IMPACTS OF SOIL MANAGEMENT PRACTICES ON SOIL FERTILITY IN POTATO-BASED CROPPING SYSTEMS IN THE BOLIVIAN ANDEAN HIGHLANDS

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by

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DEDICATION

Para mi querida esposa Cecilia y mis adorados
niños Santiago y Joaquín, por su continuo
apoyo y constante amor que motivaron
mi esfuerzo dándome la fortaleza
y sabiduría necesaria. Por ellos y
con ellos logré este anhelo

Para mi mamá, papá, hermanos,y cuñados
por su constante aliento e incondicional
apoyo desde la distancia. Gracias por
darme la tranquilidad necesaria
y depositar su confianza en mi

Los quiero mucho

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IMPACTS OF SOIL MANAGEMENT PRACTICES ON SOIL FERTILITY IN POTATO-BASED CROPPING SYSTEMS IN THE BOLIVIAN ANDEAN HIGHLANDS

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ABSTRACT

The central Andean highland plateau region (Altiplano) in Bolivia is a semi-arid region primarily inhabited by indigenous agricultural communities that have mixed livestock and potato-based cropping systems. This region is characterized by frequent adverse climatic events, such as frost, hail and drought, which increase the risk of crop failure. Due to climate change and socioeconomic developments that have occurred in this region, current soil management practices may be increasing soil degradation thereby threatening food security in this region. The objectives of this research were to: 1) determine community perceptions of the effects of climate change on the soil quality of soil resources based on local soil classification systems; 2) assess the effects of changes in the crop rotation and fallow length on soil fertility and soil organic C and N; 3) to evaluate the relative first-year and subsequent residual effects of different strategies to improve SOM and increase soil fertility, including use of traditional and new organic and inorganic soil amendments, and 4) to assess a rapid and low-cost field test to improve N fertility management. Four representative communities in the Umala Municipality were selected for this research based on their relative elevation above sea level in this mountainous region. Two communities (i.e., San José de Llanga and San Juan Circa) were located at relatively low elevation and two (i.e., Kellhuiri and Vinto Coopani) from relatively high elevations. A household baseline survey and participatory workshops

were conducted in each community to assess soil management practices, the indigenous soil classification system, and perceptions on climate change and its effects on soil management practices. Based on results of this survey, a study was conducted to assess the effects of cropping and decreasing lengths of fallow periods on soil organic C, total N and other soil properties in the crop rotation in order to determine if increased soil degradation had occurred due to the decreasing fallow length. On-farm trials were conducted for three growing seasons from 2006 to 2009 in each community to determine the agronomic effects for growth of potato (*Solanum tuberosum* L.) in the first year and quinoa (*Chenopodium quinoa* Willd.) in the second year of an unfertilized control and separate and combined applications of local and alternative organic sources (i.e., composted cow and sheep manure, household compost and Biofert, a solid biofertilizer), and inorganic fertilizer (diammonium phosphate+urea applied at 80 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 0 kg K_2O ha^{-1}). The manure treatments were applied at a rate of 10 Mg ha^{-1} (wet weight basis with an average dry matter (DM) of 73%), the compost treatment was applied at a rate of 5 Mg ha^{-1} (wet weight basis with a DM of 59%), and the Biofert treatment was combined with the manure and compost and applied at an application rate of 0.2 Mg ha^{-1} (wet weight basis with a DM of 88%). An additional study examined the use of a rapid and relatively low cost field test (i.e., the Cardy nitrate meter) to determine N status of potato by analysing petiole sap nitrate at blooming time. Results of the survey indicated that farmers have well-developed indigenous soil classification systems largely based on differences in soil texture, color, the presence of stones, depth of the plow layer and crop productivity. A general change perceived by community members in most cropped lands was the increase in soil erosion and the consequent reduction in soil

productivity. These changes were primarily attributed to increased frequency and intensity of wind, seasonal concentration of rainfall in fewer months and an increase in air temperature. Farmers also perceived a decrease in the length of the fallow period over the past 25 years, and this length reduction was considered one factor that contributes to reduction in soil quality and other soil characteristics. An investigation into the effects of cropping and fallow on soil fertility restoration indicated that cropping generally decreased total and active soil organic C, and total, inorganic and active soil N. In contrast, the practice of fallowing restored total and active soil organic C and total and active soil N more rapidly in the upper communities than was observed in the lower communities. This difference was mainly attributed to differences in soil properties and land management in cropped fields at both elevations. In the field trials, organic fertilizers, such as cow and sheep manure combined with inorganic fertilizers, significantly affected initial and residual soil properties, such as pH, soil test P, soil total N, soil total inorganic N and soil organic C, soil gravimetric water content and bulk density in all communities. These treatments also significantly increased the growth and yields of potato and a subsequent quinoa crop and also increased economic returns with the potato crop. The combination of inorganic and organic fertilizers was the preferred fertility treatment among farmers involved in the participatory evaluation. Results of measurement of petiole sap nitrate-N using the Cardy nitrate meter had a significant relationship with the leaf petiole total-N measured with laboratory procedures (range of $r^2= 0.07$ to $r^2=0.60$) and with the total fresh tuber yield (range of $r^2= 0.11$ to $r^2=0.50$), suggesting that this tool has some promise as a low cost alternative for conventional tissue testing for potato in the Andean highlands of Bolivia. However, further studies

assessing the tool at different potato growth stages and in different native potato varieties are needed to develop reliable interpretation information and recommendations for Andean farmers.

CHAPTER 1

GENERAL INTRODUCTION

The Altiplano and Climate Change

The Andean highland plateau region (Altiplano) in Bolivia is a semi-arid region enclosed by two Andean mountain chains, the Cordillera Occidental and the Cordillera Real. At altitudes varying from 3600 and 4300 m above sea level, the Altiplano occupies approximately 171,122 km^2 of the 1,098,581 km^2 total area of Bolivia (FAO and SNAG, 1995) (Fig. 1.1) and is home to a high proportion of some of the poorest people in the country and in Latin America. Most of the community members are Aymara or Quechua Indians who depend on agriculture and livestock production involving cultivation of several small land plots and raising of a relatively few farm animals (LeBaron et al., 1979). Several varieties of potato (*Solanum tuberosum* L.), and a few varieties of quinoa (*Chenopodium quinoa* Willd.), barley (*Hordeum vulgare* L.), and fava beans (*Vicia faba* L.) are the most important food crops in this region mostly for domestic consumption and for the market when there is a production surplus (Valdivia et al., 2001; Valdivia and Quiroz, 2003). Alfalfa (*Medicago sativa* L.), oats (*Avena sativa* L.), and barley are also planted by some farmers as forage crops to feed their cattle, especially in communities where dairy cattle are present (Valdivia and Quiroz, 2003). Sheep and cattle are the predominant livestock raised in this region and livestock herds might consist of improved animals or *criollo* (local) that are well adapted to the harsh climatic conditions of the Altiplano (LeBaron, et al, 1979; Valdivia and Quiroz, 2003).

Source: Motavalli et al., 2007

Fig 1.1. The Altiplano (High Plateau) region in Bolivia and South America.

The region's climate is characterized by high diurnal temperature variations, frost risks, low and irregular precipitation and high risks of drought during the growing season (García et al., 2007). The great insolation and solar radiation in this high elevation promotes a high evapotranspiration rate that leads to a higher hydric deficit. These harsh climate conditions result in a relatively short agricultural season which, in consequence, reduces the variety of crops and allows only one harvest per year (FAO and SNAG, 1995; García et al., 2007). This region is also affected by periodic ENSO (El Niño Southern Oscillation) events which cause important climatic variations. For instance, during the 1980 and 1983 El Niño events, the total rainfall was 231 mm and 198 mm, respectively (Valdivia and Quiroz, 2003). Although no significant evidence exists that the annual precipitation has significantly changed over the last 40 years in the Altiplano, cropping under rain-fed conditions of this region may be constantly restricted by low precipitation amounts during the growing season (ranging from 515 mm in the North to 363 mm in the South Altiplano region) (García et al., 2007).

Since the period of human occupation of the Altiplano region, the climate has changed markedly. In the Southern region of Bolivia for instance, there have been periods of relatively high rainfall that promoted plant growth and livestock that have alternated with centuries of drier or colder climates. Past and current climatic fluctuations have driven environmental changes and those changes have influenced landforms, soils, vegetation, and land use (Preston et al., 2003).

Climate change may increase the risk of crop failure and food insecurity of local indigenous communities in the Altiplano. Other economic and social changes in the region, such as urban migration, have also impacted agricultural practices, which are primarily potato-based cropping systems and livestock rearing of cows, sheep and camelids (e.g., alpaca and llama) (Valdivia et al., 2000). In many cases, it is difficult to distinguish between changes in cropping systems due to socio-economic or climatic factors.

Due to their experience with climate change, Andean farmers have developed several strategies to adapt to climate extremes, including use of genetic diversity and knowledge of differential impacts of climate events among their soil resources (LeBaron et al., 1979). Farmers have also developed a set of natural bio predictors or bio indicators of climate occurrence (e.g. bird and insect nesting behaviors prior the cropping season) that have been a reliable source for agricultural decision-making for many centuries.

However, according to young farmers, some of these indicators no longer correspond with current climate occurrences and it is mainly attributed to climate change (Valdivia et al., 2000; Gilles and Valdivia, 2009).

Farmers of the Andean region perceive changes in climate, such as increased temperature, increased wind frequency and velocity and concentration of rainfall periods in fewer months (Stacishin de Queiroz et al., 2001; Rees, 2009) that may contribute to degradation of agricultural lands and to reduction of crop productivity of this region. Soil erosion along with some inappropriate land management practices, including excessive use of tractors in primary tillage, native vegetation removal for fuel and suboptimal rates of fertilizers, are leading to a decline in soil productivity (Motavalli et al., 2009b).

Outcomes of simulation modeling on the effect of climate change on soil properties performed in different countries may be considered an important reference on the magnitude of the problem. For example, O'Neal et al. (2005) predicted a 5% increase in annual precipitation leading to a significant increase in soil erosion (10 to 274% soil loss) in the Midwestern United States when soil management practices were not taken into account. By using the Erosion Productivity Impact Calculator (EPIC) model (Williams et at., 1989), an increase of 7% in precipitation predicted an increase of 26% in soil erosion in the United Kingdom (Favis-Mortlock et al., 1995). Applying the same model (EPIC) to the United States Corn Belt and a scenario of a 20% increase in precipitation found a possible 37% increase in soil erosion and a 40% increase in water runoff (Lee et al., 1996).

Numerous researchers have stated that changes in temperature and soil moisture content potentially affect the rates of SOM decomposition and consequently affect soil characteristics. Grace et al. (2006), for instance, has predicted a significant decrease in topsoil SOC of the Australian continent by year 2100 due to climate change. Climate change might also be accompanied by changes in crop management by farmers as they are attempting to adapt to new climate patterns. Low crop yields induce farmers to make decisions, such as changing crop variety or even crop species, and changing planting dates; all these changes in crop management may alter the cropping system which, in turn, may have an impact on soil properties, such as soil erosivity.

Trends in climate change

Climate records provide strong evidence for the current rapid rate of global climate change. The records indicate that 11 of the past 12 years have been the warmest since reliable data collection began around 1850 (Collins et al., 2007). Among the important indicators that show evidence of warming are the continuous retreat of most glaciers from mid to low latitudes (Thompson et al., 2006), the changes in global temperature, sea level and snow cover that have occurred in the Northern Hemisphere (Collins et al., 2007). A 100-year analysis from 1901 to 2000 reported a warming trend of 0.6±0.2 ºC, and 0.74±0.18 ºC from 1906 to 2005 (IPCC, 2007). The 1956 to 2005 data analysis showed a warming trend of 0.65±0.15 ºC, which implies that most of the 20th century warming happened in the past 50 years (Collins et al., 2007).

Recent research has indicated that the rate of global warming will increase with altitude around the world (Bradley et al., 2006; Urrutia and Vuille, 2009). An example of this altitude effect on global climate change can be observed in the tropical Andes region which has averaged a historical temperature increase of 0.11°C per decade (Bradley et al., 2006). The consequences of climate change have been evident in accelerated glacial retreat in Bolivia, mainly due to the frequent El Niño event occurrences, changes in the patterns of its evolution, and the rise of near-surface temperature in the Andes. The same trend has been observed in other high altitude tropical mountain regions (Francou and Vuille, 2003; Thompson et al., 2006). Among the effects of climate change in this region of Latin America has been a tendency toward slightly drier conditions on the western side of Bolivia and a significant increase of the near-surface temperature in the tropical Andes (Vuille et al., 2003).

One possible effect of climate change is lower or excessive soil water content during critical periods of the growing season. For example, in Turkey an increase of 2°C, regardless of increase in precipitation, could cause a general severe water shortage and prolonged period of drought throughout the year in the region (Komuscu et al., 1998); in Indonesia predictions by 2050 showed an increase in precipitation of approximately 10% later in the crop year but a significant decrease, up to 75%, later in the dry season that will potentially reduce rice production if adaptation strategies are not implemented in the region (Naylor et al., 2007). According to case, predicted increase in temperature and decrease in precipitation could cause detrimental impacts such as increased erosion, degradation of freshwater systems, loss of valuable agricultural soils, loss of biodiversity and decreased agricultural yields (Chatzopoulos, 2008).

Many unusual extreme weather events have been registered in different countries for the last two decades. Among these weather events are intense precipitation events in 1999 and 2005 in Venezuela; the flooding in 2000 and 2002 in the Argentinean Pampas; the drought in 2005 in the Amazons region; the destructive hail storms in 2002 in Bolivia and in 2006 in Argentina; the unexpected Hurricane Catarina in 2004 in the South Atlantic; and the hurricane season in 2005 in the Caribbean Basin (Magrin et al., 2007).

Among the major consequences of climate change for Latin America are more frequent flood and drought events and the loss and retreat of glaciers that will negatively impact runoff and urban and rural water supplies (Trigoso, 2007). Vulnerability in Latin America to the negative consequences of climate is expected to increase while adaptative capacity will decline in this region (Baethgen, 1997). Simulation models performed in the highlands region of Bolivia has predicted increase in temperature and precipitation by the middle and late century (Thibeault et al., 2010), that could potentially affect the whole agroecosytem if proper actions are not designed ahead of time.

Climate change effects on agriculture

Climate variability promotes greater incidence of extreme weather events such as drought and flooding as detected in different regions of most countries of South America (Magrin et al., 2007). In the last three decades, Latin America has been impacted by climate change, such as intense episodes of El Niño occurrences in 1982/83 and 1997/98 and other severe weather extremes (Valdivia and Quiroz, 2003; Vincent et al., 2005) contributing greatly to the increase of human systems vulnerability to natural catastrophes (e.g., floods, droughts, and landslides). In agriculture, unstable wheat yields were found in Mexico from the effects of El Niño and la Niña events, along with reduction of cotton and mango growing seasons in Peru and higher incidences of plant diseases in Argentina and Brazil (IPCC; 2007b).

Climate change may have many potential implications on agroecosystems by reducing crop yields and food production in small-scale agriculture or food-insecure regions (Fuhrer, 2003). For example, Magrin et al. (2007) have predicted a generalized decrease in rice yields but an increase in soybean yields for Latin America by 2020 when the influence of CO_2 is taken into account, and Jones and Thornton (2003) have predicted a general decrease in maize production by 2055 in Latin America and Africa.

Climate change may affect local seasonal and annual water balances due to changes in rainfall and thermal regimes thereby impacting agricultural activities, such as crop production (Fischer et al., 2002). Experimental studies, mostly under controlled conditions and simulated models, have shown that an increased atmospheric CO_2 levels may result in an increased yields of most agricultural crops and a decreases in some of them depending on sensitivity of plant species and specific environmental conditions (Corobov, 2002; IPCC, 2007). Climate changes, such as increases in temperature without CO_2 fertilization, could potentially decrease yields of rice, maize and wheat up to 37% for the next 20 to 80 years (Erda et al., 2005); and reduction in precipitation amounts and changes in distribution patterns with subsequent reductions in crop production as have been observed under El Niño event in the Andes regions of South America (Orlove et al., 2000).

Predictions on climate change using climate models suggest that global warming may rise rapidly depending on the selected scenarios and regions of the world (Crosson, 1997). Developing countries, especially in Africa, and to some extent in Latin America and parts of Asia, are currently facing severe agricultural problems and the additional burden of climate change may further reduce sustainable agricultural production (Crosson, 1997). For the Highlands areas of Bolivia, simulation models predicted an average increase of temperature from 1 to 2 °C (with significant increase during the dry season and early rainy season) and of precipitation from 2.8 to 5% (during the main rainy season) by the middle century (2020-2049) and an increase of temperature from 3 to 5 °C (with largest increase in early rainy season) and of precipitation from 5 to 7.1% (during main rainy season) by late century (2070-2099) (Thibeault et al., 2010).

Rural communities in the Andes (e.g. the Andes highlands of Bolivia) are showing particular vulnerability to recent and projected changing climate trends, including increase in temperatures and later onset of rainfall during the planting season, which is challenging current local knowledge systems about agriculture. The later onset of the rainfall in this region is currently threatening the production of two of the most important sources of plant protein (i.e., quinoa and fava beans), which is reducing food security (Valdivia et al., 2010).

Farmers' perception of climate change

Perception by farmers of climate variability is important because they often make agricultural management decisions based on their perceptions. For instance, in the rural areas of Sahel (Senegal), farmers have perceived an increase in wind speed, especially in dry seasons, and an increase of temperature throughout the year causing crop yield reduction (Mertz, 2009). In Limpopo Basin (South Africa), farmers' perceptions of climatic variability corresponded with the climatic data records. Most of the farmers interviewed perceived increases in temperature, changes in rainfall patterns over the past 20 years, and noticed a decrease in the amount of rainfall or a shorter rainy season. (Aymone, 2009).

In the Bolivian Altiplano, farmers perceive several effects of climate change or climatic variations on their cropping systems (Valdivia et al., 2008). For instance, possible changes in rainfall distribution and diurnal evapotranspiration during the growing season are perceived to have resulted in a reduction of cropping land and crop diversity and caused a movement to relative higher altitude grassland areas for livestock grazing. Although most of the highland communities are highly resilient to adverse climatic conditions, they are growing many crops that are at the edge of their climatic adaptation so any change in the climate pattern might have a great impact on the cropping system performance and its sustainability. Despite the importance of climate on the growth of potato in this region, farmers often perceive other factors, such as pests and disease, as posing greater risks for poor crop performance. However, the changing incidence of pests and disease may also be affected by changes in climate (Chatzopoulos, 2008).

Effects of Soil Management Practices on Soil Quality

Soil quality has been defined by the Soil Science of America (SSSA, 1995) as "The capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water quality, and support human health and habitation", and is considered a crucial component for sustainable agriculture (Gui et al., 2009).

Among the soil management practices that have been observed to generally enhance soil quality are: 1) adding organic soil amendments to improve soil chemical, physical and biological properties, 2) avoiding excessive tillage which breaks up soil structure, speeds the decomposition and loss of organic matter, increases the threat of erosion, destroys the habitat of helpful organisms, and causes compaction, 3) managing pests and nutrients efficiently, applying only the necessary chemicals, at the right time and place to achieve the goals, 4) maintaining surface ground cover, protecting soil from wind and water erosion, and from drying and crusting which also provides habitats for soil organisms, can improve water availability, and create new soil organic matter, and 5) increasing soil biological diversity to control pest populations, because a diversity of soil organisms and diversity of cultural practices helps to control pest or disease pressure (Lewandowski, 2000).

Importance of soil organic matter

Many diverse soil properties are considered important indicators to assess soil quality and among these properties, the content of soil organic matter (SOM) may be the most crucial due to its short- and long-term impacts on various chemical, physical and biological properties that affect soil productivity (Woomer et al., 1994; Carter, 2002a). Increased SOM generally improves soil quality and the long-term sustainability of agroecosystems (Gupta et al., 1994), and this is because it buffers changes in soil properties that affect soil productivity (Fernandes et al., 1997). Because of the beneficial effects of SOM on soil properties, it is considered an important soil component that may assist in mitigating the effects of climate change.

Soil organic matter is present in a small fraction of the total mass of most soil but exerts an important influence on soil chemical, physical and biological properties (Sparks, 2003; FAO, 2005). Soil organic matter is comprised of plant and animal residues at all stages of decomposition and its structure consist of a very complex mixture of carbon compounds (Pierzynski et al., 2000). The organic matter in the world’s soils contains around three times the organic carbon found in the entire world’s vegetation;

therefore, SOM plays an important role in the global carbon balance and global warming (FAO, 2005).

Among the benefits of maintaining or increasing SOM are increased soil water-holding capacity and the proportion of water available for plant growth, improved soil structure for root growth and drainage, higher content of potentially available soil nutrients over a longer period of time, increased CEC, and greater biological activity by supplying carbon and energy to soil organisms (Woomer et al., 1994).

Because of the multiple functions of SOM, the amount and composition of SOM are important indicators of soil degradation. Increasing soil degradation can have severe consequences in the Bolivian Altiplano where agriculture is the primary source of income and sustenance for indigenous (i.e. Aymara and Quechua) households. The multiple soil organic matter benefits on soil properties including the increase in soil productivity, are very important to this region where use of manufactured fertilizer is not common or is applied at suboptimal rates (Motavalli et al., 2009b).

Soil organic matter may also assist in mitigating the effects of climate change by buffering changes in soil chemical, physical and biological properties that affect soil productivity (Fernandes et al., 1997). Numerous studies have shown the importance of SOM on soil C sequestration and therefore reducing CO_2 in the atmosphere (Post and Kwon, 2000). Significant amounts of SOM in cropping lands, especially in semiarid regions of highlands, may potentially increase soil water holding capacity and therefore mitigate drought effects which is a very limiting factor in these regions. Alterations in management practices that affect SOM may threaten the sustainability and resilience of agroecosystems when ecological perturbations, such as climate change, occur.

Both temperature and precipitation have a significant influence on SOC accumulation. Increasing temperatures caused by climate change will generally increase the decomposition rate of SOC, especially the relatively labile fraction of SOC which is important for turnover of soil nutrients for crop growth (Davidson and Janssens, 2006). Low SOC content is often found under high annual mean temperature and low rainfall (Dai and Huang, 2006).

Management practices that affect SOM levels include method and frequency of tillage, the amount and fate of crop residues, crop rotation, soil fertility management including application of inorganic and organic soil amendments, and management of possible fallow periods (Swift et al., 1994; Fernandes et al., 1997). Potential obstacles, besides the climatic restrictions, exist for adoption of some of these practices in the Andean region. For instance, the relatively higher costs of the new practice versus traditional practices exist such as the cost of the inorganic fertilizers or alternative organic fertilizers compared to local organic fertilizers (manures) and the cost and availability of suitable crop seeds to be planted in the fallowed lands. Other potential factors are the competing uses for organic materials (e.g., for fuel and livestock feed), high labor requirements (e.g. manure collection and transportation) that might interfere with normal cropping activities, lack of education and community training on soil fertility management , and the social and cultural implications of adopting the practice (Valdivia and Quiroz, 2003; Motavalli et al., 2009b).

Effect of tillage practices on SOM

Tillage is a management practice that may cause the greatest soil disturbance and can lead to significant reductions of SOM or soil organic carbon (SOC) (Alvaro-Fuentes et al., 2008). Tillage practices normally alter soil properties, distribution of nutrients, and soil organic matter in the soil profile (Hussain et al., 1999), decrease soil structure and aggregation, promote reductions in water infiltration rates, and enhance possibilities in soil erosion by wind and water (Kettler et al., 2000).

Several studies under different soil characteristics and climatic conditions have shown relevant impacts of tillage practices on SOM content. One of the main conclusions is that use of reduced tillage practices, especially no-till, will result in an increase in SOM content. For example, some studies have found a significant decrease in SOM under conventional, reduced and subsoil tillage compared to no-till practice (Alvaro-Fuentes et al., 2008), and when comparing eight years of chisel and moldboard plow use with no-till (Hussain et al., 1999). Conventional mechanical-based tillage appears to cause higher SOM reduction than the animal-based tillage practice (Riezebos and Loerts, 1998).

