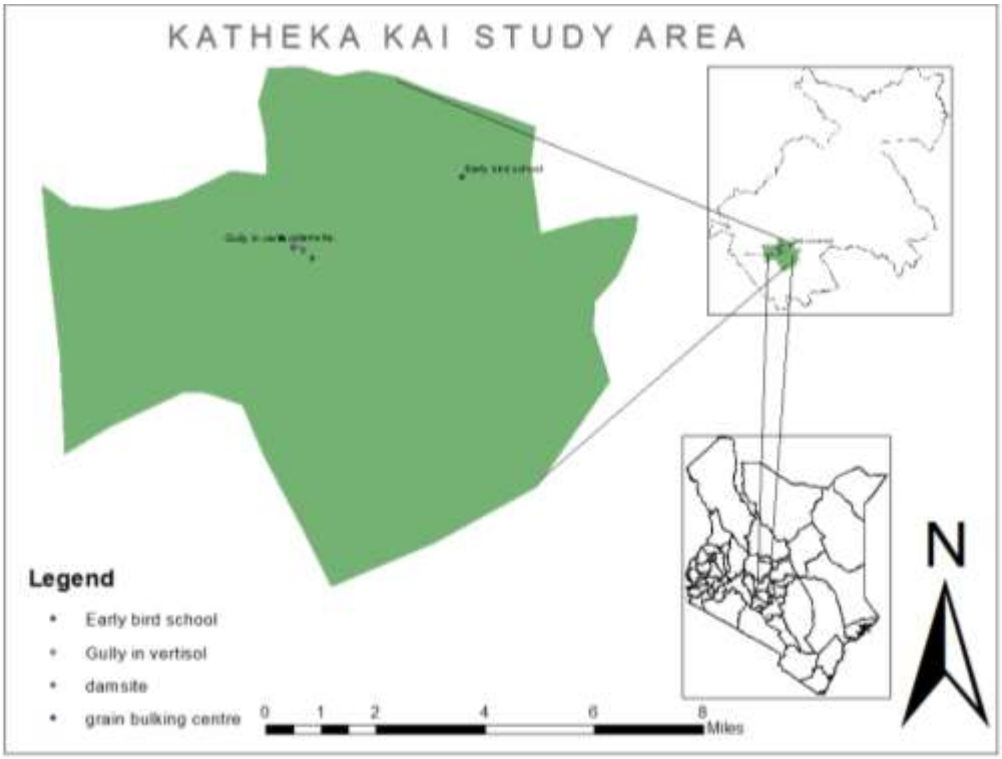

Figure 1. Study area in Machakos County.

Table 2. Terrace treatment arrangement.

Maintained terrace ditch					
Terrace position	**-**	**Description**	**CP 2**	**CP 1**	**CP 3**
Upper	Slope direction	Zone of moisture accumulation	Sole maize	Sole beans	Maize bean intercrop
Middle		Zone of moisture deficiency	Sole maize	Sole beans	Maize bean intercrop
Lower		Zone of moisture and sediments accumulation	Sole maize	Sole beans	Maize bean intercrop
Maintained terrace embankment					

CP 1 is cropping pattern with sole beans; CP 2 is cropping pattern with sole maize and CP 3 is maize-bean intercrop.

Data on crop performance indicators

Crop performance was evaluated by monitoring crop height, leaf area index and yield in the upper, middle and lower slope positions of the terraced vertisol. Maize height was measured from the base of the maize plant at soil level to the highest point and to the tip of the tassel at 9th leaf and tassel stage, respectively. The length and breadth of all fully opened leaf lamina per plant of five plants were measured and recorded at 9th leaf and tassel stage. The product of leaf length and breadth were multiplied by the correction factor (0.73309) to obtain the leaf area in dm^2 per plant. Leaf area index was determined at 9th and tassel stage. Leaf area index was calculated by dividing the leaf area per plant by the land area occupied by a single plant. Aboveground biomass was determined by selecting five plants at random in the upper, lower and middle slope positions. The samples were cut at ground level and weighed using a spring balance. A representative sample of fresh biomass weight was oven dried at about 70°C to obtain oven dried weight of above ground biomass. The number of pods from five randomly selected plants in the upper, middle and lower slope positions were recorded and used to estimate bean performance. Harvesting of both crops was done at physiological maturity from an area of 6.1 m^2 in the upper, middle and lower slope positions. Each treatment plot at the three slope positions was 10 m^2. Maize and bean grain harvested, shelled and weighed to give yield in kg per square meter which was later extrapolated to ton per hectare. Grain yield data used was for only long rain season (LRS) 2014 because short rain season (SRS) did not reach physiological maturity due to a dry spell experienced between the months of December 2014 and January 2015.