Long-term tillage can significantly reduce the quantity and quality of SOM and substantially change the physical and chemical fractions of the SOC (Ding et al., 2002). For example, cultivation of lands for up to 34 years resulted in a 30-60% reduction in SOC along with reduction in soil total N and had considerable effect in microbial biomass C and N (Saggar et al., 2001). In a monoculture system, long-term conventional tillage depleted SOC content while continuous no-till enhanced SOC content (Machado et al., 2006). In the central highlands of Mexico, no-till practices have shown significant increase in total SOC, total soil N and soil water holding capacity compared to conventional tillage (Patiño-Zuñiga et al., 2009). In the same region no-till combined with crop residues improved soil physical and chemical properties compared to conventional tillage (Govaerts et al., 2006).

Tractor use is a relatively new technology introduced in the Bolivian Altiplano that was initially adopted by few individuals of the relatively low elevation and flatter areas, such as the case of the San José de Llanga community in the central Altiplano region. Apparently due to its effects on reducing labor requirements and its convenience, use of tractor-based tillage for primary tillage in this region is currently widespread throughout the Altiplano (Markowitz and Valdivia, 2001). The effects of this method of tillage on soil quality and productivity in the Altiplano have not been well-explored.

Crop rotation and fallow

Crop rotation is considered an important practice since it can have a major impact on soil health by maintaining or enhancing SOM as well as improving soil structural stability, increasing crop water use efficiency, and promoting better control of weeds and pest infestations (Carter et al., 2002b; Liu et al., 2006). Crop rotation effects have been shown to increase crop yields and quality, especially when N-fixing leguminous crops are included since they increase soil N availability (Galantini et al. 2000; Miglierina et al., 2000). Rain-fed cropping systems under long-term cultivation that use crop rotation have been shown to have less variability in crop yields when compared to crop yields under monoculture. The soils under crop rotation also may have higher total soil C and N levels over time which is valuable for sustainable soil and crop productivity (Varvel, 2000; Kelley et al., 2003).

The fallow period is included in the crop rotation to enhance sustainability of production through maintenance of soil fertility (Sarmiento et al., 1993) and soil properties (Bravo-Garza and Bryan, 2005). According to Kaas and Somarriba (1999), traditional Latin American fallow systems have not been extensively studied from either socioeconomic or biophysical viewpoints. Some previous studies have shown that a variety of fallow systems have been used across Latin American countries for centuries to primarily maintain fertility and suppress weeds. In most cropping lands of the highlands of Latin America, soils are susceptible to degradation if they are continuously cultivated, which in turn may lead to a decrease in crop yields and a deterioration of soil structure, nutrient status and other physical, chemical and biological characteristics (Barrios et al., 2006).

Type and length of fallow is also important for soil fertility restoration and improvement of soil properties. The optimal length of fallow needed to restore desired soil conditions may vary depending on the native soil properties, previous agricultural inputs applied, climatic conditions, and the crops included in the rotation. In a short-term study on the effects of fallow in sandy soils under dry and sub-humid climates in Senegal, West Africa, four years of fallow did not significantly increase SOM concentrations under either climatic condition, although millet crop had higher yields with increasing length of fallow (Masse et al., 2004). In the Bolivian Altiplano after 10 years of fallow, there was no clear evidence of recovery of nutrient elements (Hervé, 1994). However, Miranda et al. (2009) found that five-year fallow fields had greater total porosity, macroporosity and saturated hydraulic conductivity than a two-year fallow. The longer the fallow the more mycorrhizal fungi spores are present in the soil which will affect the succeeding crop’s performance (Sivila de Cary and Hervé, 1994). In addition, increased fallow length increases the amount of regrowth of native vegetation, such as the evergreen shrub, “thola” (*Parastrephia lepidophylla*) which enhances diversity of fungal population in soils (Gomez et al., 2009). Longer fallow also reduces soil loss and water runoff mainly because of greater ground cover provided by native vegetation (Sarmiento, 2000).

Restoration of soil nutrients and maintenance of soil fertility under low input cultivation is basically achieved through natural native vegetation or cropped fallow. Native vegetation in fallow lands is an important source of pasture for livestock, although the quantity and quality of forage is limited by climatic restrictions and the forage value of the native vegetation (Genin and Fernández, 1994). In the Venezuelan Andes the soil water content was greater under natural plant re-growth fallow than in cultivated plots and higher soil runoff rates and soil loss occurred in short-term fallow plots (Sarmiento, 2000). In comparison, in the Bolivian Altiplano, research indicated that it was better to reseed fallow lands with native or introduced adapted species in order to reduce runoff and soil erosion (SID, undated).

Mostly due to poor soil quality, cropping lands in the highlands of Bolivia are frequently left under extended uncultivated fallow periods (up to 20 years) for soil fertility restoration, control of crop disease and pests, and re-growth of natural vegetation (Hervé, 1994). However, increases in human population in this region and competing land uses, such as forage crops for dairy production, are currently reducing the length of the fallow period (Coûteaux et al., 2008), and some field practices, such as use of mechanized disc plowing and the removal of native vegetation during the fallow period for different purposes, are decreasing the re-growth of natural vegetation and therefore diminishing the amount of organic inputs and the rate of soil fertility restoration (Motavalli et al., 2009a).

Organic amendments

Organic amendments are considered a very important agricultural input because they add soil organic matter that contributes to improved soil properties for crop growth. Soil organic matter, because of its contribution to high water holding capacity, has particular importance in sandy soils by improving soil water availability and storage (Rawls et al., 2003).

There are several organic amendments worldwide with different characteristics and effects on soil properties, but in the highlands of Bolivia, the most accessible local organic amendments include crop residues, manures and compost. Some alternative biofertilizers such as Biofert, Fertisol, Fertitrap, Vigortrop and Bocashi (Biotop, 2010) are also available in the markets in this region and these biofertilizers are sold to act as supplements for organic amendments.

Crop residues

Recycling crop residues back into the field is of great importance for maintaining SOM not only for nutrient value of the residues, but also for the value the residues have for reducing soil erosion, runoff, and off-site sedimentation (Karlen et al., 1994). Plant residues also stimulate soil microbial activity and population diversity which in turn are key factors for several biologically mediated soil processes including soil organic material decomposition (Al-Kaisi, 2008).

In general, maximizing return of crop residues back into agricultural fields is important for improving soil properties and conserving soil resources. Crop residues have been demonstrated to be important in conserving soil water in semiarid conditions (Wilhelm et al., 2004), in reducing soil erosion, improving soil aggregation and porosity, and increasing SOC which in turn improves soil quality (Karlen et al., 1994). Residual effects of crop residues have been observed even eight years after incorporation to improve soil properties, nutrient availability and crop yield (Power et al., 1998).

Mulching crop residues can also increase SOM and promote soil resilience against erosion and degradation. Development or identification of cropping systems which leave residue cover after harvest and extend fallow periods is needed to capture precipitation water, improve water infiltration, and enhance soil resilience. In the highland areas of Bolivia and Peru, most crops do not produce or leave sufficient residues after harvest to protect the soil (Wall, 1999). Thus, alternative practices should be developed to conserve soil and water, and improve soil productivity.

Manure

Long-term application of animal manure may improve several soil properties including increased SOM, greater plant nutrient availability of both macronutrients and micronutrients, increased soil moisture retention, and improved soil structure, which in turn increases the infiltration rate and decreases soil bulk density. These effects may depend on type, rate and years, and method of addition and manure composition (Havlin et al., 1999). Manure is an important farm resource and it should be considered an asset for sustainable production, especially in semiarid highlands with low soil quality, and it should be properly recycled to the soil under an efficient manure management program to optimize nutrient supply while minimizing potential environmental issues (Taddesse et al., 2003).

In long-term studies, farmyard manure applications have been demonstrated to significantly increase SOC and total soil N concentration compared to nonmanured plots (Mando et al., 2005) and increased soil water content compared to the unfertilized and chemically fertilized plots (Zhao et al., 2009). Taddesse et al., (2003) found that manured plots increased soil water infiltration capacity compared to nonmanured plots that were even moderatly or heavily grazed. In a sandy clay loam soil, application of 5 Mg ha^{-1} of manure improved SOC and soil test P compared to unfertilized plots and its effects were not significantly different to application of 10 Mg ha^{-1} manure (Kihanda et al., 2006).

Numerous studies state that manure generates several beneficial effects on soil properties and crop productivity, but also may pose an environmental problem when it is not properly managed. For example, emissions of ammonia gas to the atmosphere is considered a relevant threat to the environment in Europe and fields applied with livestock manure are considered an important contributor to ammonia emissions (Sommer and Hutchings, 2001), although rate of emission may depend on manure composition, and soil and climate characteristics. Nitrous oxide, a greenhouse and ozone-depleting gas, may also be generated during the process of denitrification after application of manure (Chang et al., 1998). Manure supplies significant amounts of N, P, and K, and other essential plant nutrients; but if manure is applied in amounts exceeding the crop plant use capacity and soil holding capacity, important mineral losses by surface runoff and potential contamination of groundwater by leaching is highly probable (Newton et al., 2003).

Compost

Compost is a single or mixture of organic materials which is piled and allowed to partially decompose. Advantages of composting prior to application of organic materials are that it reduces the total volume of organic material to transport, lowers the carbon-to-nitrogen ratio of the material (Giusquiani, et al., 1995), reduces odors, and kills most weed seeds, plant pathogens and other pests (Hoitink, 1986). Several studies have reported the beneficial effects of compost incorporation on several soil properties including water retention, cation exchange capacity (CEC), soil structure and SOM quality, soil enzymatic activities (Giusquiani et al., 1995; Ouédraogo et al., 2001; Rivero et al., 2004), and crop yield compared to non-composted treatments (Ouédraogo et al., 2001).

In a long-term study, compost incorporation was better than applications of inorganic fertilizer and dairy manure in building soil nutrient levels, in providing residual nutrient and in reducing nutrient losses to ground and surface waters, and promoted higher soil C and N content (Hepperly et al., 2009). Effects of compost may vary among different soil textural classes. For instance in sandy soils, compost acts as a porous medium that helps retain water in the rooting zone. In clay soils, compost increases porosity promoting better drainage thereby preventing water logging (Golabi et al., 2003).

Biofertilizers

Biofertilizers are considered a promising alternative to mineral fertilizers for increasing soil productivity and plant production. Biofertilizers are products that contain living cells of different types of microorganisms, which are able to convert important plant nutrients from unavailable to available form through biological processes (Hegde et al., 1999; Vessey, 2003). Biofertilizers have recently appeared as an important component of an integrated nutrient management system not only for improving soil properties and crop productivity, but also for being environmentally friendly (Wu et al., 2005). Biofertilizers have been shown to improve several soil properties such as soil organic matter and total N (Wu et al., 2005), and increased yield in several crops such as soybean (*Glycine max* L.) (Cattelan et al., 1999), lentil (*Lens esculenta* Moench) and pea (*Pisum sativum* L.) (Chanway et al., 1989).

Inorganic fertilizers

Inorganic fertilizers are used worldwide as a nutrient source for agricultural production and their use increased abruptly in the 1940s. The increase of inorganic fertilizers accounted for a significant increase in crop yields which in turn enabled the world to feed a large population, and to maintain a global balance between soil nutrient inputs and outflows. The nutrient composition of inorganic fertilizers is more exactly defined compared to that of organic fertilizers, and in most cases supplies the plants with readily available forms of nitrogen, phosphorus and potassium among other nutrients.

Inorganic fertilizers are an important component to achieve good crop yields, especially in systems where the main goal is crop productivity (Haynes and Naidu, 1998), although it has been observed that in some cases chemical fertilizers alone are not helpful under intense agriculture because it is associated with decline in some soil properties as well as crop yield reduction over time (Hepperly et al., 2009).

Despite the importance of chemical fertilizers in crop production, their cost and availability in most developing countries, especially in rural areas inhabited by farmers of low economical resources, are considered a critical limitation for maximizing crop production (FAO and SNAG, 1995). Identification of innovative soil management practices and/or alternative sources of locally available and affordable soil amendments is important in developing countries where mineral fertilizer use is limited.

Soil Degradation

Soil degradation is a decline in soil physical, chemical and biological properties that support important soil functions such as growth of crops. Therefore, it is an important threat to sustainable soil productivity. Many possible soil management practices are causing soil degradation in the Andean region, including soil erosion and use of several current soil management practices. Among these practices are use of conventional tillage, removal of crop residues, suboptimal rates of inorganic and organic fertilizers, and partial removal of native vegetation that serves as cover crop or for soil fertility restoration in fallow fields. For example, high rates of soil erosion, which lead to significant loss of topsoil and SOM, are a common problem because of the steep slopes and scarcity of vegetative cover in the Central Andean Region of Bolivia (Coppus et al., 2003). Soil erosion has received minimal scientific attention in Latin America even though it is a very important factor leading to soil degradation (Zimmerer, 1993; Thierfelder et al., 2005).

Growers of the highland areas of Bolivia still preserve traditional-conventional agricultural practices that may be contributing to soil degradation. Some municipalities of the Central region of the Bolivian Altiplano, are composed of both relatively higher and relatively lower elevation communities with marked differences in soil management practices, especially in use of different tillage systems. The lower elevation communities generally practice tractor-based tillage and the higher elevation communities generally practice animal-based tillage systems. Although there is no research-based information on rates of soil degradation for both elevations, use of tractor tillage in lower communities may be a major factor contributing to decline in SOM content leading to soil degradation compared to the use of animal tillage in higher communities (Motavalli et al. 2009b).

Quick Soil Fertility Assessment

Soil testing is an important management practice to optimize crop production because it assesses the ability of the soil to provide adequate plant-available mineral nutrient elements during the growing season. The quantity and availability of soil nutrient elements can be highly variable according to landscape position (Wang et al., 2001; Balkcom et al., 2005), the effects of fertilization, and nutrient losses from the rooting zone either due to crop removal (Putthacharoen et al., 1998) or other environmental loss mechanisms such as erosion (Quinton et al., 2001), leaching (Shepherd and Benett, 1998; Murphy et al., 2006) and volatilization.

In agricultural systems, soil fertility status is mostly determined by means of soil and plant tissue testing. Most agricultural plant roots grow relatively shallow throughout the soil profile, therefore, agriculture relies on soil and plant tissue testing for the purpose of guiding nutrient management. The soil testing process basically consists of three important phases: soil sampling, chemical analysis of the sample, and interpreting the results to make recommendations about the amounts of nutrients to apply (Nathan et al., 2006).

In most developed countries, a network of private and public soil and plant testing laboratories that utilize systems of interpretation and recommendations for major crops are available for use by agricultural producers. In contrast, in most developing countries there are fewer soil testing laboratories and most of them do not have interpretation and recommendation systems developed for the soil resources and crops grown in the country or based on any local research (Dierolf et al., 1997). Moreover, the laboratories are often too expensive or too far away for use by small-scale producers. However, field research on alternative rapid and inexpensive soil and/or plant testing are being assessed for use in small scale agriculture to help farmers to have an adequate soil fertility management program (Crane et al., 2006). For instance, in the upland areas of Indonesia, participatory approaches are being tested by developing, implementing, and modifying tools and methods for farmers and extension agents in order to get a simple general guideline for soil fertility assessment and fertilizer management (Dierolf et al., 1997).

Another approach to determine soil fertility status is use of plant tissue analysis which can be an effective tool to identify plant nutrient problems. This procedure is being used by farmers because research has shown that the concentration of essential elements in plant tissue is normally related to plant growth or crop yield. Use of plant tissue testing also avoids suboptimal growth when nutrients are deficient but the deficiency does not result in visible deficiency symptoms (Silveira et al., 2007). Based on research, nutrient sufficiency ranges are established for different crops at different stages of growth and for different plant parts that can be sampled for use in plant tissue testing (Hochmuth et al., 1991). When the nutrient concentration is within the sufficiency range then plant growth will not be restricted due to deficiency of that nutrient at that growth stage. At the high end of the sufficiency range, plants may be considered to be in luxury consumption where the additional nutrient uptake does not produce additional plant growth. Nutrient concentrations above the sufficiency range also may be toxic to plant cells with some nutrient elements such as Iron in rice for instance (Havlin et al., 1999).

Managing for optimal plant growth often requires synchronizing changing plant nutrient requirements over the growing season with soil nutrient availability. Inappropriate fertilizer rates or poor timing of fertilizer application may cause increasing ground and surface water pollution (Hochmuth et al., 1991; Zhang et al., 1996). Conventional plant tests give an assessment of the current plant N status but the information received may be too late for making timely N fertilizer application decisions, especially when the monitoring of plant N status during the growing season is needed (Ortuzar-Iragorri et al., 2005). That is why rapid field tests are important for growers to make quick decisions on nutrient management.

One of these quick tests is the plant petiole sap test (PPST) using the Cardy meter (Horiba Ltd., Kyoto, Japan) equipment, a low-cost portable device, which rapidly measures the nitrate-N plant status in fresh petiole sap and can be used on a regular basis over the growing season in the field (Hochmuth, 1994; Zhang et al., 1996). Although it is a tool designed for use in the field, the Cardy meter performs better indoors because it is sensitive to temperature changes and wind (Hochmuth, 1994).

Research evidence indicates that the Cardy nitrate sap test correlates well with conventional N testing in some crops. For example, the NO_3^--N concentration determined by ion selective electrode (ISE) of an extract from dried petioles and by the

Cardy meter in the petiole sap from irrigated cotton in Arizona were highly correlated (r^2= 0.92) (Smith et al, 1998). Similar results were found when comparing the Cardy meter nitrate-N values with soil nitrate-N in maize (Sims et al., 1995), with petiole nitrate-N in potatoes (Vitosh and Silva., 1994; Zhang et al., 1996) and with leaf petiole total N in potatoes (Majić et al., 2009) measured by conventional laboratory procedures.

Although the PPST is a valuable field alternative to assess plant N status, it has some limitations. For instance, several factors can affect the nitrate-N content of potato petioles including N-fertilizer applications, position of the petiole on the plant, growth stage, potato cultivar, the environmental conditions, and time of day for sample collection (Vitosh and Silva, 1993), since the effect of diurnal nutrient variations exists and may influence test results (Nagarajah, 1999). Moreover, MacKerron et al. (1995) identified that more N than detected could be allocated in other parts of the plant than petioles, and Vitosh and Silva, (1996) found that PPST varies among cultivars. Therefore, specific recommendations by cultivar should be then required for PPST. Although PPST gives quick results, it still is a time-consuming and inconvenient method compared to use of the chlorophyll meter (Goffart et al., 2008).

Participatory Research Approach

Participatory research involves a collaborative partnership between researchers and the people under study. In participatory research, both the researcher and the participant are main actors and participate actively in the research process from the initial planning of the investigation until the sharing of options for action, and interpreting and analyzing results. The concept behind this type of research is to get people to work together on common problems or needs, to jointly evaluate knowledge and experiences, and to share responsibilities (Lee, 1995).

In agricultural research, the term participatory research involves several diverse types of interactions between scientists and farmers with different levels of participation and responsibilities. For Sims et al. (2002), categories of participation include the nominal or contractual participation, when experiments are basically managed by scientists and farmers are in a passive role. Consultative participation is when research is managed by scientists and executed by farmers; farmers' priorities are recognized and there is interaction between scientists and farmers. Decisive participation is when the farmer is the main researcher, he manages and carries out the experiment, his opinion is important over the experimental design and management, and the scientist and farmer share equal partnership responsabilities. For Collinson (2001), categories of participation are: strategic research that involves understanding biophysical processes on an identified problem where farmers might not feel comfortable because of the specificity and complexity of the research. Applied research uses understanding of natural processes to define potential solutions to an identified problem, promotes alligance to commodities and disciplines, and induces farmers' participation. Adaptive research promotes understanding of the farmers' priority problems, identifying a diverse range of solutions, and working with farmers to determine alternatives that might suit well to their local circumstances.

In order to design and apply participatory research, important consideration and emphasis must be placed on the local social environment and in the details of the methodology (Biggs and Smith, 1998). Formation of strong coalitions will promote expected rural changes through research and support to participant communities (Ashby et al., 1995).

There has been a growing use of participatory research in Bolivian research projects. For example, a project was performed in 1996 in the valleys and subtropical regions of Bolivia by means of Participatory Rural Appraisals (PRA). The PRA is defined as “the family of approaches and methods to enable local people to share, enhance, and analyze their knowledge of life and conditions, to plan, and to act” (Chambers, 1994). Through PRA, farmers have observed loss of soil fertility and crop yield reductions due to erosion of topsoil from the hillside areas. With researchers’ and farmers’ agreement and collaboration, low-cost alternatives for soil and water conservation were identified, and vegetative barriers were established on the contours of the 13 sites. Adoption of this soil conservation practice as a result of the participatory research affected more than 700 families (Sims and Bentley, 2002).

Changes in climate are being detected by scientists and also sensed by farmers in the Andean region. Most farmers of the Bolivian Altiplano region have perceived climate changes to be affecting the standard cropping system and threatening the agroecosystem’s stability, but not all of them have appropriate resources to cope with these adverse situations (Valdivia and Quiroz, 2003; Gilles and Valdivia, 2009). Therefore, the current research has a community participatory approach with the goal of identifying an integrated soil management strategy to improve important soil properties such as soil organic matter content, not only to improve the soil fertility status but also helping to mitigate the negative effects of climate changes in agricultural lands of the

Bolivian Altiplano. This strategy should help to improve community resilience to achieve long-term soil productivity.

The study is basically formed on information obtained from participatory workshops performed at an individual community member's level where farmers discussed their main soil problems affecting crop and livestock production and how they think those can be solved. That information guided the development of objectives and hypotheses for this research.

Objectives

1. To determine community perceptions of the effects of climate change on the soil quality of soil resources based on local soil classification systems.
2. To assess the effects of changes in the crop rotation and fallow length on soil fertility and soil organic C and N.
3. To evaluate the relative first-year and subsequent residual effects of different strategies to improve SOM and increase soil fertility, including use of traditional and new organic and inorganic soil amendments.
4. To assess a rapid and low-cost field tests to improve N fertility management.

Hypotheses

1. Local soil classification systems are largely based on differences on soil physical characteristics and do not generally differ among communities.
2. Some of the identified soil types may be more vulnerable to climate change.
3. The cropping systems and the fallow length that are being practiced in the communities have been affected by climate change and socioeconomic factors. These effects may vary among communities at different relative elevations and

access to markets. Changes in cropping systems and the fallow length affect soil fertility and soil organic C levels.

4. Use of both traditional and alternative soil amendments will increase labile soil organic C and N availability and, consequently, soil productivity and resilience.
5. Use of the nitrate sap test in potato under the conditions encountered in the Bolivian Altiplano is a rapid and effective method to assess plant N status and yield response.

Outline of the Thesis

This thesis project contains seven separate chapters which have been written in a standard format for publication in research journals. Chapter 2 presents results with more emphasis on farmers' perceptions of the effects of climate change on soil properties. Chapters 3, 4, 5 and 6 present results of field research conducted in the Umala Municipality in the Central Region of the Bolivian Altiplano. A final chapter summarizes the main conclusions achieved in the thesis research.

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CHAPTER 2

THE EFFECTS OF CLIMATE CHANGE ON SOIL CHARACTERISTICS ACROSS DIFFERENT SOIL TYPES PERCEIVED BY FARMERS IN THE BOLIVIAN ALTIPLANO

ABSTRACT

A study was conducted in 2006 and 2007 in the central Andean highland (central Altiplano) region of Bolivia and focused on four representative communities of the Umala Municipality. Umala is inhabited by indigenous Aymara people who primarily engage in mixed cropping and livestock-rearing activities including potato-based cropping systems and dairy production. This region is frequently exposed to adverse climatic events, such as frost, hail and drought, which increase risk of crop failure. The objectives of this study were: (i) to determine farmers' local criteria for soil classification, (ii) to assess farmers' perception on the effect of climate change on agricultural soil properties and crop management over the past 20 years, and (iii) to correlate the local soil classification with chemical and physical soil analysis. Information was obtained from a baseline survey of the communities and through participatory workshops of community members. In addition, soil samples were collected from identified soils based on the local soil classification system and analyzed for selected physical and chemical characteristics. Between three to seven soil types were identified with Aymara names, and the primary criteria for soil classification were soil texture, color, the presence of stones, depth of the plow layer and crop productivity. Soil maps delineated by the community members show a general predominance of sandy-textured soils at the four communities. A general change perceived by community members in most cropped lands was the increase in soil erosion and the consequent reduction in soil productivity.

These changes were primarily attributed to increased frequency and intensity of wind, seasonal concentration of rainfall in fewer months and the increase in temperature. Farmers' soil textural classification did not match with laboratory-based soil textural analysis. Higher CEC and SOM content were primarily related to higher silt content and was generally lower as the proportion of sand increased. None of the soils sampled had cropping limitations due to salinity as determined by soil electrical conductivity (EC) measurements, and soil test P and K levels were relatively high for unamended soils. However, most of the soils would require soil amendments for maximum crop production. It is essential to combine local soil classification and scientific knowledge to achieve projects that are suitable to the socio-economic conditions of farmers of the Altiplano region.

INTRODUCTION

Central Altiplano's General Characteristics

Municipalities of the Central Altiplano region such as Umala, are exposed to frequent adverse climatic conditions, mainly frost and drought events, which limit agricultural production to just a few crops, such as potato (*Solanum tuberosum* L.), quinoa (*Chenopodium quinoa* Willd.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), alfalfa (*Medicago sativa* L.), and faba bean (*Vicia faba* L.) (Valdivia et al., 2001; Valdivia and Quiroz, 2003). In general, farm size in this region is low due to land subdivision for inheritance purposes; therefore, individuals farm small agricultural plots per year, generally around two hectares in area (FAO and SNAG, 1995).

Umala communities are inhabited by poor indigenous people with a low educational level, limited access to alternative technologies and markets, and reliance on traditional-ancestral knowledge for cropping practices. The average family has four children and although some young adults temporarily or permanently migrate to find work in cities or other countries, there has been a consistent increase in population. The higher population has led to a reduction in land size, and, in some cases, has caused a reduction in fallow length and cultivation of marginal lands located on steep slopes that traditionally were considered a source of natural pasture (FAO and SNAG, 1995).

Farmers' Perception of Climate Change

Many farmers in developing countries have perceived effects of climate change and have opinions regarding their ability to adapt to those changes. For example, in an extensive survey of over 9,500 farmers from ten countries in Africa, preliminary results showed that farmers detected changes in climate perceiving that the air temperature had increased resulting in hotter cropping seasons and the rainfall pattern had become less predictable and shorter in duration (CEEPA, 2006). Although most farmers interviewed mentioned that they do not perceive limitations to adaptation to climate change, the ones that perceive limitations attribute them to their low income and lack of access to certain resources. Based on the results of the survey, farmers with higher education levels are more likely to respond better to climate change by doing at least one adaptation practice. Farmers that perceive climate change but are not able to deal with it by adopting an adaptation practice might need special incentives or assistance (Madison, 2007).

Some research regarding farmer risk perception and the effects of climate change on agroecosystems of the highland areas of Bolivia has been conducted. In a survey of communities of the central area of the Bolivian Altiplano, farmers expressed concern regarding climate change as they perceive that the climate is getting drier with less rain, more wind is blowing and fewer frost events are occurring (Stacishin de Queiroz et al., 2001; Rees, 2009). A study about risk perception among farmers of the Bolivian Altiplano on climate variability observed a high climate risk perception by farmers, although some of them perceive more than others (Valdivia et al., 2003). In general, farmers are aware of climate change and they feel like the climate is getting hotter and drier and less predictable than it used to be in the past, and these climate change effects are significantly affecting their agroecosystem. In the past, farmers of this region used to rely on diverse natural climate indicators, such as astronomical and biological indicators (Valdivia et al., 2000), but these indicators may no longer work according to surveys. Through time, individuals have developed alternatives to cope with this climate change by increasing their portfolio of economic activities, such as diversification of agricultural crops, raising sheep and dairy and having off-farm income (Rees, 2009).

A research study focused on the effect of climatic variability on rural households was conducted in the Andean region of Bolivia and Peru (Valdivia et al., 2003). Results from this study show that Andean farmers normally use local forecast rather than scientific forecast for predicting weather conditions during the upcoming growing season. The local climate predictors are older people with long-term farm experience that have a holistic view of the agroecosystem and use techniques that include an intuitive approach to probabilities. Under climatic variability or weather stress, food crop producers react and are affected differently than dairy livestock producers. The crop producers are more vulnerable and more economically affected if climate change occurs because they do not have access to credit, while the dairy producers have access to credit to buy seed or food.

However, the crop producers have a diversity of strategies to cope with climate variability, such as by switching varieties and planting date (Valdivia et al., 2003).

Altiplano's Soil Taxonomy

Soil survey information related to the Central Altiplano region of Bolivia is limited and this lack of information is a critical problem for resource management. Some important information about the soils of this region includes publications by Clapperton (1993) and Blodgett et al. (1997). These publications indicate that during the Quaternary Period, there was a vast high lake stage of the Titicaca Lake called Ballivian Lake that covered what is now the Altiplano in the Andes Mountains of South America. The fact that the highland Andean was once an ocean floor made this region to be subject to high salt accumulation during bedrock formation, and the current soil salinity of some areas of the Altiplano is a function of the high concentrations of salts in soil parent materials (Jetté et al., 2001). According to Ruthsatz and Fiseln (1984) mentioned by Jetté et al. (2001), the mountain slopes of the Andean Cordilleras are sheltered by unweathered rock, the foothills at the bottom are still covered with fresh rock, and in the downslope there are alluvian fans, small plateaus and central plains. The soil textural gradient in this highland region ranges from sandy-silty to clay-silty and heavy clay, and there are also sandy soils resulting from eolian deposition which apparently has contributed to stabilize sand dunes over the Altiplano.

In one of the largest communities of the Central region of the Altiplano, Ledezma and Flores (2002) and Stacishin de Queiroz et al. (2001) detected four important geomorphic units, alluvial terrace, alluvial fan, deltaic deposits and a large fluvio lacustrine plain. Altiplano soils are relatively young soils with a predominance of sand particles in the topsoil (Jetté et al., 2001). The Altiplano is mostly dry but it has between 90 to 120 days of precipitation during the growing season with common drought events (Garcia et al., 2007). A high intermountaine valley with Altiplano-like climate conditions was described by PERTT (1998) to have a mesic soil temperature regime (annual average of about 10°C) and ustic moisture regime (352 mm averaged during the growing season). A previous soil survey of the Umala community of San José Llanga indicated that the soils were primarily comprised of soils classified as Ustifluvents, Fluvaquents, Haplustalfs, and Salorthids great groups in the U.S. Soil Taxonomy (Stacishin de Queiroz et al., 2001). In that community, approximately 44% of the land area was occupied by saline soils.

Local soil classification

For generations farmers have accumulated practical knowledge on local soil and land type management that may be of benefit to researchers and/or developmental institutions in formulating suitable research projects (Thrupp, 1989; Macharia and Ng'ang'a, 2005) addressing sustainable land management practices among other issues. Traditional knowledge on soil classification is important to understand how farmers' manage soil resources and the cropping practices they utilize. In one study in Mexico, farmers were interviewed to determine the local criteria for traditional soil classification and better understand farmers' perceptions (Ortiz-Solorio, 2006). Results showed that farmers use the term "land class" instead of soil categories as scientists do; and that land class can have characteristics that can be observed directly or indirectly in time and space. Although farmers use a simple land nomenclature to describe their land as sandy land, or black land, for example, in fact, their land classification system is a multidimensional concept that considers several attributes, such as color, texture, consistence, moisture retention, workability and salinity and does not consist of simplistic and superficial knowledge as many researchers have previously interpreted (Ortiz-Solorio, 2006).

According to the soil classification system of indigenous farmers of the central region of Mexico, the soil is composed of a complex mixture of diverse living and non-living components, and it is organized by layers, and soil has the flexibility to adapt to social and environmental changes. Indigenous and technical soil classifications were compared in terms of spatial correlation to determine consistency between the U.S. Soil Taxonomy (1999) and local soil classification. The study found that there was a high correlation between scientific and local soil classification systems although some discrepancies were found such as soil depth or diversity of topsoil characteristics, which tend to be ignored by technical soil classification but it is highly considered by local soil classification because according to farmers, it determines soil-related qualities for food production and soil management (Barrera-Bassols et al., 2006).

Native farmers of the Andes possess a traditional soil classification system that is mostly oriented to practical use and they are able to differentiate several soil types, soil horizons and geological materials (Macharia and Ng’ang’a, 2005). Farmers’ soil classification systems emphasize soil textural distinctions which are related to those used in “western” classification, such as soil taxonomy. Farmers can identify changes in soil performance under different conditions and adjust soil management if possible. Although most farmers have a good knowledge about their lands and they have a local soil classification that is sufficient for managing their fields in traditional ways, it would be beneficial if they could combine their local knowledge with scientific knowledge. This integration of knowledge would assist in planning and implementing agricultural projects which have a high probability to meet local community needs and which are adjusted to local socio-cultural conditions (Sandor, 1996).

Several studies have been done on farmers' soil classification systems attempting to document and understand local knowledge systems. Some studies have found great variation in local knowledge on soil classification not only among farmers of different regions (Braimoh, 2002) but also among farmers of the same region and even within the same village (Shrestha et al., 2004). Researchers normally do not use local knowledge to establish the scientific basis of farmers' soil classification systems which in turn leads to a lack of correlation between both criteria (Barrera-Bassols et al., 2006). Therefore, it might be important to integrate local and scientific knowledge to obtain a well structured soil classification system, but to achieve that is important to understand, discern and recognize local criteria and terminology on soil classification as well as its particularities (Shrestha et al., 2004).

The objectives of this study were: (i) to determine farmers' local criteria for soil classification, (ii) to assess farmers' perception of the effects of climate change on agricultural soil properties and uses over the past 20 years, and (iii) to relate the local soil classification with soil chemical and physical properties.

MATERIALS AND METHODS

Area of Study

The study was conducted in the Umala Municipality in the central region of the Andean Highlands (Altiplano) of Bolivia during the 2006 and 2007 growing seasons which runs from November to April. Umala (17° 17’ 10’’ S and 68° 08’ 19’’ W), is located 28 kilometers away from Patacamaya and 129 kilometers from the main capital city of La Paz, and its altitude ranges from 3,850 to 4,100 meters above sea level (m.a.s.l.) (INE, 2009).

Four representative communities of the Umala Municipality were selected for this research. Two communities (i.e., San José de Llanga and San Juan Circa) were located at relatively low elevation and two (i.e., Kellhuiri and Vinto Coopani) at relatively high elevation (Table 2.1). Some specific characteristics of these four communities and results of community surveys of losses experienced and perception of risks of climate change are presented in Table 2.1 and Table 2.2.

Initial Baseline Study

An initial baseline survey of 180 community members among the four communities was conducted in 2006 by Aymara-speaking interviewers who filled out a standardized questionnaire. The survey mainly addressed general agro-socio-economic conditions of the Umala’s individuals and major soil and crop management restrictions.

Participatory Workshops

Participatory workshops following procedures described by Chambers (1989) were performed to determine and assess the farmers’ perception on the effects of climate change on their agroecosystem and social and economical influences. For the purpose of this study, only information regarding farmers’ perceptions of climate change impacts on agriculture and specifically related to its impacts on soil characteristics or properties and the consequences on cropping systems by different soil types will be presented.

To optimize time on gathering information from the four communities involved in the project, an initial workshop was conducted on June 2006 in Patacamaya and was composed of 4 to 6 representative farmers from each community for a total of 19 people with 37% of the total composed of women. Representative farmers were internally selected by each community. Umala farmers are mostly fluent in their native Aymara language; however, these representative people were bilingual in both Aymara and Spanish and were very knowledgeable about their community. The workshop was designed and managed by researchers but it promoted active farmer's participation. As a part of the methodology, farmers were divided in small groups of four to five people accompanied by one or two researchers to allow more individual participation. Initially, each group filled out individual charts consisting of five to six questions addressing the following subjects: What are the local indicators of climate change? How is climate change influencing their agroecosystems? What are the main problems associated with land management and natural resources? What are some local strategies for dealing with changes in climate and other socio-economic factors?

To obtain organized information based on their perceptions, hand drawn maps were created by farmers of each community, and complementary charts were developed registering participants' statements or comments that supported their drawing, especially those comments that addressed soil changes due to climate change over the past 25 years. On the map, farmers drew the major agricultural soil types based on local criteria for soil classification, and potential factors (i.e., climatic and socio economic) influencing land use or cropping systems of each soil type was registered in charts. Additionally, a chart was developed to analyze changes on cropping systems due to climate change over time, with emphasis in changes on: crop rotation, traditional cultural practices on main crops, use of the available organic and inorganic amendments, and pest occurrence and their chemical control (data not presented). Results from this initial workshop were entered into a database, and were analyzed to detect relevant information or information that required further inquiry.

To validate and complete the information obtained with the key community members, a second workshop at the community level was carried out in August and September 2006. Ten farmers participated in Kellhuiri, 16 farmers in Vinto Coopani, 15 in San Juan Circa and 13 in the San José Llanga community. Although information was not discriminated by gender, an average of 35% women participated in all workshops. For this workshop, an individual bilingual in Aymara and Spanish, outside of the project but from the same municipality, was hired to help researchers to translate. The preliminary results from the first workshop were presented in charts at the community level allowing farmers to modify and to complement this information. Since this project was mostly targeted to detect changes in agricultural soil, a categorization of the most relevant soil types for agricultural purposes was identified.

Soil Chemical and Physical Analysis

In each of the four communities, after finishing the workshop farmers took researchers over the farm fields representing the major agricultural soil types identified, and soil samples were collected. To have comparable information among different soil types, and to better analyze and interpret results, all fields were sampled in their first cropping year after being in fallow. Ten representative soil sub-samples per plot were collected from the 0-20 cm depth by researchers and farmers, and those sub-samples were mixed into a bucket and a composite sample was collected. Two composite samples of each major agricultural soil type were sent to the Soil and Plant Testing laboratory at the University of Missouri to be analyzed for soil chemical and physical properties (i.e., pH in 0.01 M $CaCl_2$, neutralizable acidity [N.A.], inorganic N (NH_4^+-N and NO_3^--N), soil test phosphorus [Bray P1], soil test potassium [NH_4AOc-extractable K], exchangeable calcium [Ca], exchangeable magnesium [Mg], cation exchange capacity [CEC], electrical conductivity [EC], and soil texture). Soil chemical and physical analyses were determined by the University of Missouri Soil and Plant Testing Laboratory using standard methods (Nathan et al., 2006). Soil total inorganic N (NH_4^+-N and NO_3^--N) was extracted by shaking 4-g soil samples in 40 mL of 2 *M* KCl at approximately 180 rpm for 1 hour and filtering the extract through Whatman No. 2 filter paper. Analysis of the extract was performed using methods (Lachat Instruments, 1992 and 1993) recommended for the Lachat QuikChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). In addition, three bulk density soil samples were collected from each plot using the core technique (Grossman and Reinsch, 2002).

RESULTS AND DISCUSSION

Some important differences between the relatively higher and lower elevation communities are also shown in Table 2.3. The population among the four communities ranges from 55 to 395 people and the education level of the head of household ranges from fourth to seventh grade. The average land area in fallow ranges from 4.0 to 7.4 ha and area in grassland ranges from 0.6 to 3.8 ha. As a part of the local food security strategy and to mitigate adverse climate effects, farmers of these communities grow at least three different crop species and within the potato crop at least three different varieties are produced.

General agro-socio-economic information at the community level (PROINPA, 2005, INE, 2001) and response to climate change and market risk perception obtained through a base line survey are described in Valdivia et al. (2010) and Romero (2008). In general, communities at higher elevation (i.e., Kellhuiri and Vinto Coopani) and at lower elevation (i.e., San Juan Circa and San José de Llanga) practice mixed cropping and livestock production. Potato is the staple crop in these communities and it is the main source of food and income and is the major crop that receives soil nutrient amendments. Each family grows at least four different potato varieties as a strategy to cope with climate variability. Major crop production losses are due to pests and diseases, drought, frost and hail. The most frequent crop rotation is potato-quinoa/barley-barley/oat/-fallow or potato-quinoa/barley-barley/oat-perennial grasses. Fallow is a traditional practice used for soil restoration and grazing and the average fallow length range from 3 to 5 years but it might last up to 20 years in less fertile soils. There is a general trend of suboptimal and inadequate use of organic (e.g., cow and sheep manure) and inorganic fertilizers (i.e., diammonium phosphate and urea).

In both workshops, the key community leaders and community members of the four communities stated less confidence on natural indicators as reliable source of climate information for cropping making decisions as used to be in the past 25 years. For centuries all growers of this region used to rely on astral-constellation and biological indicators but currently no more that 65% of the community (Table 2.4) uses these sources of information. In both participatory workshops, participants identified soil problems as one of several factors limiting their crop production and they highlighted as major soil-based problems as low soil quality and soil fertility (i.e., low soil nutrient content, high clay content making the soil hard to crop, and stoniness), excessive water- and wind-induced soil erosion and inadequate soil management practices. Inadequate soil management practices cited were inappropriate tractor tillage practices, lack of a clear crop rotation strategy, carelessness of incorporating manure, and overgrazing by sheep. In addition, farmers identified different soil types, using indigenous Aymara names, according to the local criteria of each community and they listed soil characteristics or properties of each soil type (Table 2.5a and 2.5b).

Between three to seven soil types were identified among the four communities, and the primary criteria for soil classification were soil texture, color, the presence of stones, depth of the plow layer and productivity (Table 2.5a and 2.5b). Some of these criteria were also found by farmers of the Southern area of Bolivia who classified their soils based on colour, texture, consistency, topography, soil water conditions and best use (Fairbairn, 2001), and by indigenous farmers in Brazil based on soil color, texture, stoniness and soil moisture (Cooper et al., 2005). Farmers in the volcanic highlands areas of central México also classified their native soils mainly based on texture, color, consistence and stoniness as a major diagnostic attributes at the higher levels of the classification system (Barrera-Basolos et al., 2006). These farmers also had hierarchical indigenous soil taxonomy because they were able to distinguish four categories of soils.

The soil classification criteria was somewhat similar across the four communities and native names based on soil characteristics were consistent, except for the sandy soil which was called Saj’e in Vinto Coopani and Ch’alla in the other three communities

(Table 2.5a and 2.5b), and the clayey soil which was called Llinqi in San Juan Circa and Ñeq’e in the other three communities; although the Llinqi soil was stated as having a darker color compared to the Ñeqé soil. The collection of the Aymara names and their general characterization for the different soil types was obtained directly from farmers of the Umala municipality and was similar to soil classification acquired from farmers in the Andean region of Peru (Sandor et al., 1996), but in this case it was obtained in the indigenous Quechua language.

Soil maps drawn by farmers at the initial workshop, gave an idea about the major agricultural soil types for each community, although only the four more common and more representative agricultural soils across the four communities were plotted (Fig. 2.1).

One important observation made during the initial workshop was the fact that farmers differed on classifying rocky soils. For instance in the Kellhuiri community, where presence of stones and rocks is significant almost all over the village and considered a limitation for agricultural production, rocky soils were classified as lands with a dense presence of rocks that range from 3 cm to more than 15 cm diameter; whereas in San José de Llanga, where rockiness is not significant and not considered a problem, rocky soils are lands with a relative high presence of stones that range from 2 to 15 cm diameter.

Soil maps drawn by the representative farmers in the first workshop show a general predominance of sandy soils in the four communities, which was also confirmed at the second set of workshops, and these sandy soils are mainly designated to grow potato, quinoa, barley and oats, with a preponderance of potato. In Kelhuiri a high presence of rocky soils also exists, and in Vinto Coopani, San Juan Circa and San José de Llanga, clayey soils are second in importance as agricultural soils.

The land and crop management had a slight variation among soil types and among communities (data not shown). For instance in Kellhuiri, in the clayey soils farmers grow only barley and quinoa; whereas in Vinto Coopani farmers grow potato, barley and alfalfa. In San Juan Circa, farmers grow potato, quinoa and barley, and in San José de Llanga they grow alfalfa, barley, faba beans, and quinoa.

Farmers of the four communities have noticed changes in soil characteristics that range from slight to significant across soil types over the past 25 years, mainly attributed to climate change, land management and lack of resources (Table 2.6a and 2.6b). In some communities, those changes have been perceived with more or less intensity than the others. For instance, in Vinto Coopani all seven identified soil types were perceived to have been affected due to climate change over the past 25 years; altering the normal pattern of the cropping system. However, in San Juan Circa none of the soil types have significantly changed due to variations in climate.

A general effect perceived across soil types and across communities is soil erosion, which the participants attributed to the effect of changes in wind, rainfall and temperature. Compared to the last 25 years, farmers sense more frequent high wind speeds and that precipitation is more concentrated in fewer months which has caused greater loss of surface soil, especially on hillside areas. These perceptions agree with historical climatic information registered for this region from 1950 to 2000, that shows a change in the rainfall distribution pattern toward reduced precipitation in early rainy season and increased precipitation during the main rainy season (Seth et al., 2010 mentioned by Thibeault et al., 2010), However, UMSA (2007) reported no significant change in total annual precipitation in the Central Altiplano region from 1946 to 2004, but detected a significant increase in the minimum and maximum annual temperature from 1968 to 2001.

Climate change perceptions by community members of the Central Altiplano region are similar to those found in the Nile Basin of Ethiopia, where 51% of 1000 surveyed farmers have noticed increasing temperature and 53% have perceived precipitation reduction. Around 58% have responded to climate change by adopting some agricultural strategies, such as planting trees, following soil conservation practices, use of different crop varieties, planting early or late in the season, and utilizing irrigation. Farmers in the Nile Basin which are not responding to climate change are limited mainly due to lack of information, insufficient money, shortage of labor, shortage of land and poor potential for irrigation (Deressa et al., 2009).

One significant change in soil characteristics is the case of Pajre oraque soil (white soil) at Vinto Coopani, which was previously used for agricultural purposes 25 or more years ago, but now is no longer cultivated. According to farmers of the region, the rainfall and wind have taken all the nutrients out of the soil and it has become infertile. Although in Kellhuiri, San Juan Circa and San José de Llanga no major changes in most soil types were noticed by majority of farmers, some of the oldest participants mentioned that some of their agricultural lands are not productive as they used to be 25 or more years ago, stating as main drivers soil erosion caused by wind, lack of resources to keep or improve soil fertility, and lack of alternative options besides the local ones to deal with those climatic variations.

One relevant observation was the fact the farmers of the four communities are not very precise determining soil textural class. In general, the soil textural classification by farmers did not match with the soil textural results achieved by the laboratory from same soil types (Table 2.7). One common response across all the communities was the ranking of clayey soils (Ñeq'e or Llinqi), as one of the major agricultural soil types, mentioned by individuals of the four communities, but in fact those soils range from clay loam to silt loam soils according to laboratory results (Table 2.7). This outcome reveals the need of combining local and scientific knowledge not only to bridge gaps between farmers' and scientists' soil classification but also to plan developmental projects that are suitable for farmers' local conditions (Shrestha et al., 2004).

The bulk density results basically match with characteristics of the different textural classes identified by the laboratory analysis that the heavier soil per unit of volume are the ones with higher proportion of sand particles compared to the ones with a higher proportion of silt particles (Table 2.7).

Higher SOM content appeared to primarily relate to higher silt content and was generally lower as the proportion of sand increased (Tables 2.7 and 2.8). A similar trend occurred with CEC. None of the soils sampled had cropping limitations due to salinity as determined by EC measurements. Soil acidity indicated by soil pH_s and neutralizable acidity varied considerably among the soils indicating a possible constraint for growth of some crops due to soil reaction. Soil test P and K levels were relatively high for unamended soils, but most of the soils would require soil amendments for maximum production.

CONCLUSIONS

In the Central Bolivian Highlands, farmers perceived several effects of climate change to their agroecosystems. The effects of climatic variability alter characteristics of agricultural soils in different degrees: in some regions changes in climate are considered positive and in most regions are considered negative. Most farmers have perceived increases in temperature and a decrease in rainfall amounts during the growing season, although experienced farmers stated that rainfall is concentrated in fewer months and it is causing greater soil erosion.

Farmers of the Umala municipality do not have enough soil classification background to determine soil textural class. It seems like they are not familiar with principal characteristics of silt and clay particles and that is why they have named as clayey soils all the ones that ranged from silty loam to clay loam soils. This issue should be considered by developmental institutions and/or researchers in order to combine local and technical knowledge to achieve suitable projects for these rural remotes areas where soil testing laboratory access is very limited.