Data analysis

The soil moisture, crop performance and yield data collected were subjected to analysis of variance (ANOVA) to evaluate the treatment effects using GenStat for Windows 14th Edition statistical software. One way analysis of variance was used to assess

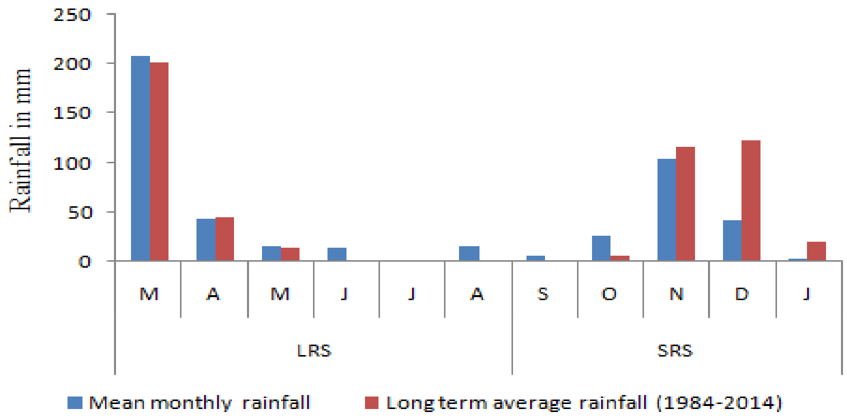

Figure 2. Seasonal rainfall received in study area 2014 against the long-term average rainfall of the area. LRS: Long rain season; SRS: short rain season.

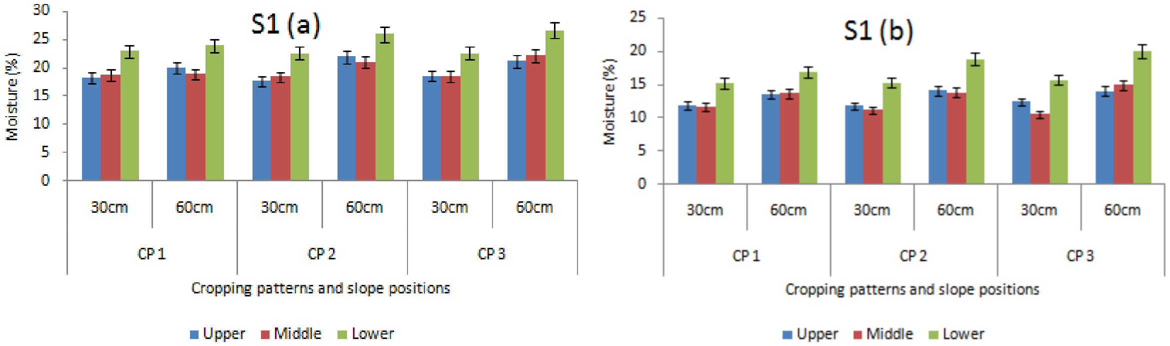

Figure 3. Soil moisture content in season 1 at 9th leaf stages (a) and tassel formation stage (b). Treatments: CP 1: Sole bean crop in all the upper, middle and lower slope positions; CP 2: Sole maize crop in all the upper, middle and lower slope positions; CP 3: Intercrop of maize and beans in all the upper, middle and lower slope positions.

significant differences among treatments. Levene's test was used to check for equality of variances and the study found insufficient evidence to claim that variances are not equal. Significant differences between and within treatments means were separated at P<0.05 using Duncan's LSD.

RESULTS AND DISCUSSION

Seasonal distribution of rainfall

The pattern of rainfall distribution showed marked variations in both frequency and amount of rainfall during the two rainy seasons (Figure 2). The long rainy season (March-April-May) in 2014 was not well distributed whereby most of the rainfall was received in the month of March while in the second season (Oct-Nov-Dec) rainfall showed a fairly normal distribution. In seasons 1 and 2, the total rainfall was 266.2 and 172.9 mm which was 46.8 and 65.4%, respectively lower than the long-term average rainfall for the area (500 mm). Rainfall totals in 2014 were 27.9% lower than what had been received in 2013 and 28.6% lower than the long-term average and this deficit was greatly felt in the second season of 2014 where no maize grain was realized and the maize crop dried before flowering towards the end of December 2014. The non-availability of water at any growth stage will affect the productivity of the crops. A number of authors (Rockström and De Rouw, 1997; Gomez et al., 2000; Huang et al., 2003; Moroke et al., 2005) have reported that the maximum plant water availability favors the growth and development of plants. They concluded that under normal soil moisture content, the growth of the plant is not affected but under drought stress, the plants wilt due to low plant water availability.