Up to seven different soil types were identified by farmers but only four were selected as most predominant agricultural soil types across the four communities. According to farmers, the most predominant soil is sandy, follow by clayey, rocky and silty soils, but according to laboratory analysis, the most predominant soil is loam, followed by silty loam and sandy loam.

Single changes in any climatic event originate changes in the normal pattern of their cropping system, especially in vulnerable locations where not much resilience capacity has been developed or lack of suitable alternatives to deal with this issue exists.

Farmers have been detecting these changes due to climate and perceiving risks but not all of them have appropriate resources to deal with these changes.

Although most farmers stated that climatic variations over 25 or more years ago did not significantly affect soil properties or characteristics, experienced older farmers affirmed that some agricultural lands are no longer as productive due to climate change and land management. Those farmers pointed out that increases in temperature which dry out the soil, concentration of seasonal rainfall in few months, and higher frequency and intensity of wind are the main drivers of change. Because many farmers do not have the appropriate means to deal with these changes, those lands are subjected to eventual grazing when native hardy vegetation grow back.

Except for the Ñeq'e soil in San José de Langa and Kellhuiri (2.4 and 2.5% SOM, respectively) and the Llinqi in San Juan Circa (2.7% SOM), all different soil types have a relatively low SOM that ranges from 1.6 to 0.3%. Higher SOM content was highly related to higher silt content and it was generally lower as the proportion of sand increased.

Higher CEC was related to higher silt particles content and it was lower as the proportion of sand particles increased. This trend was similar the one found with the SOM. Silty soils are considered very productive soils by individuals of the four communities of Umala.

Although some individuals at the San José de Llanga community stated some minor problems of crop production due to salinity, especially right after a La Niña event in 1999, none of the different soil types appeared to have cropping limitations due to salinity as determined by soil EC measurements.

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Table 2.1. Selected characteristics of four rural communities in Umala in the Central Altiplano region of Bolivia in 2006.

	Community			
Characteristics	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
Altitude (meters above sea level)	4,070	4,013	3,806	3,771
Human capital				
Population	108	55	179	395
Education head of household (years)	5.2	4.4	5.3	7.1
Age head of household (years)	52.4	50.4	48.6	49.3
Total household labor (adult equivalent)	3.2	3.8	3.3	3.4
Natural capital				
Plowed fields (ha) 2006-2007	1.2	0.9	2.6	1.3
Fallow fields (ha)	4.8	4.0	7.4	4.0
Alfalfa (ha)	0.5	0.8	2.1	2.1
Grasslands (ha)	2.2	0.6	3.8	2.3
Diversity of potatoes (No. of varieties)	4.4	3.8	3.2	3.8
Crops diversity (No. of crops)	2.8	2.7	2.7	2.8
Cultural capital				
Local knowledge of biophysical indicators for agriculture (% HH)	52.0	34.5	51.6	59.5
Economic Capital				
Cattle (Head)	4.2	3.7	8.7	3.2
Sheep (Head)	51.7	27.2	35.2	34.1
Income sources (%)				
Crop and livestock production	82.1	72.0	92.5	90.5
Eventual employments	12.2	23.2	5.2	6.3
Others	5.7	4.8	2.3	3.2
<u>Crop and livestock production:</u>				
Cropping	52.3	57.1	64.3	64.2
Livestock	27.4	24.0	10.8	15.5
By-products	18.3	18.9	24.9	20.4

HH= Household; ha= Hectares

Source: Valdivia et al. (2010) and Romero (2008)

Table 2.2. Losses experienced and perception of risks of climate change in four rural communities in Umala in the Central Altiplano region of Bolivia in 2006.

	Community			
	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
Losses experienced				
Important losses in agriculture (% HH)	92.0	89.7	71.0	97
Losses due to drought (%)	10	20.6	21.9	28.7
Losses due to floods (%)	11.5	0	12.4	30.1
Losses due to frost (%)	0	0	0	21.9
Losses due to hail (%)	20	22.2	40	16.0
Losses due to crop pests (%)	9.4	12.6	9.6	12.3
Type of threat	------------------- 1 to 5 scale ------------------			
Hail impacting on crops and livestock	4.3	4.2	3.8	3.9
Impact of floods	4.3	3.8	4.2	4.5
Impact of drought	3.0	3.0	2.9	3.0
Impact of frost on agriculture	4.3	4.7	4.5	4.3
Impact of changing climate	3.8	3.3	3.8	3.9
Impacts of pests	3.9	3.5	3.1	3.2

HH= Household

1= it is not a threat; 2= it is a minimal threat; 3= it is a moderate threat; 4= it is a very strong threat; 5= it is an extreme threat

Source: Valdivia et al. (2010)

Table 2.3. Some general characteristics of the relatively high and low areas of the Umala Municipality.

Relatively high land area	Relatively low land area
- Mean altitude 4,040 m.a.s.l	- Mean altitude 3,790 m.a.s.l.
- High presence of sloping areas exposed to water runoff and consequent soil erosion	- Predominantly flat area exposed to wind erosion
- Rockier but arable lands with moderate SOM (between 1.3 to 1.6%) content	- Sandier soils with very low SOM (between 0.3 to 0.9%) content
- Predominance of animal-based tillage system	- Tractor-based tillage system which apparently is leading to a lower native vegetation re growth in fallow lands and decline in SOM
- Sheep and cattle livestock with higher sheep units	- Sheep and cattle livestock with higher sheep units and with important incursion on dairy production
- Use primarily organic (manure) fertilizers	- Use of organic (manure) and inorganic fertilizers
- Lower access to markets	- Higher access to markets
- Approximately 85% of income comes from crop and livestock production and 12% from eventual employments	- Approximately 95% of the household income comes from crop and livestock production
- Potato production mainly for auto-consumption and for market when surplus exist	- Potato production primarily market oriented
- Around 9% temporal or permanent migration of young adults	- Around 5% temporal or permanent migration of young adults

SOM= Soil organic matter

Table 2.4. Source of climate information for making cropping decisions recollected from 180 households in four communities of Umala Municipality.

	Access to climate information[†]				
Community	Natural indicators	Community members	Radio	Almanac	Farmers' comments
	----%----	----%----	----%----	----%----	
Higher elevation communities					
Kellhuiri	53	20	0	0	In the past, almost all community members used to rely in astral-constellation and biological indicators as climate information to make decisions on soil and crop management. Due to climate changes now those indicators have changed and not all people rely on them especially the younger generation.
Vinto Coopani	34	48	7	0	
Lower elevation communities					
San Juan Circa	51	40	0	0	
San José de Llanga	61	33	7	3	

[†] Percentage of interviewed that use the information

Source: Adapted from Turin et al. (2008) and Romero (2008).

Table 2.5a. Local soil classification system with soil names and characteristics used in communities at relatively high altitude in Umala.

Soil types			
Aymara	Spanish[†]	English	Characteristics described by farmers
Vinto Coopani			
Pajre oraque	Suelo blanco	White soil	Soft soil; spiny plants grow in it; very susceptible to rainfall erosion.
Ñeq'e oraque	Suelo gredoso	Clayey soil	The surface soil can be cultivated but with wind erosion the soil becomes hard like cement.
Jach'oca	Suelo areno-arcilloso	Sandy/clayey soil	The soil has both clay and large stones: susceptible to wind erosion.
K'arpi	Suelo con arcilla dura	Hard clay soil	Has clay that is used for making ceramics. Affected by wind erosion.
Saj'e/Ch'alla	Suelo arenoso	Sandy soil	Has little soil on the surface and below has gravel. It dries out quickly and is good soil for production.
Chiar laq'a	Suelo negra	Black soil	The clay is neither hard or soft; susceptible to wind erosion.
Laq'a oraque	Suelo gris claro	Fine sand soil	Good soil with the color of skin; it has very fine sand; and it is affected by rainfall and wind erosion.
Kellhuiri			
Cha'lla	Suelo arenoso	Sandy soil	Loose soil; dries out fast under sunny conditions; has small rocks of brown color.
Ňeq'e	Suelo arcilloso	Clayey soil	Does not have rocks; yellow-orange color; soil becomes hard when dry.
Khala	Suelo pedregodo	Rocky soil	Big rocks; loose soil of brown color.
Jach'oca	Suelo areno-arcilloso	Sandy/clayey soil	Dark soil; very good soil for agriculture; susceptible to rainfall erosion.

[†] Name assigned in Spanish based on translation and soil descriptions given by farmers.

Table 2.5b. Local soil classification system with soil names and characteristics used in communities at relatively low altitude in Umala.

Soil types			
Aymara	Spanish[†]	English	Characteristics
			San José de Llanga
Cha'lla	Suelo arenoso	Sandy	Loose soil; affected by wind erosion
Ñeq'e	Suelo arcilloso	Clayey	Very hard and heavy, is not much affected by water or wind erosion.
Kaima	Suelo limoso	Silty	Land with a lot of mud near the river. Very susceptible to wind erosion.
Qullpa	Suelo salitroso	Saline	Land for grazing; soil is neither soft or hard; affected by wind erosion.
K'ala	Suelo pedregoso	Rocky	Presence of large rocks; not affected by climatic variations.
			San Juan Circa
Cha'lla	Suelo arenoso	Sandy	Loose soils with a light color; dries out fast but produce well; somehow susceptible to wind erosion.
Llinqi	Suelo oscuro arcilloso	Clayey	Has a color of brown to black, it is dry and difficult to work.
K'ala chajua	Suelo pedregoso	Rocky soil	Has rocks and some sand; the stones are about 30 cm in diameter; the surface soil is brown and the subsoil is reddish

[†] Name assigned in Spanish based on translation and soil descriptions given by farmers.

Table 2.6a. Effects of climate change on soil characteristics perceived by farmers in communities at relatively high altitude in Umala.

Soil types Aymara	Major changes in use[†]	Drivers of change over the past 25 or more years ago
		Vinto Coopani
Pajre oraque	Before it was used for agriculture and now it is not.	Rainfall, hail and wind have removed nutrients from soil, and that is why it does not produce any more.
Ňeq'e oraque	The soil used to be much stronger but it has been washed away.	It might have been a good soil (laq'a oraque) in the past, but erosion have changed the plow layer.
Jach'oca	The moisture content is decreasing and there are more rocks.	It has more stones compared to many years back, and is less strong as well.
K'arpi	It has become less fertile.	It did not change much but is less fertile than before, and needs more water to produce.
Saj'e	Used to be more fertile because it was maintained in fallow longer.	The soil color has changed. Now is lighter than before and used to be more productive.
Chiar laq'a	Used to be more fertile because it was maintained in fallow longer.	It used to be more fertile and used to keep more moisture. The wind has affected some characteristics.
Laq'a oraque	It appears to have more rocks.	It has more stones than before, but still keeps its productivity.
		Kellhuiri
Cha'lla	Decrease production	In the four soil types no significant change on soil properties or characteristics were noticed by farmers in the past 25 years, but they stated that rainfall, hail and wind are affecting soil quality and/or productivity over time, and less native vegetation such as thola is found in these soils.
Ňeq'e	No change	
K'ala	No change	
Jach'oca	No change	

Ch'alla and Saj'e=Sandy; Ñeq'e (oraque)=Clayey; Kaima=Silty; Llinqi=Dark clayey; K'ala chajua=Rocky; Jach'oca=Sandy/clayey

[†] Observed changes in use of soil over the last 25 years.

Table 2.6b. Effects of climate change on soil characteristics perceived by farmers in communities at relatively low altitude in Umala.

Soil types Aymara	Major changes in use[†]	Drivers of change over the past 25 or more years ago
		San José de Llanga
Cha’lla	No change	Higher temperature and less rainfall are making this soil less able to hold water.
Ñeq’e	It has become drier	Increase in temperature and decrease in rainfall, along with higher presence and intensity of wind, are making this soil less able to produce native vegetation.
Kaima	Use to grow more native vegetation (thola)	In Qullpa, K’ala and Ch’alla soils no significant change on soil properties or characteristics were noticed by farmers in the past 25 years, but they stated that those soils are getting tired and are producing less than before, assuming that increase in temperature, change in rainfall pattern and wind are weakening these soils.
Qullpa	No change	
K’ala	No change	
		San Juan Circa
Cha’lla	No change	In the three soil types no significant change on soil properties or characteristics were noticed by farmers in the past 25 years, but they perceived that higher temperature and less rainfall over the growing season are making soil less productive.
Llinqi	No change	
K’ala chajua	No change	

Ch’alla and Saj’e=Sandy; Ñeq’e (oraque)=Clayey; Kaima=Silty; Llinqi=Dark clayey; K’ala chajua=Rocky; Jach’oca=Sandy/clayey

[†] Observed changes in use of soil over the last 10 years.

Table 2.7. Selected soil physical properties of major soil types based on the local soil classification system used in Umala communities. Soil samples collected from the 0-20 cm depth.

	Soil type		Particle size analysis				
Community	Aymara	English	Sand	Silt	Clay	Textural class	Bulk density
			------------------------ %	----------------------			--- g cm^{-3} ----
San José de Llanga	Cha'lla	Sandy	88.8 ± 1.8	6.3 ± 1.8	5.0 ± 0.0	Sand	1.58±0.08
	Ňeq'e	Clayey	20.0 ± 0.0	55.0 ± 7.1	25.0 ± 7.1	Silt loam	1.33±0.05
	Kaima	Silty	41.3 ± 1.8	51.3 ± 1.8	7.5 ± 0.0	Silt loam	1.38±0.05
San Juan Circa	Cha'lla	Sandy	52.5 ± 17.7	37.5 ± 14.1	10.0 ± 3.5	Loam	1.45±0.12
	Llinqi	Dark clayey	21.3 ± 1.8	52.5 ± 3.5	26.3 ± 5.3	Silt loam	1.34±0.10
	K'ala chajua	Rocky	67.5 ± 14.1	25.0 ± 10.6	7.5 ± 3.5	Sandy loam	1.36±0.06
Vinto Coopani	Cha'lla	Sandy	51.3 ± 1.8	38.8 ± 1.8	10.0 ± 3.5	Loam	1.49±0.09
	Jach'oca	Sandy/clayey	68.8 ± 1.8	26.3 ± 1.8	5.0 ± 0.0	Sandy loam	1.51±0.05
	Ňeq'e oraque	Clayey	33.8 ± 1.8	33.8 ± 1.8	32.5 ± 3.5	Clay loam	1.39±0.17
Kellhuiri	Cha'lla	Sandy	61.3 ± 1.8	32.5 ± 3.5	6.3 ± 1.8	Sandy loam	1.48±0.11
	Ňeq'e	Clayey	38.8 ± 1.8	47.5 ± 0.0	13.8 ± 1.8	Loam	1.17±0.06

Values represent the average ± standard deviation of two occurrences of the soil collected in each community. All fields sampled were going into their first year of cropping after varying fallow periods.

Table 2.8. Selected soil chemical properties of major soil types based on the local soil classification system used in Umala communities. Soil samples collected from the 0-20 cm depth.

Community	Soil type	pH_s	Organic Matter	Inorganic N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
			--- % ---	-------------------------------------	mg kg^{-1}	-------------------------------------			$cmol_c\ kg^{-1}$	$dS\ cm^{-1}$
San José de Llanga	Cha'lla	5.5 ± 0.6	0.3 ± 0.0	6.9 ± 2.1	35.0 ± 3.6	166 ± 45	311 ± 90	44 ± 13	3.1 ± 0.3	0.1 ± 0.3
	Ňeq'e	7.5 ± 0.1	2.4 ± 0.3	24.9 ± 3.1	20.5 ± 5.0	424 ± 108	4520 ± 347	279 ± 45	26.0 ± 2.4	0.5 ± 0.0
	Kaima	7.5 ± 0.1	0.5 ± 0.0	20.7 ± 12.2	14.8 ± 0.4	158 ± 29	2337 ± 162	125 ± 20	13.1 ± 0.9	0.3 ± 0.1
San Juan Circa	Cha'lla	6.0 ± 0.0	0.9 ± 0.4	6.1 ± 1.4	22.8 ± 1.8	172 ± 58	1290 ± 336	181 ± 65	9.1 ± 2.7	0.1 ± 0.0
	Llinqi	5.3 ± 0.2	2.7 ± 0.1	3.5 ± 0.4	28.2 ± 7.4	438 ± 74	2299 ± 406	503 ± 82	20.8 ± 2.2	0.1 ± 0.0
	K'ala chajua	5.1 ± 0.1	1.4 ± 0.1	7.4 ± 0.3	16.0 ± 0.7	259 ± 17	646 ± 89	159 ± 17	8.0 ± 0.3	0.1 ± 0.0
Vinto Coopani	Cha'lla	5.7 ± 0.0	1.3 ± 0.1	2.9 ± 0.8	46.8 ± 6.0	271 ± 17	1102 ± 168	148 ± 14	8.9 ± 0.9	0.3 ± 0.3
	Jach'oca	5.5 ± 0.1	1.2 ± 0.1	12.9 ± 8.0	45.2 ± 1.1	240 ± 4	580 ± 70	70 ± 10	5.8 ± 0.1	0.2 ± 0.1
	Ňeq'e oraque	6.9 ± 0.2	1.5 ± 0.1	1.6 ± 0.0	3.0 ± 0.0	159 ± 48	3763 ± 241	578 ± 173	24.3 ± 3.1	0.2 ± 0.1
Kellhuiri	Cha'lla	5.5 ± 0.4	1.6 ± 0.4	11.4 ± 7.3	51.0 ± 19.1	243 ± 90	972 ± 294	101 ± 35	8.3 ± 0.1	0.2 ± 0.1
	Ňeq'e	6.3 ± 0.6	2.5 ± 0.7	19.5 ± 8.5	38.2 ± 8.1	231 ± 35	2644 ± 75	160 ± 7	15.9 ± 0.8	0.3 ± 0.0

Ch'alla=Sandy; Ňeq'e (oraque)=Clayey; Kaima=Silty; Llinqi=Dark clayey; K'ala chajua=Rocky; Jach'oca=Sandy/clayey

Values represent the average ± standard deviation of two occurrences of the soil collected in each community. All fields sampled were going into their first year of cropping after varying fallow periods.

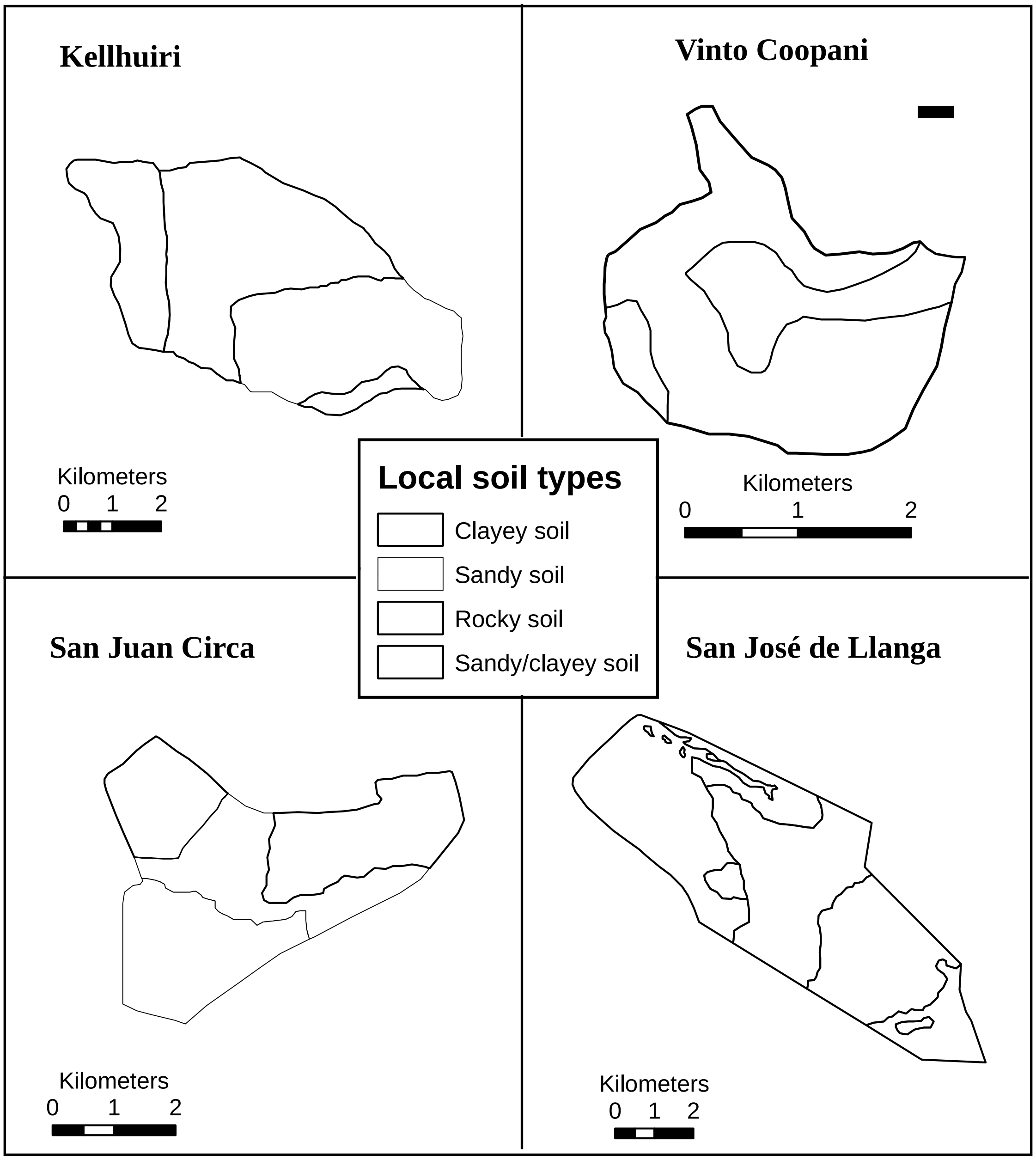

Fig 2.1. Major agricultural soil types identified by farmers of four communities at the Umala Municipality based on local soil classification systems.

CHAPTER 3

IMPACTS OF CROP ROTATION AND FALLOW LENGTH ON SOIL NITROGEN AND CARBON AVAILABILITY IN THE BOLIVIAN ALTIPLANO

ABSTRACT

A study was conducted in semiarid soils of the Andean highland region (Altiplano) of Bolivia during the 2006 and 2007 growing seasons to assess the effects of crop rotation and varied length of fallow periods on soil properties under low agricultural inputs and adverse climatic restrictions. The objective of this study was to assess and compare the effects of years of cropping and fallow on soil degradation or soil restoration and potential soil C and N mineralization. Four representative communities of the Central Altiplano region were selected based on their relative elevation so that two communities were at a relatively higher elevation and two communities were at a relatively lower elevation. An initial baseline survey and two participatory workshops were conducted at the community level to obtain farmers' perceptions on possible changes in local cropping systems due to climate and socioeconomic changes over time with emphasis on changes in crop rotation and fallow periods. The typical three-year crop rotation at both low and high elevations is potato-quinoa or barley-barley where organic and inorganic fertilizers are only applied to the first crop. Following cropping, fields are often left fallow for varying periods up to 10 years. This practice of fallowing is considered an important soil restoration practice to allow for future cropping. For this research, soil samples were collected from fields at the first, second and third year of crop rotation and from 1, 10, 20, 30 and 40 years of fallow and analyzed for several soil characteristics. Currently the 20, 30 and 40 years of fallow is rarely used but some lands

were identified and sampled as a control for assessing the extent of organic C accumulation at varied age of fallow. In general, the upper elevations had significantly higher SOC, total N, inorganic N, soil test P and K, exchangeable Ca and Mg and CEC compared with the lower elevations. In general, cropping significantly decreased total and active SOC, and total, inorganic and active soil N. Fallow restored total and active SOC and total and active soil N more rapidly in the higher communities than was observed in the lower communities and this difference was mainly attributed to differences in soil properties and land management in cropped fields at both elevations.

INTRODUCTION

Importance of Crop Rotation

Systems of crop rotation vary in their duration and sequence of crops and they offer several cropping advantages. Crop rotation may prevent or reduce pest and disease incidence because some insect pests and disease-causing organisms have specific crop hosts (Abawi and Widmer, 2000; Chen and Tsay, 2006), and may also decrease weed population and severity mainly through shading, and competition for nutrients and water (Schreiber, 1992; Bárberi and Cascio, 2000). Rotation can also significantly improve soil physical properties, such as improvement in soil water infiltration (Katsvairo et al., 2002), and reduction in soil bulk density and penetration resistance (Karlen et al., 2006). Rotations may also stimulate soil biological activity and diversity (Dick, 1992), promoting an increase in soil nutrient availability and decrease in the amount of soil CO_2 emissions compared to a continuous crop production, which helps to preserve the environment (Wilson and Al-Kaisi, 2008).

Crop rotation can also result in increased soil N and soil organic matter (SOM), especially when an N-fixing legume is included. Inclusion of a legume in the rotation can improve crop production and agricultural sustainability (Miglierina et al., 2000). In a two year study in Eastern South Dakota, corn (*Zea mays* L.) grown in annual rotation with soybean (*Glycine max* (L.) Merrill) had significantly higher soil total nitrogen (TN) and NO_3^--N amounts and lower levels of soil test phosphorus (P) when compared with continuous corn (Riedell et al., 1998). These results confirm the findings of many other studies of rotation effects that, for example, show an increase of soil NO_3^--N in crop rotations that included legumes such as soybeans after sorghum (*Sorghum vulgare* Pers.) or soybean after corn (Peterson and Varvel, 1989) or when using red clover within the crop rotation (Raimbault and Vyn, 1991). In general, the effects of crop rotation often result in increases in crop yields and higher economic returns (Halvorson et al., 2002).

Effects of Fallow on Soil Properties

The inclusion of a fallow period in the crop rotation is an ancient agricultural management technique practiced over many centuries by farmers to restore soil productivity after cropping, mainly by accumulation of nutrients, water and /or organic matter (Sarmiento et al., 1993; Doran et al., 1998; Sarmiento, 2000). Rain-fed agriculture alternating with unmanaged fallow is widespread in semiarid regions of Latin America, but little information on changes in soil properties, soil degradation, and natural rehabilitation is available.

Type and length of fallow is also important for soil fertility restoration and improvement of soil properties. Five-year fallow fields recovered higher total porosity, macroporosity and saturated hydraulic conductivity compared to two years of fallow

(Miranda et al., 2009). Soil organic C (SOC) and soil nutrient (i.e., N, P and K) concentrations significantly increased with increasing fallow duration up to 7 years. These increases have been attributed to the decay of above ground and root biomass of fallow vegetation and the presence of native leguminous species among the vegetation (Samaké et al., 2005). Other researchers have also observed a gradual accumulation of soil organic matter and improvements in other soil properties at ten years of fallow (Areola et al., 1982). In a semiarid area in Mexico on sites abandoned for 22 years, the SOC and TN recovered 34 and 62% respectively of its original levels, but this recovery level attained only 50% of that registered under native vegetation for the same fallow period. Although the observed levels of SOC and TN depletion under conventional rain-fed agriculture are very difficult to alleviate by natural fallows; this practice has been observed to have beneficial effects on soil properties (Bravo-Garza and Bryan, 2005). However, four years of fallow in sandy soils of Senegal did not significantly increase SOM and soil nutrient concentrations (Masse et al., 2004), and after 10 years of fallow there was no clear evidence of recovery of nutrient elements and any clear improvement in soil physical (e.g., bulk density) and chemical properties (e.g., SOC) with increasing fallow in the Bolivian Altiplano (Hervé, 1994).

In the Andean highlands region of Bolivia, little research has been conducted or at least published that determines the effects of cropping and fallow length on soil restoration and soil characteristics. Moreover, few studies have examined the issue of the optimum length of fallow to achieve desired soil restoration. In this region, crop rotations are often initiated with potato followed by two to three years of cereal crops (e.g., quinoa, barley, oats) and then an extended uncultivated fallow period which can last between 1 to 15 years (Stacishin de Queiroz et al., 2001) and up to 20 years (Hervé, 1994; Motavalli et al., 2009). These extended periods of bare fallow is expected to restore soil fertility mainly through the supplement of organic matter due to the decomposition of both above- and belowground plant biomass of native vegetation, to control crop diseases and pests, and to generate a mix of short evergreen shrubs (e.g., "thola" (*Parastrephia lepidophylla*)) and perennial bunch-grasses for grazing and fuel for cooking (Hervé, 1994; Stacishin de Queiroz et al., 2001). However, the increase in rural human population in this region and competing land uses are causing important reductions in the length of fallow (Coûteaux et al., 2008). Moreover, soil management practices, such as use of mechanized disc plowing, continuous hand removal of scarce native vegetation and overgrazing have reduced the re-growth and population of natural vegetation, probably diminishing the amount of organic inputs and the rate of soil fertility restoration (Motavalli et al., 2007; Motavalli et al., 2009).

Farmers of this region are still using ancient knowledge with the simple idea of "the longer the fallow the better for soil restoration" but they do not have research-based information on optimum fallow length. Some farmers fallow their cropping lands up to 40 years in less fertile soils with the expectation that native vegetation will re-grow. The objectives of this study were to: 1) assess and compare the effects of the length of cropping and fallowing periods on soil degradation or soil restoration, and 2) determine potential soil C and N mineralization from a range of cropped and fallow lands.

MATERIALS AND METHODS

Area of Study

This research were conducted during the 2006 and 2007 growing seasons in the Andean Highland (Altiplano) region of Bolivia located in South America. Four representative communities (i.e., Kellhuiri, Vinto Coopani, San Juan Circa, and San José de Llanga) located in the Central Altiplano were selected for this research. These communities are located in the Umala Municipality of Bolivia and were selected to represent traditional indigenous communities located at relatively low and high elevations. The Umala Municipality is mostly a semi-arid region situated between 3,750 and 4,100 meters above sea level (masl), with low rainfall (annual average of 350 mm) and erratic distribution during the growing season and low air temperatures (annual average of 11°C) (PROINPA, 2005). The potential productivity of this region for agricultural purposes is limited by several factors. Among these factors are adverse climate, such as delays in early season rainfall for planting, early frost and hail and drought during the growing season (FAO and SNAG, 1995; García et al., 2007). Other factors limiting growth are the presence of multiple pests and diseases, poor seed quality (PROINPA, 2005), and several soil restrictions including rockiness, salinity, poor drainage, low water retention, shallow topsoil depth due to erosion, and low SOM content (Hervé, 1994).

The communities of Kellhuiri and Vinto Coopani are situated at relatively higher elevations and San Juan Circa and San José de Llanga are located at relatively lower elevations. Some selected characteristics of each individual community are described in more detail in Tables 2.1 and 2.2 of Chapter 2; however, a short summary is presented here. The altitude difference among communities in the higher elevation versus lower elevation communities is approximately 250 m. At the higher elevations, the land has more hills and steeper slopes and soil tillage practices are generally dependent on animal traction. The soil at this elevation has a high proportion of rocks and farmers do not use adequate amounts of manure and manufactured fertilizers for optimizing crop growth. The primary work for people in the communities is crop and sheep production with potato production the major source of food and income. A small percentage of the population is also involved in dairy production. This area has difficult access to the nearest market because of poor roads and distance. In contrast, the low elevation communities are situated in relatively flat areas where people frequently use mechanical traction for tillage. The soils are generally sandier and show high evidence of erosion mainly attributed to a high wind frequency and intensity. In addition, dairy production is a major economic activity at the lower elevations and there is greater access to schools and markets.

At both elevations, potato is the initial crop of the crop rotation and barley is usually the last crop before local farmers leave fields to natural fallow to recover soil fertility and then initiate a new cropping phase. An important native evergreen shrub called “thola” (*Parastrephia lepidophylla*) is the most predominant evergreen vegetation that re-grows in natural fallow lands and is considered an important soil cover for preventing soil erosion by water (steep slope areas) or wind (flat uncovered areas) and it might be an important source of soil nutrients inputs and SOM accumulation as well. However, farmers of the region also use this bush as source of fuel, as a building material, and as a medicinal herb.

Baseline and Participatory Workshops

An initial baseline survey of 180 community members among the four communities was conducted in 2006 by Aymara-speaking interviewers who filled out a standardized questionnaire. Subsequent participatory community workshops (Chambers, 1994) were conducted in August and September 2006 to determine local criteria for use of crop rotation and fallowing. Among the four communities, a total of 54 farmers (35% women) participated in the workshops. Individuals were asked to determine local criteria for fallow length after cropping, if the fallow periods were being affected due to climate change, and other management practices associated with cropping and fallow.

Soil Sampling and Analysis

Between two to three replicate soil samples were taken just prior to the growing season in October 2007 from agricultural fields in the four communities which were in traditional potato-based cropping systems and had different lengths of cropping and fallow. All the fields contained one soil type with a sandy loam textural class which was classified as a sandy, mixed, frigid Typic Ustifluvents in the U.S. Soil Taxonomy (1999). This soil type is an important common agricultural soil in the four communities and is locally classified as “ch’alla” soil.

Based on farmers’ information on the cropping history of each field, researchers and farmers of the four communities collected a total of 31 soil samples from cropped lands having 1, 2 and 3 years of crop rotation, and a total of 50 soil samples from 1, 10, 20, 30 and 40 years of fallow. Farmers of this region do not have a written cropping history of their agricultural lands; therefore, we assumed that lands assigned as 20, 30 and 40 years of fallow might have ± 2 years of variation. Fallow land with 20, 30 to 40 years of fallow is rarely used by members of the Umala Municipality, but some fields were identified and soil samples collected as a control for assessing the extent of SOM accumulation at varied age of fallow. Some basic information on cropping history of each collected field was obtained to supplement soil analysis results.

Soil samples were collected to a 20 cm depth and were the result of compositing 15 to 20 subsamples collected over the extent of each field which were often approximately 1 ha or less in size. All soils were air-dried, ground, and passed through a stainless steel sieve with 2-mm openings prior to analysis. Soils were analyzed for SOC and TN by combustion using a LECO TruSpec® C/N analyzer. This analyzer determines the total amount of N and C in all forms using a flash combustion system joined to an infrared detector and to a thermal conductivity detection system (AOAC International, 1997). Soil total inorganic N (NH_4^+-N and NO_3^--N) was extracted by shaking 4-g soil samples in 40 mL of 2 *M* KCl at approximately 180 rpm for 1 hour and filtering the extract through Whatman No. 2 filter paper. Analysis of the extract was performed using methods (Lachat Instruments, 1992 and 1993) recommended for the Lachat QuikChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). Other soil properties (i.e., soil pH, soil test P and K, exchangeable Ca and Mg, CEC and EC) were analyzed following the standard procedures of the University of Missouri Soil and Plant Testing Laboratory (Nathan et al., 2006).

Soil C and N mineralization potentials of the cropped and fallowed soils were determined using an aerobic leaching incubation method (Motavalli et al, 1995). In this procedure, 100 g of each soil sample was incubated for 84 days in 150 mL Corning filter units at -47 kPa soil moisture tension and a constant temperature of 25 ºC. Each filter unit was fitted with a 0.22 μm cellulose acetate membrane filter covered with a glass microfiber prefilter of 47 mm diameter, extra thick with high wet strength and loading capacity. A glass fiber filter of 70 mm diameter, with similar characteristics as the 47 mm diameter filter, was placed on the top of the soil in the unit to prevent dispersion. At scheduled sampling times (i.e., 1, 3, 7, 14, 21, 28, 42, 56, 70 and 84 days after initiation of the experiment), mineralized soil total inorganic N (TIN) (NO_3^- and NH_4^+) was displaced from samples by addition of 50 mL of an N-free nutrient solution and leaching of this solution through the soil in the filter unit. The amount of NO_3^- and NH_4^+ were determined in the leachates using the Lachat QuikChem automated ion analyzer (Lachat Instruments, Milwaukee, WI). For the C mineralization, samples were periodically placed in sealed mason jars and the headspace swept with CO_2-free air. The jars were then sealed for approximately 45 hours and changes in head space CO_2 concentration due to soil CO_2 evolution was then determined using a gas chromatograph (GC) (Buck Scientific Inc., East Norwalk, CT, USA) fitted with a thermal conductivity detector (TCD).

Statistical Analysis

Because of the number of soil sample replications for each treatment and years of fallow were not balanced among communities, PROC GLM was used to compare the effect years of cropping and fallow on soil pH, SOC, TN, inorganic N, soil test P and K , exchangeable Ca and Mg, CEC and EC (SAS Institute, 2002-2003). PROC ANOVA was used to compare the effect of years of cropping and years of fallow on cumulative soil inorganic N and CO_2-C mineralization. Means were separated using the Tukey-Kramer test at the probability level of $p \leq 0.05$. PROC REG was used for stepwise regression analysis for comparing relationship between years of cropping or years of fallow with soil inorganic N, soil organic C, soil total N, cumulative inorganic N mineralized and cumulative CO_2-C mineralized.

RESULTS AND DISCUSSION

Baseline Survey and Workshops

A brief summary of the baseline survey results obtained from interviewed members of the four communities are presented in Tables 3.1 and 3.2. Results show smaller farm size (from 6 to 8 has) and higher access to irrigation (0 to 32% of the population) in the high elevation communities compared to the low elevation ones (farm size from 9 to 13 has, and 3 to 6% of population with access to irrigation), although the irrigation source comes primarily from small hand-made rainfall catchments. Among the most predominant farm animals, a relatively lower number of cattle and a higher number of sheep exist in the higher compared to the lower area communities. Only between 4 to 14% of the population uses tractors in the higher elevations, whereas 100% of the population uses this technology as primary tillage in the lower elevations. This greater use of tractor-based tillage is apparently contributing to higher thola reduction in this region. However, in the higher elevations, greater thola reduction is mainly attributed to its removal for fuel.

Farmers also perceived a decrease in the length of the fallow period over the past 25 years, and the reduction of this practice is considered one factor that contributes to reduction in soil quality and other soil characteristics. Across communities, current fallow length lasts between 2 to 10 years which is shorter in relation to the last two decades when this practice lasted up to 20 years in the central areas of the Bolivian

Altiplano (Hervé, 1994). One reason mentioned for the shortening of the fallow periods is the switch from agricultural lands planted to annual row crops to land planted to forages since livestock and/or dairy activity has rapidly increased in the region over the last ten years.

General results across communities indicated that these communities rely primarily on potato-based cropping systems and a significant proportion of land is devoted to native pasture to support livestock. Over the four communities, an average of 51% of those interviewed stated that the ch'alla soil (sandy), as called in native Aymara language, is the most common soil type for agricultural purposes, 100% of those interviewed mentioned that fertilizers are applied only in potato crop, and 85% have perceived climate change effects on their agroecosystems in the last 25 years. The most common crop rotation was potato-quinoa/barley-barley/oat-fallow.

Members of the community were aware of some cultural practices that were negatively affecting their cropping lands. One of those was the increasing use of tractors for primary tillage, mainly in the low elevation communities. The type of tillage practice may have effects on the restoration of soil fertility during the fallow period since farmers have identified that native vegetation, such as thola, do not re-grow well in fallow areas with tractor-based tillage compared to with animal-based tillage.

Several soil-related problems were identified among the communities during the participatory workshops (Table 3.3). In general, land preparation is performed between 7 to 9 months prior to planting whenever sufficient precipitation occurs during the current growing season. However, in Kellhuiri, land preparation is also performed 3 months before planting if snow events occur. The major primary tillage system in high elevation communities was animal traction and tractors were used in low elevation communities. Across communities, farmers expressed a general concern for the effects of soil degradation mainly caused by soil erosion (i.e., both water and wind erosion), low soil fertility and use of poor land and crop management practices. Farmers stated that inadequate soil management practices that are currently being practiced include thola removal and overgrazing in fallow lands, inappropriate tractor tillage practices, lack of a clear crop rotation strategy and carelessness of incorporating manure.

Crop Rotation and Fallow Length Analysis

The effects of years of cropping and years of fallow on soil pH, soil total inorganic N (NH_4^+-N and NO_3^--N), SOC, TN, soil test P and K, exchangeable Ca and Mg, Cation Exchange Capacity (CEC) and Electrical Conductivity (EC) in the four communities are presented in Table 3.4a and Table 3.4b. No significant differences in soil pH, soil test P, and EC among treatments and in the four communities were detected. There was a significant difference in total inorganic N (TIN) in the four communities among treatments with the highest content in the first year of cropping across communities. At the higher elevations, soil TIN decreased with years of cropping (from 7.9 to 5.2 mg kg^{-1} in Kellhuiri and from 6.1 to 5.8 mg kg^{-1} in Vinto Coopani) and increased with years of fallow (from 4.9 to 6.5 mg kg^{-1} in Kellhuiri and from 5.5 to 7.0 mg kg^{-1} [at 30 years of fallow] in Vinto Coopani). However, in the lower elevations, soil TIN gradually decreased almost linearly with years of cropping and years of fallow (from 8.0 to 4.5 mg kg^{-1} in San Juan Circa and from 6.5 to 2.5 mg kg^{-1} in San José de Llanga).

The relationship between years of cropping and years of fallow with soil TIN content in the high and low area communities are shown in Fig 3.1. The soil TIN content was higher in the upper elevations compared to the lower elevations at the first and second year of cropping, but at the third year it was the opposite. In both elevations, upper and lower, there was a significant relationship between soil TIN and years of cropping, observing a linear decrease of soil TIN with years of cropping ($r^2 = 0.71$ and $r^2 = 0.25$ for the upper and lower communities respectively). These results are due to the fact that inorganic fertilizers containing N are only applied to the first crop (i.e., potato) of the rotation and the potato crop can utilize much of the applied nutrients leaving little for subsequent crops in the rotation. The soil inorganic N restoration with years of fallow in the higher communities could be attributed to greater regrowth of native vegetation in this area compared to that of the lower communities which possibly generates more vegetative biomass which decays and adds organic N to the soil.

There was a significant relationship between TIN and years of fallow only in the upper elevations ($r^2 = 0.60$) with a maximum accumulation reached approximately after 30 years of fallow. In the lower elevations no significant relationship between TIN and years of fallow was detected.

Except for Vinto Coopani community, the cumulative soil potential N mineralization determined by an 84-day incubation showed significant differences among years of cropping and years of fallow (Table 3.5). In Kellhuiri, San Juan Circa and San José de Llanga, the amounts of N mineralized decreased with years of cropping and increased with years of fallow. Although not statistically significant, a similar pattern was found for the Vinto Coopani community. Across communities, high amounts of cumulative inorganic N were observed for the first year of cropping, and Kellhuiri and Vinto Coopani (upper communities) had considerably higher amounts (467 and 418 mg

kg^{-1}, respectively) compared to that of the lower communities of San Juan Circa and San José de Llanga (304 and 119 mg kg^{-1}, respectively). When grouping higher and lower communities, the cumulative soil potential N mineralization also showed similar differences between both elevations as was observed for soil TIN content, indicating higher labile organic N in the upper elevations compared to the lower elevations (Fig. 3.2). The cumulative potential soil N mineralization showed no significant relationship with years of cropping and with years of fallow for both the upper and lower communities, although a general decrease of cumulative soil N mineralized was observed with years of cropping for both elevations (Fig. 3.2).

The SOC content showed significant difference among treatments only in Vinto Coopani and San Juan Circa community (Tables 3.4a and 3.4b). In Vinto Coopani, SOC basically did not change with years of cropping but it gradually increased with years of fallow from 0.8 to 1.2 mg kg^{-1}. In San Juan Circa, SOC showed a decrease with years of cropping (from 0.7 to 0.5 mg kg^{-1}) and fallow showed a significant increase only at 40 years.

When communities were grouped by elevation, the SOC was significantly lower in soils collected from farm fields in the lower elevation communities (San Juan Circa and San José de Llanga) compared to the upper elevation communities (Kellhuiri and Vinto Coopani) (Fig. 3.3). This difference was probably due to the generally higher sand content of the soils in the lower communities, possibly due to the more intensive mechanized tillage used in those communities, and possibly to the relatively higher temperature registered in these communities compared to the upper communities which may have contributed to a higher SOC decomposition.

No significant linear or polynomial relationship was determined between SOC and years of cropping in both elevations (Fig. 3.3). These results are in agreement with other studies that reported no significant differences for SOC among crop rotations (Martin-Rueda et al., 2007), but are not in agreement with research that found differences in SOC concentrations attributed to the effects of incorporated residue in a crop rotation system (Collins et al., 1992; Robinson et al., 1996; Soon and Ashad, 1996).

Increases in SOC due to fallowing were more rapid in soils collected from communities at higher elevations compared to the lower elevation (Fig. 3.3). The fitted polynomial curve determined in both elevations showed a consistent increase of SOC with years of fallow and generally a maximum accumulation was reached at higher elevations after approximately 20 to 30 years of fallow and continued to accumulate in the lower communities over 40 years of fallow (Fig. 3.3). These results are consistent with findings by Pestalozzi (2000) in the High Andes of Bolivia (i.e. elevations between 4000 and 5000 meters above sea level), who detected that plant biomass and SOM content increased as years of fallow increased from 1 to 9 years in fertile farm fields and from 1 to 21 years in less fertile lands. In the southwestern region of Nigeria, Salako et al. (1999) found an increase in SOC content as fallow length increased from 1 to 3 years. For the same region, Aweto et al. (1981) observed an increase in SOM accumulation as natural fallow increased until the tenth year of fallow. On the other hand, Herve et al. (1994) evaluations in the Central Bolivian Altiplano's soils found no clear evidence of recovery of nutrient elements even after 10 years of fallow.

The CO_2-C mineralized during incubation provides a relative measure of active organic C (Sherrod et al., 2009). Except for the Vinto Coopani community, the cumulative soil potential CO_2-C mineralized showed significant differences among years of cropping and years of fallow (Table 3.5). In Kellhuiri, San Juan Circa and San José de Llanga, the amount of CO_2-C mineralized decreased with increasing years of cropping and increased with increasing years of fallow. High amounts of CO_2-C mineralized were observed in the first year of cropping, and Kellhuiri and Vinto Coopani (upper communities) obtained higher amounts (2923 and 3427 µg g^{-1} respectively) than San Juan Circa and San José de Llanga (lower communities) (2087 and 1464 µg g^{-1} respectively) did.

When grouping higher and lower communities, the cumulative soil CO_2-C mineralized showed similar differences between both elevations (Fig. 3.4) as was observed for SOC (Fig. 3.3). The SOC content was considerably larger in the higher elevations compared to that of the lower elevations either during the cropping or fallow periods. At both elevations, SOC was significantly reduced after several years of cropping and it continued to accumulate over 40 years of fallow (Fig 3.2). Others have observed in the Andes in Venezuela that the maximum level of active C occurred after 8 years of fallow (Cabaneiro et al., 2008).

Except in San José de Llanga, soil TN content was significantly different among treatments in all communities (Table 3.4a and Table 3.4b). In Kellhuiri, soil TN gradually decreased with years of cropping (from 0.14 to 0.08%) and did not change much with years of fallow. In Vinto Coopani, soil TN content was consistent through years of cropping but it increased with increasing years of fallow (from 0.08 to 0.10%). In San Juan Circa, soil TN content was consistent in almost all years of cropping and fallow, except for the 40 years of fallow which had a significant increase (from 0.05 to 0.08%).

Soil TN was significantly lower in soils collected from farm fields in the lower elevation communities compared to the upper elevation communities either from cropping or fallow fields (Fig. 3.5). A regression analysis showed no significant relationship between years of cropping and years of fallow and TN content. This result is not in agreement with Barrios et al. (2005) in a study of Andean hillsides in Colombia, where they found a consistent increase in TN across time of fallow.

This difference in SOC, soil TN and soil TIN between the upper and lower communities was probably due to the lower re-growth of native vegetation (e.g., thola) as mentioned, in the baseline survey and participatory workshops, by community members from these communities causing less biomass inputs into the soil and, subsequently, lower SOM and nutrient accumulation. Other reasons may be the generally higher sand content of the soils and the more intensive mechanized tillage used in the lower communities compared to that of the upper communities.