Effects of slope position on soil moisture content

Soil moisture content at 9th leaf and tassel stages varied with slope positions in both seasons 1 and 2 (Figure 3). Soil moisture content was significantly ($p<0.05$) higher in

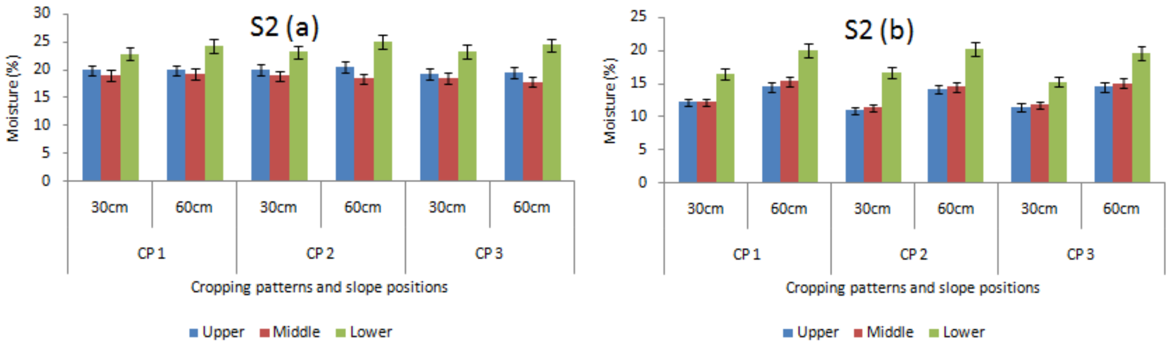

Figure 4. Soil moisture content in season 2 at 9th leaf stages (a) and tassel formation stage (b). Treatments: CP 1: Sole bean crop in all the upper, middle and lower slope positions; CP 2: Sole maize crop in all the upper, middle and lower slope positions; CP 3: Intercrop of maize and beans in all the upper, middle and lower slope positions.

the lower slope position compared to middle and upper slope positions irrespective of the cropping patterns and seasons (Figures 3 and 4). These findings are credited to water movement down the slope and deposition of sediments at the lower slope providing a bigger soil moisture storage capacity at this position. The terrace embankment apparently played a key role in trapping and retaining soil moisture at the lower slope position. Earlier studies have also shown that along the slope topo-sequence, soil moisture content increases significantly downslope and is entirely dependent on rainfall distribution (Fu et al., 2000; Wang et al., 2001; Dijk et al., 2003; Fu et al., 2003). Liu and Zhang (2007) reported that soil water content along a slope in a regosol decreased more rapidly on the upper slope compared to the middle and lower slope positions.

Soil moisture content at 30-60 cm soil depth was significantly ($p<0.05$) higher compared to 0-30 cm depth regardless of the slope position and cropping pattern in both seasons 1 and 2 (Figures 3 and 4). Qiu et al. (2003) and Fu et al. (2003) observed that the mean soil moisture content increased significantly with increasing soil depth. Surface soil (0-15 cm) of hill slope recorded lower soil moisture content compared to the subsurface soil (10-75 cm) and they concluded that maximum soil moisture is accumulated on the subsurface of terraced lands. The results of the current study correlate with the findings of Brocca et al. (2007) who evaluated the soil moisture variability in Central Italy. Their comparison of the terraced and sloppy field's soil moisture content showed that the subsurface terraced field had more moisture as compared to sloppy fields.

Effects of slope positions on the height of maize and leaf area index

Leaf area index and maize height are presented in Table 3 for both seasons 1 and 2 as influenced by soil moisture content at various slope positions along the toposequence.