Soil test K was significantly different among treatments only in San Juan Circa and San José de Llanga (the lower communities). In both communities, soil K decreased with years of cropping (from 184 to 133 mg kg^{-1} and from 111 to 90 mg kg^{-1}) and increased with years of fallow (from 142 to 193 mg kg^{-1} and from 114 to 163 mg kg^{-1}[at 30 years of fallow]). The exchangeable Ca was significantly different among treatments only in Vinto Coopani and San Juan Circa. In Vinto Coopani, the exchangeable Ca increased with years of cropping and with years of fallow up to 30 years (from 957 to 3479 mg kg^{-1}), but in San Juan Circa it decreased with years of cropping (from 1846 to

912 mg kg^{-1}) and increased with years of fallow (from 844 to 1387 mg kg^{-1}). The exchangeable Mg was different among treatments only in San Juan Circa and San José de Llanga (lower communities). In both communities exchangeable Mg decreased with increasing years of cropping (from 300 to 133 mg kg^{-1} and from 68 to 65 mg kg^{-1} respectively) and increased with years of fallow (from 153 to 220 mg kg^{-1} and from 49 to 87 [at 30 years of fallow] respectively). Among all communities, San José de Llanga registered the lowest amounts of exchangeable Mg across years of cropping and years of fallow. The CEC was significantly different among treatments only in San Juan Circa. The CEC gradually decreased with years of cropping and with years of fallow up to 30 years (from 13.9 to 5.3 $cmol_c$ kg^{-1}) and thereafter a sudden comeback at 40 years of fallow (10.1 $cmol_c$ kg^{-1}) was noticed. These results suggest that cultivation generally decreased and fallowing normally increased soil fertility in certain soil characteristics, but the effects of cultivation and fallowing were not consistent in all communities that were included in this research.

CONCLUSIONS

The upper communities of Umala Municipality have higher initial soil fertility status than the lower communities with higher soil total organic C, total N, inorganic N, soil test P and K, exchangeable Ca and Mg and CEC. These results match the perceptions of community members from lower communities who highlighted increased soil degradation caused by diverse factors, including climate change (e.g. increased wind frequency and intensity that leads to increased soil erosion) and inappropriate soil management practices, such as the excessive tractor use as primary tillage and suboptimal use of organic fertilizers.

In general, years of cropping under the semiarid conditions of the Bolivian highlands significantly decreased soil chemical properties in the Kellhuiri, Vinto Coopani, San Juan Circa and San José de Llanga communities, although this effect varied among soil elements and among the four communities. Years of cropping had an impact on more soil elements in the low elevation communities (San Juan Circa and San José de Llanga) then in the high elevation communities (Kellhuiri and Vinto Coopani). Years of cropping have also been shown to decrease labile organic C and N at both elevations.

The fallow practice increased soil chemical properties in agricultural lands of the four communities of the Umala Municipality. Length of fallow had a significant impact on restoration of important soil elements such as soil organic C and N although it varied among higher and lower communities with more rapid restoration in the higher than in the lower communities. This trend may be associated with soil management practices performed in lower communities such as the use of conventional tillage system, scarce use of soil organic amendments, higher thola removal and overgrazing of fallowing lands. The soil restoration detected in these communities suggests the fallow length may be important in changing certain soil properties, such as soil organic C that may have been affected by cropping. In general, increasing years of fallow practice increased labile organic C and N in all communities.

The decreasing length of the fallow period and reduction in native vegetation caused by competing uses and mechanized tillage may be removing an important mechanism by which total and active soil organic C is restored in potato-based cropping systems in this region.

The impact of fallowing appears to be greater in soils collected at higher elevations which may reflect differences in some soil particle size characteristics and management practices, such as greater re-growth of native vegetation, reduced presence of sand particles and the use of animal-based tillage system.

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Table 3.1. Selected results from the baseline survey from interviewed farmers of the four communities of Umala Municipality.

Community	Farm size	Irrigation†	Tractor‡	Fallow	Thola reduction§	
	-- ha --	------------ % ----------		- years --	-- % --	--- Reasons for thola reduction ---
High elevation communities						
Kellhuiri	8	32	4	2 - 4	40	78% blamed its removal for fuel, 12% due to land use competition and 10% due to drought.
Vinto Coopani	6	0	14	6 - 10	68	21% attributed its decline to reduced soil fertility, excessive use of tractor in flat regions, 26% to its removal for fuel, 27% to land use competition and 26% to drought.
Low elevation communities						
San Juan Circa	13	3	100	6 - 10	62	4% attributed to selling, 11% to decline in soil fertility due to excessive use of tractor in flat regions, 43% to its removal for fuel, 27% to land use competition and 15% to drought.
San José de Llanga	9	6	100	2 - 4	90	4% attributed to selling, 21% to decline in soil fertility due to excessive use of tractor in flat regions, 22% to its removal for fuel, 53% to land use competition and 4% to drought.

† Percentage of interviewed with access to small rainfall catchments used as eventual source of irrigation

‡ Percentage of interviewed that use tractor as primary tillage

§ Percentage of interviewed that perceived thola reduction over the past 25 years

Table 3.2. Percentage of households that own farm animals and average number of animals per household in four communities of Umala Municipality

Community	Animals							
	Cattle		Sheep		Camelids		Pigs	Chicken
	--%--	Units	--%--	Units	--%--	Units	--%--	--%--
High elevation communities								
Kellhuiri	92	4	84	41	20	3	4	4
Vinto Coopani	97	3	97	26	-	-	7	14
Low elevation communities								
San Juan Circa	90	9	77	21	-	-	0	0
San José de Llanga	94	9	81	21	-	-	2	6

Source: Adapted from Turin et al. (2008)

Table 3.3. Major farmers' land preparation criteria stated in the participatory workshops with the four communities of Umala Municipality

		Land preparation[‡]		
Community	Use of residue[†]	Timing	Reasons for tillage	Main tillage system
		-- months --		
High elevation communities				
Kellhuiri	Livestock food	3 - 9	Early loosening and aeration of soils improves soil and crop performance	Animal
Vinto Coopani	Livestock food	8 – 9	Save labor because moist soils are easier to till. Early prevention of crop pests by killing them at dormant stages	Animal
Low elevation communities				
San Juan Circa	Livestock food	8	Early tillage loosens the soil and kills weeds before they seed	Tractor
San José de Llanga	Livestock food	7 - 9	Easier to till when soil gets some moisture, and early tillage improves soil aeration	Tractor

[†] Major use of native vegetation residues removed by land preparation

[‡] Land preparation before planting which is usually in November. Three months means land preparation in August if there are snow events and the 7 to 9 months means land preparation in February, March or April taking advantage of rainfall during the current growing season.

Table 3.4a. Selected soil properties due to different cropping and fallow length in Umala communities at relatively higher elevation.

Community/ Type of rotation	Time of rotation	pH_s (0.01 *M* $CaCl_2$)	Total inorganic N	Total organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	- yr -		mg kg^{-1}	---------%--------		---------------- mg kg^{-1} ----------------				$cmol_c$ kg^{-1}	dS cm^{-1}
Kellhuiri											
Cropping	1	6.2	7.9	1.1	0.14	22	270	1154	151	9.0	0.3
	2	5.3	5.8	0.9	0.09	39	250	778	85	8.1	0.2
	3	5.9	5.2	1.0	0.08	54	316	1403	121	10.7	0.2
Fallow	1	5.5	4.9	1.1	0.11	49	242	1197	124	10.0	0.1
	10	6.0	5.7	1.1	0.13	35	316	1904	171	12.8	0.3
	20	5.8	6.4	1.2	0.11	15	250	1267	164	10.3	0.3
	30	7.0	6.5	1.1	0.12	19	162	1550	159	10.7	0.2
Tukey-Kramer$_{(0.05)}$†		NS	1.7	NS	0.03	NS	NS	NS	NS	NS	NS
Vinto Coopani											
Cropping	1	6.1	9.9	0.8	0.07	55	413	957	121	8.0	0.3
	2	5.8	7.1	0.7	0.06	19	145	1435	230	10.8	0.1
	3	5.8	6.0	0.8	0.07	34	181	1157	154	9.4	0.1
Fallow	1	5.8	5.5	0.8	0.08	18	155	1276	221	10.0	0.1
	10	5.9	5.9	1.0	0.10	26	294	1562	240	11.7	0.2
	20	6.6	6.2	1.1	0.11	22	243	3479	188	20.8	0.4
	30	7.6	7.0	1.1	0.09	28	173	3345	193	20.0	0.3
	40	5.8	6.8	1.2	0.10	34	238	1262	203	10.1	0.3
Tukey-Kramer$_{(0.05)}$†		NS	1.9	0.4	0.05	NS	NS	NS	NS	NS	0.3

† Tukey-Kramer minimum difference at $p \leq 0.05$; NS = not significant

Table 3.4b. Selected soil properties due to different cropping and fallow length in Umala communities at relatively lower elevation.

Community/ Type of rotation	Time of rotation	pH_s (0.01 *M* $CaCl_2$)	Total inorganic N	Total organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	- yr -		mg kg^{-1}	---------%--------		------------------- mg kg^{-1} -----------------				$cmol_c$ kg^{-1}	dS cm^{-1}
<u>San Juan Circa</u>											
Cropping	1	6.3	8.0	0.7	0.05	28	184	1846	300	13.9	0.2
	2	5.9	7.1	0.6	0.04	23	131	1007	136	7.4	0.1
	3	5.9	6.6	0.5	0.04	22	133	912	133	7.0	0.1
Fallow	1	5.7	5.0	0.6	0.05	23	142	844	153	6.9	0.2
	10	5.8	4.4	0.6	0.05	29	169	710	119	6.0	0.1
	20	6.3	4.6	0.6	0.05	22	129	1061	143	7.6	0.2
	30	6.1	4.2	0.6	0.05	24	138	675	113	5.3	0.1
	40	5.9	4.5	0.8	0.08	22	193	1387	220	10.1	0.1
Tukey-Kramer$_{(0.05)}$[†]		NS	1.1	0.2	0.03	NS	62	905	180	5.9	NS
<u>San José de Llanga</u>											
Cropping	1	6.1	6.5	0.5	0.02	25	111	443	68	4.3	0.2
	2	6.0	5.5	0.5	0.02	30	108	465	68	4.7	0.2
	3	7.4	5.2	0.4	0.02	20	90	722	65	5.1	0.2
Fallow	1	5.7	3.3	0.5	0.02	22	114	317	49	2.9	0.1
	10	5.6	3.7	0.5	0.02	29	150	285	42	3.1	0.1
	20	6.0	2.3	0.5	0.02	20	128	319	49	3.0	0.2
	30	6.3	2.6	0.5	0.02	25	163	727	87	5.3	0.1
	40	6.2	2.5	0.5	0.02	21	134	386	57	3.3	0.1
Tukey-Kramer$_{(0.05)}$[†]		NS	1.0	NS	NS	NS	70	NS	39	NS	NS

[†] Tukey-Kramer minimum difference at $p \leq 0.05$; NS = not significant

Table 3.5. Cumulative soil potential N (NO_3^- + NH_4^+) and C (CO_2) mineralization due to different cropping and fallow length in four Umala communities.

Community		Kellhuiri		Vinto Coopani		San Juan Circa		San José de Llanga	
	Rotation	Inorg N	CO_2-C	Inorg N	CO_2-C	Inorg N	CO_2-C	Inorg N	CO_2-C
	- yr -	-mg kg^{-1}-	-µg g^{-1}-	-mg kg^{-1}-	-µg g^{-1}-	-mg kg^{-1}-	-µg g^{-1}-	-mg kg^{-1}-	-µg g^{-1}-
Cropping	1	467	2923	418	3427	304	2087	119	1464
	2	353	2348	320	2856	170	1525	111	1309
	3	378	2026	325	2609	144	1368	81	1237
Fallow	1	410	2725	318	2714	201	1561	69	1203
	10	464	2899	366	2896	197	1502	67	1287
	20	480	2971	382	3134	167	1517	74	1317
	30	467	3025	330	3194	209	1578	101	1412
	40	-	-	400	3497	357	1990	84	1461
Tukey-Kramer$_{(0.05)}$†		119	938	NS	NS	204	490	46	255

† Tukey-Kramer minimum difference at $p \leq 0.05$; NS = not significant

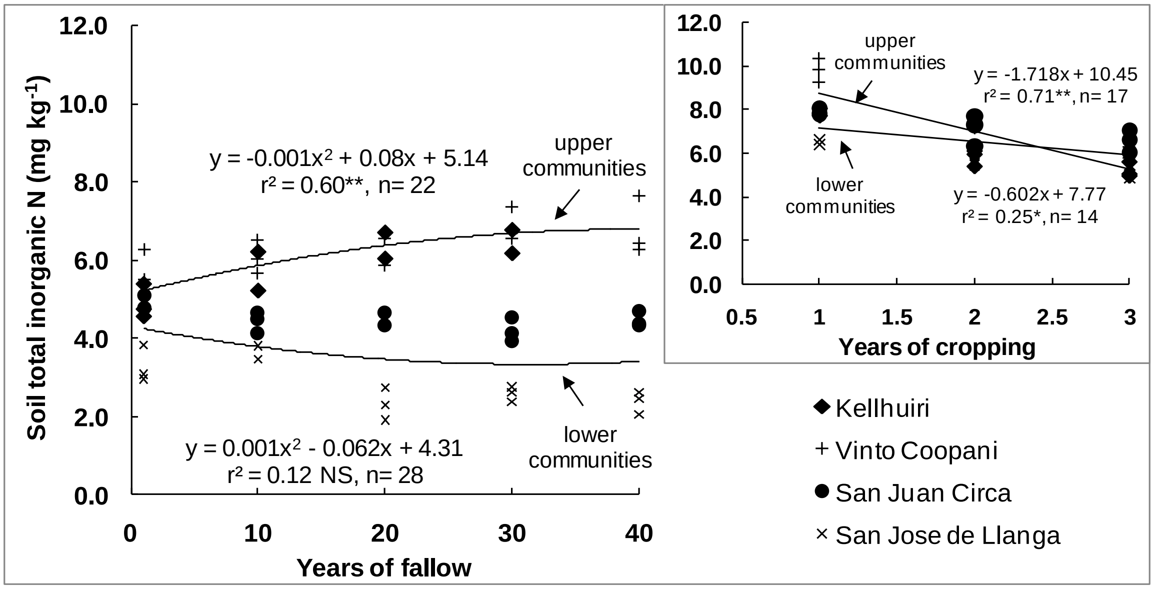

Figure 3.1. Soil total inorganic N content (NH_4^+-N + NO_3^--N) under different years of cropping and fallow in the upper and lower Umala communities. *, ** = significant at $p<0.05$ and $p< 0.01$, respectively; NS= not significant.

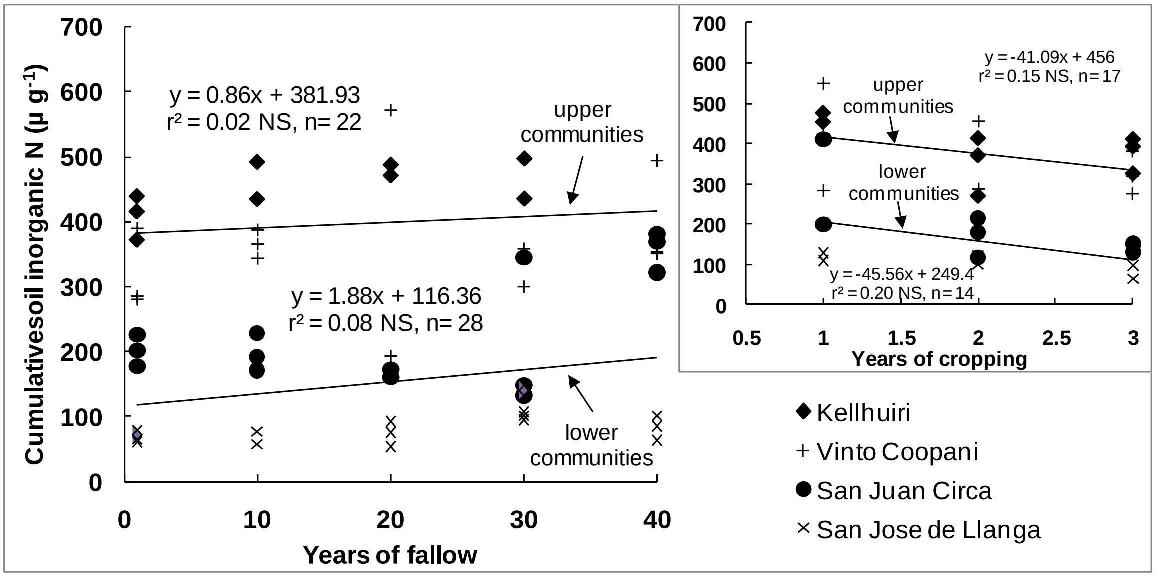

Figure 3.2. Cumulative soil N mineralized after 84 days of incubation of samples collected from different years of cropping and fallow in the upper and lower Umala communities.

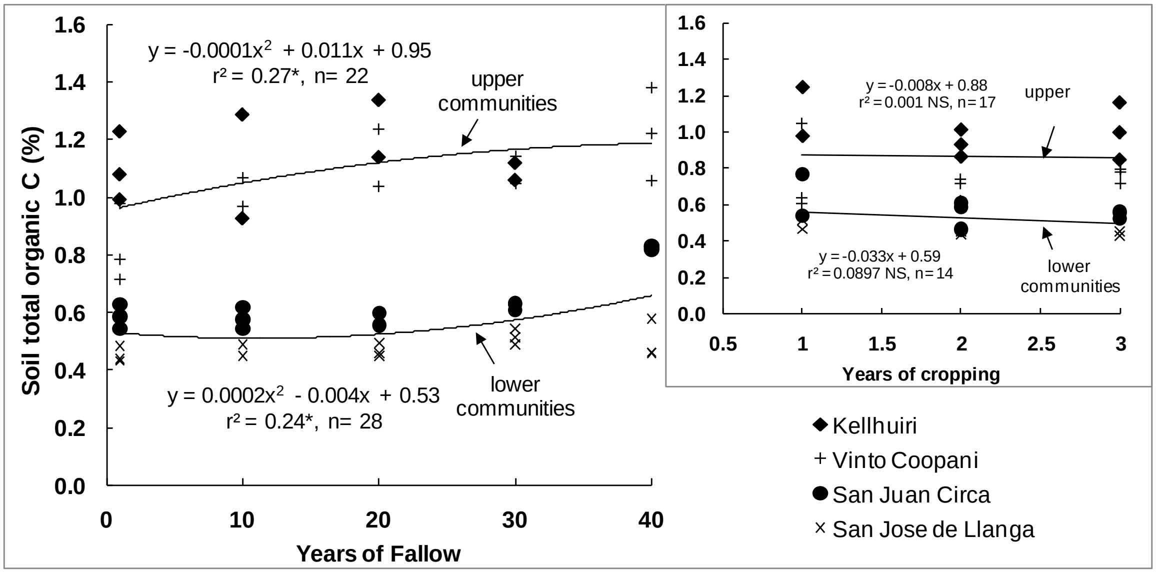

Figure 3.3. Soil total organic C content under different years of cropping and fallow in the upper and lower Umala communities. * = significant at p<0.05; NS= not significant.

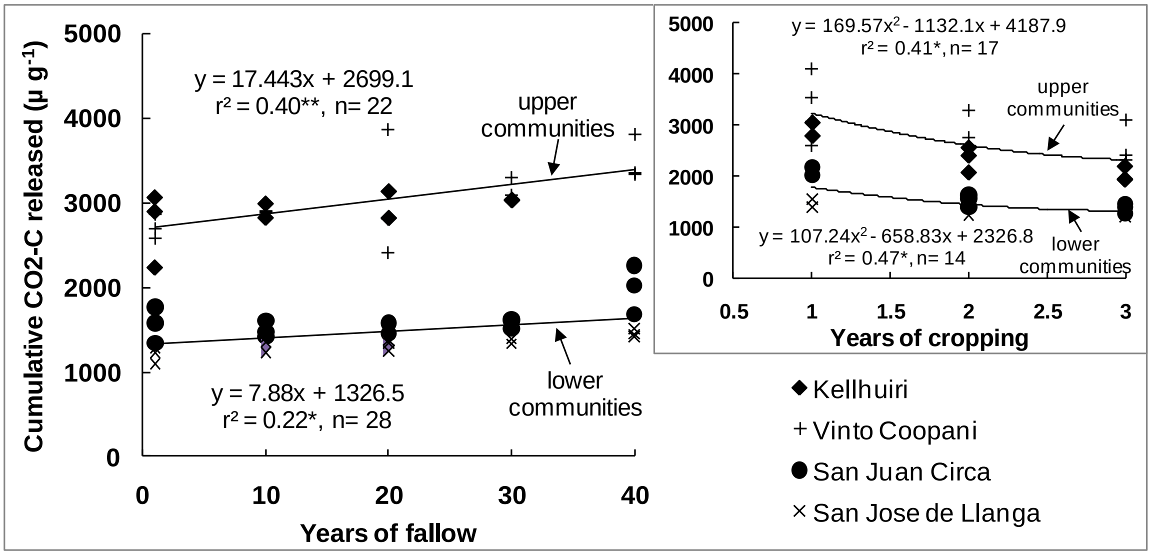

Figure 3.4. Soil CO_2-C released after 84 days of incubation of samples collected from different years of cropping and fallow in the upper and lower Umala communities. *, ** = significant at p<0.05 and p< 0.01, respectively; NS= not significant.

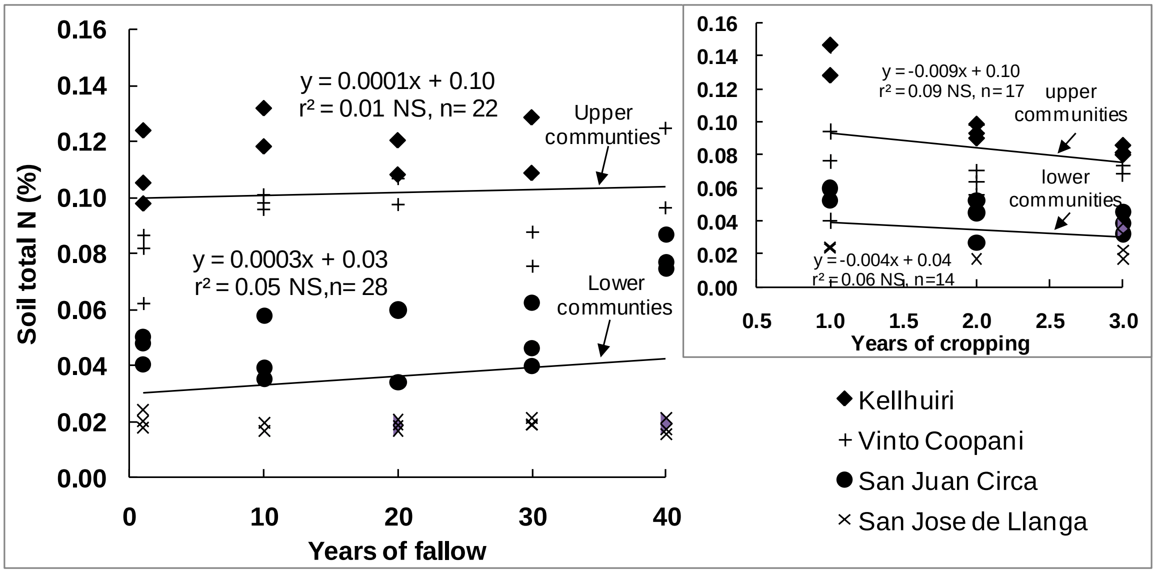

Figure 3.5. Soil total N content under different years of cropping and fallow in the upper and lower Umala communities. NS= not significant.