There was no significant ($p<0.05$) variation in maize leaf area index at 9 leaf and tassel stages in both seasons 1 and 2. Maize height showed significant variations at tassel stages but none in the 9 leaf stage in both seasons 1 and 2. The study revealed that the lower slope position recorded the tallest maize (150.1 cm) followed by the upper and middle slope positions (134.0 and 132.2 cm, respectively) in descending order in season 1 at tassel stage. In season 2, the lower slope position recorded the enhanced maize height (145.0 cm) followed by the middle and upper slope positions (128.2 and 125.0 cm) in descending order. The upper and middle slope positions recorded shorter maize plants and this could be attributed to the fact that these positions are soil moisture loss zones. Plant vegetative growth is generally affected by soil moisture stress. High maize plant height recorded in the lower slope positions was probably due to the presence of the terrace embankment which promoted infiltration of soil moisture at this slope position. Increased soil moisture content in the lower slope position could have resulted in improved translocation of nutrients resulting in increased maize height and plant growth and development at this slope position. Generally, sole maize in all the slope positions recorded taller maize crop compared to intercropped maize. A number of studies have reported high plant height in terraced farms than in non-terraced farms (Homma et al., 2003; Husain et al., 2013). The findings of the current study are consistent with those of Ruto et al. (2017) who observed high plant height in terraced andosols which was attributed to the interaction of increased nutrient and soil moisture content leading to better uptake and efficient use of water.

Effects of slope position on aboveground biomass and grain yield

Table 4 shows data on bean grain, maize grain and

Table 3. Leaf area index and maize height at 9th leaf and tassel growth stages along the toposequence.

Growth stage	Parameter	Season	Upper slope position	Middle slope position	Lower slope position	SE	P<0.05
9th leaf stage	Leaf area index	S1	1.21^a	1.23^a	1.26^a	±0.06	Ns
		S2	1.11^a	1.13^a	1.14^a	±0.07	Ns
	Maize height	S1	81.60^a	82.60^a	84.00^a	±2.47	Ns
		S2	73.50^a	72.50^a	73.90^a	±1.93	Ns
Tassel stage	Leaf area index	S1	3.72^a	3.79^a	4.05^a	±0.25	Ns
		S2	3.12^a	3.14^a	3.58^a	±0.20	Ns
	Maize height	S1	134.00^a	132.20^a	150.10^b	±3.69	*
		S2	125.00^a	128.20^a	145.00^b	±4.11	*

Means not sharing a common letter in a row differ significantly with each other at *=0.05 level of probability. Ns: Non significant effect of soil moisture content on different parameters at different slope positions. Maize height is given in cm. SE is the standard error of means.

Table 4. Maize and bean grain yield and maize biomass yield along the toposequence.

Yield (t/ha)	Season	Upper slope position	Middle slope position	Lower slope position	SE	P<0.05
Maize biomass	S1	4.39^a	4.49^a	5.26^b	±0.22	*
	S2	3.96^a	4.10^{ab}	4.61^b	±0.19	*
Bean grain	S1	0.64^a	0.63^a	0.77^b	±0.03	*
Maize grain	S1	2.57^a	2.58^a	3.07^b	±0.05	*

Means not sharing a common letter in a row differ significantly with each other at *=0.05 level of probability. Ns: Non significant effect of soil moisture content on yield at different slope positions. SE is the standard error of means.

maize biomass yield at different slope positions as influenced by soil moisture content at various slope positions along the toposequence.

There were significant differences ($p<0.05$) in maize biomass yield with different slope positions. The lower slope position had on average maize biomass yield of 5.26 ton/ha followed by the middle and upper slope positions (4.49 and 4.39 ton/ha, respectively) in season 1. During the second season, season 2 the lower slope position recorded 4.61 ton/ha maize biomass more than the middle (4.10 ton/ha) and upper (3.96 ton/ha). The higher aboveground biomass yield could be attributed to the accumulation of soil moisture in the lower slope position due to the presence of the terrace embankment. Maize aboveground biomass was hence found to increase with increased soil moisture availability. Ruto et al. (2017) attributed increased biomass yield at the lower slope position to the synergetic interaction between increased soil moisture content and availability of major nutrients (N, P and K) at this slope position.