CHAPTER 4

EFFECTS OF ORGANIC AND INORGANIC SOIL AMENDMENTS ON SOIL PROPERTIES IN A POTATO-BASED CROPPING SYSTEM UNDER THE SEMIARID CONDITIONS OF THE BOLIVIAN CENTRAL HIGHLANDS

ABSTRACT

A study on the initial and residual effects of organic and inorganic fertilizers in sandy loam soils in a potato (*Solanum tuberosum* L.)-based cropping system in the semiarid central highland plateau (Altiplano) region of Bolivia was conducted over three growing seasons from 2006 to 2009. The objectives of this study were to determine the effects of applications of organic and inorganic soil amendments on: 1) initial and residual soil total organic C, total N and total inorganic N and other soil characteristics, 2) soil physical properties, and 3) soil C and N mineralization rates. Field experiments were established under a Randomized Complete Block design with four replications in two low and two high elevation communities with active community participation in the experimentation. Initial soil samples were taken from all the sites prior to application of treatments and planting of potatoes, during the growing season and at harvest. Treatments included a control, and applications of sheep and cow manure, compost, Biofert (i.e., a commercial microbial activator soil amendment), urea and diammonium phosphate and combinations of these different treatments for a total of 12 treatments. The inorganic fertilizer was applied at 80 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 0 kg K_2O ha^{-1}, the manure treatments at a rate of 10 Mg ha^{-1} (wet weight basis with an average dry matter of 73% across locations and years, the compost at a rate of 5 Mg ha^{-1} (wet weight basis with a DM of 59%, and the Biofert, combined with the manures, at a rate of 0.2 Mg

ha^{-1} (wet weight basis with a DM of 88%). In general, no significant effect of growing season and community factor was detected on treatments. Cow and sheep manure applications showed no significant differences in chemical characteristics and their effect on soil chemical or physical characteristics did not differ as well. Soil pH, soil total organic C, total N, total K increased due to application of organic fertilizers with or without inorganic fertilizers. Soil inorganic N and soil test P (Bray1) were increased by inorganic fertilizers alone or when combined with organic fertilizers. The residual effect of most selected soil nutrients was detected in the subsequent growing season. Soil potential mineralizable C and N increased as organic fertilizers rates increased from 0 to 30 Mg ha^{-1}. In general, lower soil bulk density and higher soil moisture were observed after organic fertilizers were applied with or without inorganic fertilizers and their residual effect persisted for the next crop in the rotation.

INTRODUCTION

Soil organic and inorganic fertilizers are of importance to agricultural sustainability mostly for their significant beneficial effects on soil properties and soil productivity. Several studies have been conducted to assess the effects of soil organic and inorganic fertilizers on soil properties and crop yields, and different outcomes have been observed depending on the specific agroecosystems (Saha et al., 2008).

The importance of organic fertilizers in agricultural lands primarily is because they increase soil organic matter (SOM) and improve soil properties for crop growth (Hati et al., 2006; Saha et al, 2008). Among the benefits of maintaining or increasing SOM are increased soil water-holding capacity, improved soil structure for root growth and drainage, accelerated rates of nutrient cycling (García-Gil et al., 2000), and higher content of soil nutrients over a longer period of time, increased CEC, and greater soil biological activity (Woomer et al., 1994). These changes in soil properties improve soil quality and the long-term sustainability of agroecosystems (Gupta et al., 1994). Because of its high water holding capacity, SOM has particular importance in sandy soils since it improves soil water availability for plants and water storage (Tester, 1990; Rawls et al., 2003).

Cultivation of soil, especially through tillage, affects soil physical properties by altering soil structure and promoting loss of SOM. However, these potentially negative impacts of tillage can be minimized by adding large amounts of crop residues (Karlen et al., 1994) or organic fertilizers, such as farm manure (Mando et al., 2005).

Inorganic fertilizers are an important management input to achieve good crop yields especially in systems where soil resources are nutrient deficient and the main goal is to increase crop productivity (Haynes et al., 1998). However, use of chemical fertilizers alone may not be sufficient under intensive agricultural management because it has been associated with declines in some soil properties and crop yields over time (Hepperly et al., 2009) and significant land problems, such as soil degradation due to over exploitation of land and soil pollution caused by high doses of fertilizers and pesticide application (Singh, 2000). Most research has found non-significant effects of inorganic fertilizers on soil chemical (CEC, pH, soil organic C, total N and exchangeable Ca) and physical (bulk density) properties (Banik et al., 2006; Yussuf et al., 2007), which is mainly attributed to the fact that mineral fertilizers had no significant impact on SOM.

Residual effects of applied organic and inorganic soil fertilizers on soil properties vary based on different factors including type, rate and timing of application and soil characteristics. Extensive research has reported improved soil properties including a higher content of residual soil nutrients over a longer period of time due to organic soil amendments. For example, manure and vermicompost significantly increased soil organic C (SOC) and decreased bulk density over time (Saha et al., 2008), and the residual effect of total SOC and soil P lasted up to seven to eight years when manure was applied in a semi-arid dryland agriculture (Kihanda et al., 2006). Inorganic fertilizer application modestly increased SOC (Yadav et al., 1998; Kihanda et al., 2006; Saha et al., 2008) mainly attributed to increased biomass production which resulted in increased soil organic C input from root and crop residues.

Inorganic and organic fertilizers applied together are of importance to agricultural sustainability mostly for their significant effect on soil productivity as well as on soil properties. Numerous studies reported that combinations of soil organic with soil inorganic fertilizers are more beneficial for soil properties and crop production than either fertilizer applied alone. For instance, in a cassava-based cropping system with application of organic and inorganic fertilizers, soil available P was increased and SOC was relatively stable (Ayoola, 2006). Other studies reported that SOC and total soil N were increased with organic and inorganic soil amendments (Goyal et al., 1999). A combination of manure and chemical fertilizer resulted in consistent availability of NO_3^- during the growing season (Nyiraneza and Snapp, 2007). In plots that received a combination of inorganic and organic fertilizers for the last 11 years, the SOM concentration and soil microbial activities, which are important for the nutrient turnover and long-term productivity of the soil, were significantly increased compared to plots that received inorganic fertilizer only (Goyal et al., 1999). Due to their residual value that could last for several years of cropping, organic amendments can be intermittently applied to soils and supplemented by chemical fertilizers to rapidly supply immediate nutrients required by crop plants (Kihanda et al., 2006).

The Bolivian Altiplano’s climate is characterized by high diurnal temperature variations, frost risks, low and irregular precipitation and high risks of drought during the growing season (Garcia et al., 2007). Recent research has indicated that the rate of global warming will increase with altitude and that the tropical Andes region has averaged a historical temperature increase of 0.11°C per decade (Bradley et al., 2006). Among the effects of climate change in this region of Latin America has been a tendency toward slightly drier conditions on the western side of Bolivia and a significant increase of the near-surface temperature in the tropical Andes (Vuille et al., 2003). Simulation models for the central region of the Bolivian Altiplano have predicted increases in air temperature from 1 to 2°C and from 3 to 5°C and in precipitation from 3 to 5% and from 5 to 7% by the middle of century (2020-2049) and late century (2070-2099) respectively (Thibeault et al., 2010). An important component of soils that may assist in mitigating the effects of climate change is SOM or SOC. Increased SOM generally improves soil quality and the long-term sustainability of agroecosystems (Gupta et al., 1994), and this is because SOM buffers changes in soil chemical, physical and biological properties that affect soil productivity (Fernandes et al., 1997).

Soil organic matter also has several other functions in increasing soil productivity, which are very important to this region where use of manufactured fertilizer is not common or is applied at suboptimal rates. Because of the multiple functions of SOM, the amount and composition of SOM are important indicators of soil degradation (Carter, 2002). Increasing soil degradation can have severe consequences in the Altiplano where agriculture is the primary source of income and sustenance for indigenous (i.e. Aymara and Quechua) households.

Many possible soil management practices are causing soil degradation in this region. For example, high rates of soil erosion, which lead to significant loss of topsoil and SOM, are a common problem because of the steep slopes and scarcity of vegetative cover in the Central Andean Region of Bolivia (Coppus et al., 2003). Most farmers of this region are aware of the reduction of soil fertility on their agricultural lands and of the importance of using appropriate soil management practices, but several potential obstacles for adoption of these practices may be affecting these growers including the relatively higher costs of the new practice versus traditional practices, competing uses for organic materials (e.g., for fuel and livestock feed), lack of community training and education, and the social and cultural implications of adopting the practice (Motavalli et al., 2009).

The objectives of this study were to determine the effects of local and alternative soil organic and inorganic soil fertilizers on: 1) soil organic C and total and inorganic soil N availability and other soil characteristics, 2) soil physical properties, such as bulk density, gravimetric water content and water-holding capacity, and 3) potential soil C and N mineralization rates.

MATERIALS AND METHODS

Area of Study

The study was conducted over three growing seasons from 2006 to 2009 on farm field sites in the Central Highland (Altiplano) region of Bolivia. As mentioned in previous chapters of this manuscript (Chapters 2 and 3), the Altiplano region of Bolivia is located at elevations ranging between 3,700 and 4,100 m above sea level with an average annual temperature of 11°C and an average annual precipitation of 350 mm. This region is exposed to frequent occurrences of frost and drought events during the growing season. One representative area selected for this study was the Umala municipality located in the Central Altiplano region where potato-based cropping systems and dairy farming are common.

Four representative indigenous Aymara communities of the Umala municipality were selected for the study: Kellhuiri and Vinto Coopani at relatively higher elevations and San Juan Circa and San José de Llanga at relatively lower elevations. Detailed information on selected characteristics of each individual community is presented in Chapter 2 and a brief summary is presented here. There are some important differences between the high and low area communities. The communities at the higher elevations have a high proportion of steep slopes and rocky areas with a predominance of animal-based tillage systems and sheep livestock, individuals of this region use only manure as source of fertilizer, and have relatively low farm size (average 7 has per household). The soil organic matter content ranges between 1.3 to 1.6%.

In contrast, the lower elevation communities are predominantly located on flat areas with high sand content and they mainly utilize tractor-based tillage and cows for livestock with most families involved in dairy production. This region has less native vegetation in fallow lands, mostly attributed to excessive tractor use and its removal for fuel purposes, compared to higher elevations. The soil organic matter content ranges from 0.3 to 0.9%. Community members use organic soil amendments for potato production although a few of them combine with inorganic fertilizer. Only around 250 m difference exists between the elevations of the low and high communities.

Local Land and Crop Management Workshop

In August and September, 2006, participatory workshops as described by Chambers (1994) were conducted in each community to determine farmers' perceptions of the effects of climate change and/or socioeconomic factors on local land management and their perceptions of the principal local restrictions for crop production. Additional information was obtained from each community regarding their suggested solutions to overcome these restrictions that would be suitable for local socioeconomic conditions. Results of these participatory workshops supported the need for research farm trials that would focus on improvement of soil quality using traditional and alternative soil amendments.

Through a local communal authority, all members of each community were invited to voluntarily participate in the workshops. Participatory workshops had a total of 10 participants in Kellhuiri, 16 in Vinto Coopani, 15 in San Juan Circa and 13 in San José de Llanga. As a part of the methodology, individuals were separated in three small groups accompanied by one researcher to allow and encourage more individual participation, and each group had at least one woman participant. A tree problem analysis approach was used to identify causes and effects of perceived problems by examining and analyzing the issues surrounding those problems (Chevalier, 2008).

Initially, participants determined main land and/or crop management problems and thereafter those problems were ranked by importance on a 0 to100% scale. For each general problem, more specific information was requested by the researchers. For instance, if crop pests and diseases were an important productive problem mentioned, the specific kind of crop pests and diseases were identified and those were also ranked by importance on a 0 to 100% scale. In general, the issues around a perceived problem were discussed with participants and organized into a tree structure ending up with major and specific problems and their causes and effects (Fig. 4.1). This analysis helped to identify the aim and main objectives of this study. When soil quality and/or fertility management was mentioned as a relevant restriction, more specific information was gathered from participants.

Experimental Design for Field Trials

The experiment was designed based on workshop results where farmers expressed a concern over declining soil quality and crop performance. According to most farmers, the main drivers affecting soil quality were changes in climate, some economic factors such as the high cost and availability of inorganic fertilizers and the common use of traditional-conventional cropping systems.

With a participatory approach, field trials at the community level were established according to the local cropping system. In an initial meeting performed in October 2006 in each community, responsibilities to conduct the research were designated for both researchers and farmers. Major community members' responsibilities were to provide prepared lands and manure for establishing the experimental plots and be in charge of seeding, hilling, controlling crop pests and diseases and harvesting following traditional-local technology. Specific researchers' responsibilities were to provide the seed of potato (*Solanum tuberosum* L.) and quinoa (*Chenopodium quinoa,* Willd), inorganic fertilizers, alternative organic soil amendments (urban household compost and Biofert), pesticides if needed, and to train farmers on innovative soil amendment management practices included in the research. Sharing knowledge on land and crop management practices and performing field technical evaluations on tested treatments during the growing season were joint responsibilities shared between farmers and researchers.

This trial included four conventional and alternative nutrient amendments (i.e., composted cow manure, composted sheep manure, household compost, Biofert) alone or combined with inorganic fertilizer (i.e., urea + diammonium phosphate [DAP]) making a total of 12 treatments (Table 4.1). Farmers in this region normally apply local cow or sheep manure alone or combine both together but often at suboptimal rates (PROINPA, 2005). Biofert is a solid biofertilizer released by a Bolivian private company that is designed to be a supplement for organic fertilizers. It contains a source of organic N which the manufacturer claims enhances soil microbial activity. In addition, the product literature says it contains *Mycorrhiza* fungi that make nutrient and moisture assimilation more efficient, and *Bacillus* bacteria that promote plant growth (PROINPA, 2005). Biofert was hand mixed with the manure treatments and applied to potato field trials.

Results of the individual community participatory workshops indicated significant variation in application rates of organic (0.8-3.3 Mg $ha^{-1}$of manure) and inorganic (13-104 kg ha^{-1} of diammonium phosphate [DAP] and 13-42 kg $ha^{-1}$of urea) soil amendments among families (Gilles et al., 2009). However, for this research, recommended rates for both organic and inorganic fertilizers were applied as shown in Table 4.1. To reach the recommended mineral fertilization rate for potato crops in the Altiplano region, as mentioned by Alvarez (1988) and Bellot (1991), 80 kg N, 120 kg P_2O_5 and 0 kg K_2O ha^{-1}, 261 kg ha^{-1} of DAP (18% N – 46% P_2O_5 – 0% K_2O) was applied at planting and 72 kg ha^{-1} of urea (46% N) at hilling time.

Changes in soil properties due to initial organic and inorganic fertilizer application for the potato crop were assessed and then residual effects were determined on the successive crop in the rotation. The study was set up over three growing seasons starting with potato as the first crop followed by quinoa. A separate set of fields received initial fertility treatments for potato in the first year so that there would be two seasons of initial fertilization of potato and two seasons of residual effects in quinoa. All practices for the establishment and management of the trials followed were based on commonly used local practices including land preparation, hand-seeding and placement of fertility treatments in the side of the hill. All the trials contained one soil type with a sandy loam textural class which was classified as a sandy, mixed, frigid Typic Ustifluvents.

The field trials were established in the relatively higher elevation communities of Kellhuiri and Vinto Coopani and in the relatively lower elevation communities of San Juan Circa and San José de Llanga. Approximately 11 local community members participated in the establishment and periodic evaluations of each trial. Planting of the potato crop (*Solanum tuberosum* ssp. *andigena* cv. Waycha) in all four trials occurred on November 6-11, 2006 and on November 13-27, 2007. Treatments were arranged in a randomized complete block (RCB) design with four replications. Each experimental plot had 5 rows (80 cm apart) and was 5 m in length. At the higher elevation communities, both tractor-mounted disc plows and animal traction cultivation equipment were used for initial plowing and only animal traction for planting and hilling; whereas, at the lower elevation tractors were used for land preparation, planting and hilling. At both elevations, potato tuber seed was planted at a depth of approximately 20 cm in rows that were spaced 80 cm apart and with 30 cm spacing between plants. Along with the seeding, with the exception of the urea treatment, all treatments were broadcast-applied in the rows at planting time. Hilling of the potato plants was performed when plants reached around 15 cm in height and urea was band- broadcasted at the same time just on the side of the hill. Andean weevil (*Premnotrypes* spp.) and potato tuber moth (*Phthorimaea operculella* [Zeller]) are common potato pests in this region and were controlled with Karate® (active ingredient (a.i): Lambda-cyhalothrin; Syngenta, Greensboro, NC) applied once at the rate of 400 mL ha^{-1} (52.5 mL ha^{-1} a.i.). Potatoes were hand harvested in 5 m lengths from three central rows of the five plot rows after plants and tubers reached physiological maturity in April of both 2007 and 2008.

For assessment of the residual effects of the fertility treatments on soil properties, quinoa field trials were established on November 22-27, 2007 and from November 4 to December 3, 2008 in the harvested potato trials. For the 2008-09 growing season, quinoa trials were established only in Kellhuiri, Vinto Coopani and San Juan Circa communities. Before planting, the fields were tilled using animal traction in the high elevation and with tractor in the low elevation communities in order to loosen soil and facilitate planting. Quinoa crop (*Chenopodium quinoa* cv. Jach'a grano) seed was hand-planted at a rate of 10 kg ha^{-1} and was placed at a depth of approximately 3 cm in rows spaced 40 cm apart and with 10 cm between plants. At emergence, an initial hand weeding was done to facilitate crop plant establishment. At approximately 40 days after planting, plants were thinned to be spaced 10 to 15 cm apart to avoid excessive plant competition. Presence of quinoa moths (*Eurysacca melanocampta* Meyrick [Lepidoptera: Gelechiidae]) and armyworm complex (*Copitarsia turabata* H.S. [Lepidoptera: Noctui-dae]), were controlled by application of Karate® (active ingredient: Lambda-cyhalothrin; Syngenta, Greensboro, NC) applied at the rate of 100 mL ha^{-1} (13.1 mL ha^{-1} a.i.) and downy mildew (*Peronospora farinosa* Fr.) by application of Ridomil® (active ingredient: mefenoxam; Syngenta, Greensboro, NC) at rate of 1 kg ha^{-1}(0.024 kg ha^{-1} a.i.). By the third week of April 2008 and 2009 when the quinoa seedheads were sufficiently dry, plants were hand harvested by cutting the aboveground portion of the plant.

Soil and Organic Amendments Sampling and Analysis

Initial soil samples were taken from all the sites prior to application of treatments and before the planting of potato and quinoa crops. In addition, soil samples were taken during the growing season to assess relative differences in soil nutrient content and other soil properties due to the treatments. Three soil samples were collected to a depth of 20 cm within each plot, mixed in a plastic bucket, and a composite sample was then removed and stored in a labeled plastic bag. The soil samples were subsequently air-dried, ground using a mortar and pestle, and then passed through a sieve with 2 mm openings. All the samples were then analyzed for soil pH (0.01 M $CaCl_2$), neutralizable acidity [N.A.], total organic carbon [SOC], total nitrogen [N], inorganic N (NH_4^+-N + NO_3^--N), exchangeable calcium [Ca] and magnesium [Mg], soil test phosphorus [Bray P1], soil test potassium [1 *M* NH_4AOc at pH 7], effective cation exchange capacity [CEC], electrical conductivity [EC] and soil physical (bulk density and soil gravimetric water content) analyses. Soil chemical analyses (except for total inorganic N, total organic C and total N) were determined using standard methods for the University of Missouri Soil and Plant Testing Laboratory (Nathan et al., 2006).

Total inorganic N (NH_4^+ -N and NO_3^- -N) was extracted by shaking 4-g soil in 40 mL of 2 *M* KCl solution at approximately 180 rpm for 1 hour and filtering soil and extracting solution through Whatman no. 2 filter paper. The extracts were then stored in well-sealed plastic scintillation vials at less than 4 ºC prior to analysis. Ammonium-N and NO_3^- -N were determined colorimetrically using a flow injection analyzer (Lachat Instruments, 1992, 1993). Total organic C and total N were determined by combustion of approximately 0.200 g soil samples using a LECO TruSpec® CN analyzer. This analyzer determines the total amount of N and C in all forms using a flash combustion system joined to an infrared detector and to a thermal conductivity detection system (AOAC International, 1997).

Soil bulk density was determined for all sites and treatments over the three growing seasons using the core technique (Grossman and Reinsch, 2002). In the potato trials, four initial composite samples per community were collected prior to planting or application of treatments and three samples in each experimental plot prior to harvesting. In the quinoa trials, three samples per plot were collected prior to harvest. The field-moist soil collected from the cores was weighed, dried at 110°C for 48 hours, and then reweighed for determination of the total dry weight of the soil in the cores.

The cow and sheep manure, household made compost and the commercial biofertilizer used in all potato trials were also analyzed for selected chemical characteristics. One replicate sample of the sheep and cow manure used in the potato plots in each community, and one sample of the household compost and one of the biofertilizer were collected, and properly labeled in plastic bags. Organic amendments were thereafter air-dried, ground with mortar and pestle, and sieved using a sieve with 1 mm openings. All the samples were then analyzed for total organic C, total N, total P and total K. Chemical analyses for total P and total K were determined using standard methods for the University of Missouri Soil and Plant Testing Laboratory (Nathan et al., 2006). Total organic C and N were determined by combustion of approximately 0.100 g samples using a LECO TruSpec® CN analyzer.

Soil C and N Mineralization Potential and Water-Holding Capacity

To determine soil C and N mineralization potential and changes in water-holding capacity with addition of organic amendments used in the field experiment, an aerobic leaching incubation experiment (Motavalli et al., 1995) was conducted. Bulk sandy loam soil was collected from a depth of 20 cm from a representative farm field in the Vinto Coopani community for use in the experiment. The farm field was in its first cropping year after being in fallow. The soil was air-dried, ground and passed through a sieve with 2-mm openings. Analysis of this soil is presented in Table 4.2 and it showed that it contained 1.0±0.1% total organic C.

Treatments consisted of rates of dried and ground cow and/ or sheep manure, compost and Biofert collected from the field trials. The organic amendments were mixed with the soil at equivalent rates of 7.5, 15 and 30 Mg ha^{-1} (dry weight basis). To reach the desired rates, 2.82, 5.64 and 11.28 g of organic amendments were added for each kg of soil, respectively. The Biofert was added at an equivalent rate of 0.2 Mg ha^{-1} in a combined treatment with the sheep and cow manures. For each treatment, 100 g of dry bulk soil was well-mixed with each organic fertilizer rate before the initiation of the incubation. The treated soils were placed in 150 mL Corning filter units and leached initially with 100 mL and subsequently with 50 mL of minus-N nutrient solution at -47 kPa soil moisture tension (Motavalli et al., 1995). Each filter unit was fitted with a 0.22 µm cellulose acetate membrane filter covered with a glass microfiber prefilter of 47 mm diameter with high wet strength and loading capacity. A glass fiber filter of 70 mm diameter, with similar characteristics as the 47 mm diameter filter, was placed on the top of the soil in the unit to prevent dispersion. The filter units were maintained at a constant temperature of 25 ºC and incubated for a total of 84 days. Leaching and collection of the leachates for determination of mineralized N (NH_4^+-N and NO_3^--N) was performed after 1, 3, 7, 14, 21, 28, 42, 56, 72 and 84 days of incubation. It was assumed that the initial leaching of the treated soil removed any initial inorganic N contained in the soil. The volume of the leachates was determined by weighing the leachate collected in the vacuum flask and mineralized N calculated on the basis of soil weight.

For determination of soil C mineralization potential after each leaching event, the filter units were placed in sealed mason jars and the headspace swept with CO_2-free air. Changes in the CO_2 concentration in the head space of the jar due to soil CO_2 evolution was then determined after a period of approximately 45 hours using a gas chromatograph (GC) (Buck Scientific Inc., East Norwalk, CT, USA) fitted with a thermal conductivity detector (TCD).

Soil water holding capacity (WHC) represents the water available for plants in the soil and can be estimated by the difference between field capacity (FC) water content and wilting point (WP) water content (Veihmeyer and Hendrickson, 1955). The treated soils were collected from each of the filter units used in the incubation study and changes in soil water-holding capacity due to the addition of the organic amendments were determined using the pressure chamber technique (Dane and Hopmans, 2002). Three replicates of each soil sample were saturated with tap water on a porous ceramic plate which was then placed in a closed pressure chamber. Due to the sandy loam textural class of the bulk soil, the amount of pressure applied to approximate FC was -10 kPa and to determine WP was -1500 kPa of pressure which were maintained for five days until the soil water content in the samples was equilibrated. Samples then were removed from the chamber, weighed, placed in an oven at 105°C for 24 hours and then weighed again for determination of gravimetric soil water content.