There was a severe drought in the tassel and silk formation stage in season 2 and no grain yield was recorded. The lower slope position recorded significantly ($p<0.05$) higher bean grain yield (0.77 ton/ha) compared to the upper and middle slope positions (0.64 and 0.63 ton/ha, respectively) in season 1. The higher yields recorded in the lower slope position is credited to sufficient soil moisture leading to improved nutrient uptake and utilization by the bean plants. Lack of bean grain yield in season 2 was attributed to lower rainfall received compared to season 1 (172.9 and 266.2 mm, respectively). Homma et al. (2003, 2004) noted that the effect of drought on yields is most severe when crops are stressed by water deficit in pre-flowering phase. In season 1, the lower slope position recorded significantly ($p<0.05$) high maize grain yield (3.07 ton/ha) compared to upper and middle slope positions (2.57 and 2.58 ton/ha, respectively). The higher yields recorded in the lower slope position were attributed to increased soil moisture availability at the terrace embankment that led to enhanced nutrient uptake and use by the maize plant. The upper and middle slope positions may have suffered from the loss of soil moisture and nutrients through erosion hence the low yields recorded (Rockström and De Rouw 1997). Additionally, higher leaf area index noted at the lower slope position meant production of more photosynthates consequently leading to increased maize and bean grain yields. Aung et al. (2013) while assessing the spatial variability in soil characteristics and crop yield in Vietnam reported that grain yields were lowest on upper slopes and increased progressively downslope. They attributed the increase in yields to higher nutrient levels at the lower slope position. In addition to the soil moisture availability, Homma et al. (2003) in their study in Northeast Thailand reported that the available soil nutrients depend greatly upon water flow along the toposequence. Accordingly, soils in the lower position of the toposequence have higher organic carbon and clay content, as a result of the runoff of surface water and the selective erosion of finer particles from upper to lower slope positions. Similarly, Ruto et al. (2017) reported that maize grain yield was 50% more than the upper and middle slope position and bean grain yield in the lower slope position were four times the yields in the upper slope position.

Conclusions

Soil moisture distribution in the vertisols varies with slope position and this variation is more pronounced with the presence of soil and water conservation structures (embankment). Thus, in a toposequence of a terraced field, upper slope positions will record lower amounts of available soil moisture. The upper slope position becomes the input in the lower slope position resulting in higher yields and better crop performance. There was no significant interaction between cropping patterns and slope positions in both seasons 1 and 2. This implies that either sole maize or maize-bean intercrop can be embraced and expected to perform well at the lower slope position in presence of an embankment. The current study indicates that the presence of terrace embankment at the lower slope position facilitated the accumulation of soil water and nutrients as a result of selective erosion of finer particles from the upper to lower slope positions. Farmers can, therefore, take advantage of increased soil moisture content in the lower slope positions and use of embankments in terraced fields to increase yields. The study has great policy implications for the drylands of Kenya on how soil quality, as well as crop yields, could be improved and maintained sustainably with proper design and implementation of soil and water conservation structures.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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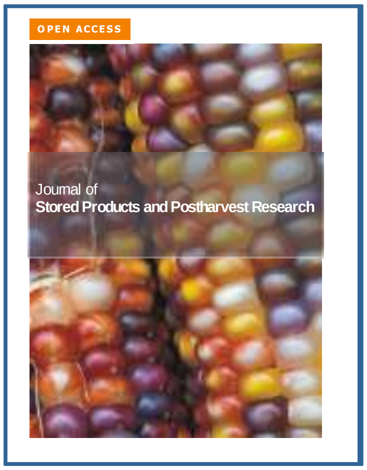

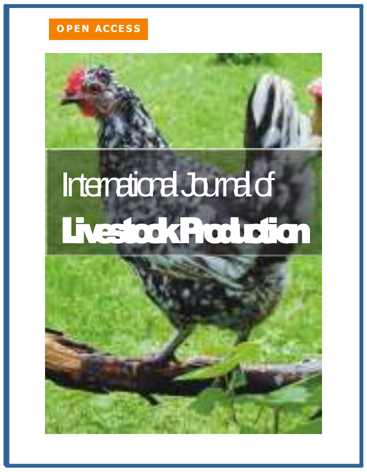

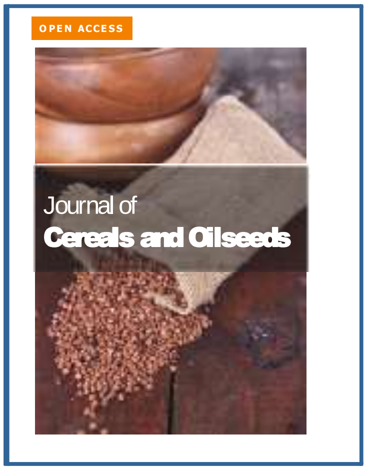

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