Soil samples were also collected periodically over the growing season at depths of 0-15 cm and 15-30 cm to determine the effects of the treatments on gravimetric soil water content. During the growing season of 2006-07 in the potato trials, soil samples were collected at 104, 125 and 149 days after planting (Dap), and since no major differences were found in this season, soil samples were collected earlier in the 2007-08 season starting after plant emergence at 41, 60, 83, 104 and 125 Dap. In both growing seasons soil samples were collected only in Kellhuiri, Vinto Coopani and San Juan Circa. In the quinoa trials, soil samples were collected only during the growing season 2007-08 and at 47, 68, 94 and 115 Dap. All field-moist samples were weighed, oven dried at 105°C for 48 hours, and then reweighed to calculate gravimetric water content.

Statistical Analysis

Data generated in all experimental plots and incubations trials were analyzed by using the SAS statistical program (SAS Institute, 2002-2003). The analysis of variance (ANOVA) was performed by using PROC ANOVA. Means were separated using Fisher's protected least significant difference (LSD) test at the probability level of $p \leq 0.05$.

RESULTS AND DISCUSSION

Participatory Workshops

Community members in the workshops mentioned several problems affecting their cropping systems including climate variability and soil related factors (Table 4.3) and they also stated some management aspects of the organic and inorganic amendments use (Table 4.4). Members of the four communities perceived that their agricultural lands are having lower soil fertility and are less productive compared to 10 or more years ago. Salinity problems were perceived only in San José de Llanga possibly due to the large proportion of land in this community with saline soils (Stacishin de Queiroz et al., 2001). Rocky areas are perceived as a problem by some farmers in Kellhuiri, and the presence of the rocks restricts land preparation and cultural practices. There is presence of a relatively shallow soil claypan in agricultural lands of Kellhuiri and San José de Llanga, limiting water infiltration and deeper plant root growth.

The community members have generally perceived that in recent times both the lower and higher elevation agricultural soils have been degraded by wind (San Juan Circa and San José de Llanga) and water erosion (Vinto Coopani). Individuals have observed more intense and frequent high wind velocities compared to 10 or more years ago. Most farmers mentioned that rainfall is now concentrated in fewer months and it is washing out topsoil, especially on cropped hillside lands. Overgrazing is considered to be affecting soil quality in Kellhuiri and San Juan Circa with greater impacts of this problem in the second community, which might be linked to higher tractor use in these low area communities. Shortening the fallow length is also believed as important soil related-problem in higher elevations, especially in Kellhuiri.

Among the crop production limitations that farmers observed, problems with soil quality and soil fertility were considered major limitations. Individuals strongly believe agricultural soils are getting less and less productive over time due to poor soil fertility management. More than the 90% of population in the high area communities (Kellhuiri and Vinto Coopani) and less than the 25% of the population in the low area communities (San Juan Circa and San José de Llanga) use manure as a source of organic fertilizer (sheep or cow alone or both mixed), and it is normally broadcasted-applied in the rows at planting time. Rates of manure application (average of 2.9 Mg ha^{-1} in high elevations and 0.8 Mg ha^{-1}in the low elevations) are lower than the recommended rate for the area which is 10 Mg ha^{-1} (FAO and SNAG, 1995).

Most of the community members (99%) of San José de Llanga, no one in San Juan Circa and less than 10% in Kellhuiri and Vinto Coopani use inorganic fertilizers (DAP and urea). Despite the widespread use of inorganic fertilizers in some communities, many of the farmers are not aware of the optimum application rates and timing for manufactured fertilizers. To reach the recommended mineral fertilization rate for potato crops in this region, 80 kg N, 120 kg P_2O_5 and 0 kg K_2O ha^{-1}, 261 kg ha^{-1} of DAP (18% N – 46% P_2O_5 – 0% K_2O) at planting and 72 kg ha^{-1} of urea (46% N) at hilling time should be applied. In the four communities DAP is applied less than 105 kg ha^{-1} and urea less than 45 kg ka^{-1}. In San José de Llanga, one third of the population applies urea at planting and DAP at hilling and in Kellhuiri; all farmers that use urea apply it at planting. Only farmers in San José de Llanga (23% of population) and in Vinto Coopani (3%) combine manure and chemical fertilizers.

In the relatively higher elevation communities, animal traction-powered tillage was typically used for all soil agricultural practices, although in some cases, depending on land size and resource availability, soil preparation could be combined with tractor tillage. In the lower communities, tractor-based operations were used for all soil agricultural practices.

Rainfall Distribution During Growing Season

The cumulative precipitations in the study area for the 2006-2009 growing seasons were similar. From potato planting to harvest during 2006-07 growing season, 365 mm of precipitation was received, during 2007-08, 388 mm was recorded and during 2008-09, 346 mm was registered (Figure 4.2). However, the distribution pattern differed among growing seasons with high rainfall concentration in February and March, 2007 and almost an even distribution from the middle of November, 2007 to the middle of March, 2008, and almost uniform distribution from the end of January to end of April 2009. These differences in rainfall distribution among growing seasons may have caused some variability on the effects of application of soil organic and inorganic fertilizers on soil properties.

Initial Soil Analysis

Chemical characteristics of initial soil in the field plots and of organic fertilizers are presented in Tables 4.5 and 4.6, respectively. In general, the soils in the field plots initially contained very low amounts of total organic C and total N during both growing seasons and at both elevations, confirming several reports about the low soil quality of agricultural lands of this region (FAO, 1999). In contrast, based on these soil test results, soil test P and K, exchangeable Ca and Mg would not be considered as limiting factors for plant production as reported by Westermann (2005). The lower content of some mineral nutrients in lower communities could possibly be attributed to the relatively greater use of tractor-based tillage, the presence of sandier soils and greater soil erosion caused mainly by wind.

For most of the chemical characteristics analyzed, no major differences were found between cow and sheep manure samples either at the higher and lower elevations (Table 4.6). Both manure types used during the 2006-08 growing seasons had relatively high proportions of total organic C, total N, total K and total P. However, higher concentrations of soil total C and total N were observed either in cow and sheep manure at higher elevations (Kellhuiri and Vinto Coopani) than those at lower elevations (San Juan Circa and San José de Llanga). Compost had less total organic C, than both manure types, and Biofert had higher total organic C and total N, but lower total P and total K than the other organic fertilizers.

Soil Chemical Properties During Growing Season

Results of selected soil properties analyzed in potato field trials at blooming time during both the 2006-07 and 2007-08 growing seasons and in both higher and lower elevations are presented in Table 4.7a. Soil pH, soil test P, total organic C and total N were not significantly affected by growing season and communities but were significantly affected by application of the organic and inorganic fertilizers. Exchangeable soil total Ca and Mg and the CEC were not affected by any factor. Soil pH was significantly increased with application of cow and sheep manure alone or when either manure was combined with fertilizer. This result confirms research that found increases in soil pH when farm manure (Clark et al., 1998) or organic and inorganic fertilizers were applied to agricultural lands (Mabuhay et al., 2006); although some studies observed very slight soil pH response to addition of either organic or inorganic fertilizers (Nastri et al., 2009), no differences in soil pH receiving organic, inorganic fertilizers or combination of both (Kaur et al., 2005), or even reduction of soil pH when green manure or farmyard manure was used in alkaline soils (Yaduvanshi, 2003).

In general, soil organic C and soil total N were increased by addition of organic and inorganic fertilizers either alone or combined together, although no clear significant effect was observed in soil organic C when sheep manure was added alone or combined with inorganic fertilizers and with Biofert. Similarly no significant effect on soil total organic C was observed when compost was added. In general, soil total N was significantly increased by additions of organic and inorganic fertilizer either alone or combined. These findings corroborate several similar studies in which a significant increase of soil total organic C and soil total N was detected with application of poultry manure (Hati et al., 2006; Agbede et al., 2008), combinations of organic amendments with inorganic fertilizers (Goyal et al., 1999) and through long-term inorganic fertilizer application (Haynes et al., 1998).

Soil P test significantly increased only when inorganic fertilizer alone and combined with either cow or sheep manure were applied. A similar increase of soil available P was observed when inorganic fertilizer, green manure or farmyard manure (Yaduvanshi, 2003), or manure or compost were applied (Eghball, 2004).

Significant interactions were found for the growing season and treatment factors on soil total inorganic N (TIN) (NH_4^+ -N and NO_3^- -N). In 2006-07 all treatments increased soil TIN, but in 2007-08 mostly treatments including inorganic fertilizers alone or combined with cow, sheep or both together significantly increased soil TIN.

Significant interaction was found for the community and treatment factors on soil total K (Table 4.7b). Soil total K was not significantly affected by treatments in Kellhuiri, but it was increased in Vinto Coopani although only with application of organic fertilizers, and it was increased in San Juan Circa and San José de Llanga by addition of organic and inorganic fertilizers either alone or combined together, although no significant effect was observed when compost was added. These results disagree with Kaur et al. (2005) who observed higher soil K in inorganic fertilized plots compared to plots receiving organic fertilizers with or without added chemical fertilizer.

Results for the residual soil chemical characteristics of quinoa field trials before planting time are presented in Table 4.8. In trials established in 2007-08 growing season, no significant interactions were found between communities and treatments and no significant differences among treatments for soil total N and for C:N ratio. Soil organic C and soil TIN were significantly greater in plots where cow or sheep manure were applied alone or combined both together or combined with inorganic fertilizers or Biofert in previous crop, although soil TIN content was greater in plots where inorganic fertilizers were applied alone or combined with organic fertilizers in the previous crop. The residual effect of treatments showed a significant increase in soil test P when inorganic fertilizers were applied alone or combined with cow or sheep manure alone or combined both together. This result complements research that found a residual effect of application of organic amendments on soil test P and inorganic N (Eghball et al., 2004).

Soil Potential C and N Mineralization in Incubation Experiments

Significant differences were observed among treatments for both the cumulative soil TIN (NH_4^+ -N and NO_3^- -N) and cumulative soil CO_2-C released (Table 4.9). In general, both cumulative soil TIN and soil CO_2-C mineralized increased as application rate of organic fertilizers increased from 0 to 30 Mg ha^{-1} (Figs. 4.3 and 4.4). These results support data from both the first year potato and second year quinoa field trials during both growing seasons and both elevations where higher soil total inorganic N was found under organic fertilizers application alone or combined at 10 Mg ha^{-1} rate compared to the control.

For the cumulative soil TIN mineralized, there were no significant differences among treatments at 7.5 Mg ha^{-1} rate; however, 15 and 30 Mg ha^{-1} of sheep manure combined with Biofert caused the highest accumulation followed by 15 and 30 Mg ha^{-1} of sheep manure (Fig. 4.3). For the cumulative soil CO_2-C mineralized, no significant differences among treatments at 7.5 Mg ha^{-1} was detected. Except for compost, 15 and 30 Mg ha^{-1} of sheep and cow alone and combined with Biofert showed significantly higher accumulation (Fig. 4.4). The 30 Mg ha^{-1} rate at each organic fertilizer was expected to generate higher accumulation of potentially mineralizable N, but sheep and cow manure generated higher accumulation than compost did. Except for compost, cumulative CO_2-C mineralized during incubation showed a linear increase as organic fertilizer rate increased from 0 to 30 Mg ha^{-1}. This result indicates higher soil microbial activity as organic fertilizer rate increases. Compost generated a sharp cumulative increase of CO_2-C until 15 Mg $ha^{-1}$was reached and afterwards a plateau trend was observed. Other research studies have also found increases in mineralizable C and N when farmyard, wheat straw or green manure were applied combined with inorganic fertilizers (Goyal et al., 1999). They also observed higher CO_2 evolved in soils receiving organic fertilizers with or without inorganic fertilizers and higher mineralizable N in soils receiving combinations of organic and inorganic manure (Kaur, 2005).

Soil Physical Characteristics

Bulk density

The bulk density in potato field trials before planting showed no significant differences between growing seasons but it did among communities (Table 4.10). For instance, averaging 2006-7 and 2007-08 growing seasons, in Kellhuiri and San Juan Circa lower soil bulk density (1.40 and 1.39 g cm^{-3} respectively) was detected than in Vinto Coopani and San José de Llanga (1.49 and 1.48 g cm^{-3} respectively).

Statistical analysis of the effects of treatments, communities and season on soil bulk density at harvesting time showed significant differences only among treatments (Fig. 4.5). In general, all plots treated with organic fertilizers had reduced soil bulk density compared to the control, confirming literature and several research studies that found beneficial effects of organic fertilizers on soil physical properties. Studies have observed lower soil bulk density and improved soil porosity as a consequence of organic fertilizers application (Agbede et al., 2008, Hati et al., 2006); although some research found no significant effect on bulk density in soils receiving compost composed of a mixture of chicken dung and sawdust (Yusuff et al., 2007), or receiving organic fertilizers combined with inorganic fertilizers (Benbi et al., 1998). Treatments including Biofert had the lowest bulk density confirming beneficial effects of Biofert on soil structure (PROINPA, 2005).

Soil bulk density in quinoa field trials were analyzed only at harvest time in the 2008-09 growing season, and results showed no significant interactions for communities and treatments and significant differences among treatments (Fig. 4.6). Soil bulk density was significantly lower in plots where organic fertilizers compared to control were applied in previous crop. These results might be related to the significant difference among treatments found for soil organic C. Sakar et al (2003) found decreases in soil bulk density, especially at 0-15 cm depth, when organic fertilizers were applied, although the decrease of soil bulk density was less when organic and inorganic fertilizers were combined.

Soil gravimetric water content

During the 2006-07 growing season, soil gravimetric water content in potato plots was determined at 104 days after planting (Dap) at 0-15 cm, and at 125 and 149 Dap at 0-15 cm and at 15-30 cm soil depths, and results of this analysis are presented in Table 4.11. No significant interaction was found for communities and treatments and among treatments at 104 and 149 Dap either at depths of 0-15 or 15-30 cm. At 125 Dap at the 0-15 cm depth, there was no significant interaction for communities and treatments but there were significant differences among treatments. In general, higher soil water content was observed when organic fertilizers were applied alone or combined with inorganic fertilizers. At 125 Dap at the 15-30 cm depth, a significant interaction for communities and treatments was observed. No significant differences among treatments were found in Kellhuiri, but in Vinto Coopani and San Juan Circa there were significant differences among treatments and in general significantly higher soil water content when organic fertilizers were applied with or without inorganic fertilizers.

In the 2007-08 potato field trials, soil gravimetric water content was determined in five sampling times at 41, 60, 83, 104 and 125 Dap at 0-15 and 15-30 soil depth, and results of this analysis are presented in Table 4.12. No significant interaction was found for communities and treatments in all sampling dates, but there were significant differences among treatments at 83 Dap at 0-15cm depth and at 125 Dap in both 0-15 and 15-30 cm depth, observing in general higher soil moisture content when organic fertilizers were applied with or without inorganic fertilizers. Research has also showed increase in soil water content as a result of straw and farmyard manure application (Zhao et al., 2009**)**.

In the 2007-08 quinoa field trials, soil gravimetric water content was determined at 47, 68, 94 and 115 Dap at 0-15 and 15-30 cm soil depth, and results of this analysis are presented in Table 4.13. There was no significant interaction for communities and treatments in all sampling dates, but significant differences among treatments were found at 47 and 68 Dap at 0-15 cm depth and at 94 Dap in both the 0-15 and 15-30 cm depths. In these occurrences, significant differences were detected among treatments with similar results as registered in both potato trials where there was higher soil water content when organic fertilizers were applied with or without inorganic fertilizers.

Water holding capacity of incubated samples

According to statistical analysis, no significant differences were observed among treatments of organic amendments when soil was at approximate field capacity (10 kPa), at wilting point (1500 kPa) (Fig. 4.7). However, there was a general trend showing higher soil water content at field capacity as organic fertilizer rate increased. This result agrees with studies that have detected increases in soil water-holding capacity with application of organic fertilizers (Sarkar et al., 2003; Mabuhay et al., 2006), or combination of farmyard manure with inorganic fertilizers (Benbi et al., 1998). In general, soil water content at wilting point was less affected by addition of organic fertilizers even at high rates (Fig. 4.7).

CONCLUSIONS

Initial and residual soil chemical properties, such as pH, soil test P, soil TN, soil TIN and soil organic C, and physical characteristics, such as soil gravimetric water content and bulk density, of agricultural lands at either relatively higher or lower communities in the central Altiplano were highly influenced by use of organic fertilizers, such as cow and sheep manure applied alone, combined both together, combined with Biofert or combined with inorganic fertilizers.

Increases of soil organic C due to application of cow and sheep manure alone, combined both together, combined with Biofert or combined with inorganic fertilizers may have significantly influenced the improvement of other soil properties such as soil gravimetric water content, soil bulk density and microbial activity at the initial and subsequent growing season in the communities in Umala.

The cow and sheep manure effects, when applied alone or combined with inorganic fertilizers or with Biofert, did not differ from each other on most soil chemical and physical properties; therefore, either manure type can be applied by farmers of the Altiplano as soil organic fertilizer. However, cow or sheep manure applications caused significant effects on soil chemical and physical properties when applied at recommended rates, and therefore these local organic sources could potentially reduce continuous soil degradation of this region or even increase soil quality of agricultural lands of the central Altiplano region if applied in adequate amounts.

Compost did not significantly improve soil chemical or physical properties of the Umala communities under field conditions and did not cause as high an increase in microbial activity compared to the cow and sheep manure tested in the research. Therefore, compost does not look like a promising alternative for this region or it may need to be tested for periods beyond two growing seasons.

Biofert combined with cow or sheep alone or with both together increased soil initial and residual soil chemical and physical properties compared to control, but its effect was not significantly higher compared to manure applied alone either under field conditions or during a laboratory incubation. Biofert is a newly released commercial fertilizer and further research may be needed to determine its potential impacts under the semiarid conditions of low and erratic rainfall and cold temperatures such as experienced in the central Bolivian Altiplano region.

Accumulation of potentially mineralizable C and N measured in an incubation experiment using soil from the field trials increased as rate of organic fertilizers increased from 0 to 30 Mg ha^{-1}. The observed rise in CO_2-C released as the rate of organic fertilizer application increased is a good indicator of higher soil microbial activity caused by these amendments. This measure of cumulative CO_2 is also a good measure of the soil active C pool which may be critical to improve the soil nutrient turnover in the agricultural lands of the Central Bolivian Altiplano, especially for soil N and P that are present in limited amounts in this region.

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Table 4.1. Recommended soil organic and inorganic fertilizers rate and total N, P and K applied in potato field trials in selected higher and lower Umala communities.

Treatment identification	Nutrient source and application rates	Total N	Total P	Total K
		---------------	kg ha^{-1}	--------------
T1	Control (unfertilized)	0	0	0
T2	DAP + Urea	80	52	0
T3	Cow manure (CM) (10 Mg ha^{-1} w.w. or 7.3 Mg ha^{-1} D.M.)	88	31	99
T4	Sheep manure (SM) (10 Mg ha^{-1} w.w. or 7.3 Mg ha^{-1} D.M.)	95	29	99
T5	CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1})	92	30	99
T6	Compost (5 Mg ha^{-1} w.w. or 2.9 Mg ha^{-1} D.M.)	35	9	21
T7	CM (10 Mg ha^{-1}) + DAP + Urea	168	83	99
T8	SM (10 Mg ha^{-1}) + DAP + Urea	175	81	99
T9	CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}) + DAP + Urea	172	82	99
T10	CM (10 Mg ha^{-1}) + Biofert (0.2 Mg ha^{-1} w.w. or 0.17 Mg ha^{-1} D.M.)	105	31	100
T11	SM (10 Mg ha^{-1}) + Biofert (0.2 Mg ha^{-1})	112	29	100
T12	CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}) + Biofert (0.2 Mg ha^{-1})	109	30	100

w.w.= wet weight basis; D.M.= Dry Matter

Table 4.2. Selected soil properties of the bulk soil from the Vinto Coopani community used for the incubation trial

	pH_s (0.01 *M* $CaCl_2$)	Total org. C	Total N	C:N ratio	Inorganic N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC
		---------- % --------			- mg kg^{-1}-	--------------------- mg kg^{-1} --------------------				$cmol_c$ kg^{-1}
Bulk soil	6.2±0.2	1.0±0.1	0.09±0.01	11±1	10.1±1.9	18±1	123±10	2132±130	435±29	16±0.8

Values represent the average and ± standard deviation of 3 replicates.

Table 4.3. Percentage of participants in the workshops that highlighted important soil related-problems in their cropping lands in the four communities of Umala Municipality.

		Rocky	Shallow	Low	Erosion		Shorter	Overgrazing
Community	Salinity	Soils	clay pan	fertility	wind	water	fallow	
	------------------------------ % ------------------------------							
High elevation communities								
Kellhuiri	-	14	14	30	-	-	65	21
Vinto Coopani	-	-	-	30	-	40	20	-
Low elevation communities								
San Juan Circa	-	-	-	30	40	-	-	40
San José de Llanga	80	-	80	20	30	-	-	-

Table 4.4. Selected characteristics of the average use of organic and inorganic amendments in four communities of Umala Municipality.

Community	Manure			Diammonium phosphate			Urea			Manure + chemical
	Proportion of those interviewed	Time of season	Rate of application	Proportion of those interviewed	Time of season	Rate of application	Proportion of those interviewed	Time of season	Rate of application	Proportion of those interviewed
	-- % --		Mg ha^{-1}	-- % --		kg ha^{-1}	-- % --		kg ha^{-1}	-- % --
High elevation communities										
Kellhuiri	92	Planting	2.4	8	Planting	104	8	Planting	41	0
Vinto Coopani	97	Planting	3.3	7	Planting	13	7	Hilling	13	3
Low elevation communities										
San Juan Circa	10	Planting	0.8	0	-	-	0	-	-	0
San José de Llanga	24	Planting	0.8	99	68% Pl, 32% Hill	56	99	33% Pl, 67% Hill	42	23

Source: Adapted from Gilles et al. (2009)

Table 4.5. Initial soil properties of the potato field trials in two growing seasons and in four communities of Umala. Samples were collected prior to planting and treatment application.

Year/ community	Total org C	Total N	C:N ratio	pH$_s$ (0.01 *M* CaCl$_2$)	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	------------ %	------------			----------------------	mg kg^{-1}		---------------------	cmol$_c$ kg^{-1}	dS cm^{-1}
2006-07										
Kellhuiri	0.9±0.0	0.08±0.01	12±3	5.2±0.1	35±9	232±10	690±33	84±9	7.5±0.1	0.4±0.2
Vinto Coopani	0.7±0.0	0.07±0.01	10±1	5.1±0.0	53±5	226±11	520±51	72±7	6.5±0.5	0.5±0.1
San Juan Circa	0.6±0.0	0.05±0.01	13±3	5.7±0.1	35±2	174±12	686±104	110±13	5.9±0.7	0.3±0.1
San José de Llanga	0.5±0.1	0.04±0.01	13±5	5.4±0.1	39±8	149±7	298±47	51±5	3.4±0.5	0.3±0.1
2007-08										
Kellhuiri	0.9±0.2	0.09±0.02	10±0	5.9±0.2	17±2	199±25	1965±125	171±22	12.6±1.2	0.2±0.1
Vinto Coopani	0.9±0.1	0.08±0.01	12±1	5.8±0.1	101±16	490±85	935±106	137±10	9.0±0.5	0.2±0.0
San Juan Circa	0.6±0.0	0.03±0.00	17±2	6.4±0.2	27±1	228±19	2312±337	330±47	15.5±2.0	0.3±0.1
San José de Llanga	0.8±0.1	0.08±0.01	10±1	7.6±0.2	15±1	152±18	2327±433	139±30	13.2±2.5	0.2±0.0

Values represent the average and ± standard deviation of 4 replicates of soil collected in each community.

Table 4.6. Selected properties of the organic fertilizers used in the field trials during the 2006 to 2008 growing seasons in Umala.

	Sheep manure[‡]						Cow manure[‡]					
Year/community	D.M.[†]	C:N ratio	Total org. C	Total N	Total P	Total K	D.M.[†]	C:N ratio	Total org. C	Total N	Total P	Total K
	-%-		------------------%--------------------				-%-		-------------------%------------------			
2006-07												
Kellhuiri	71.6	18	26.4	1.5	0.34	2.00	69.3	19	26.1	1.4	0.34	1.86
Vinto Coopani	68.1	18	18.6	1.1	0.45	0.97	71.9	14	23.9	1.7	0.41	0.73
San Juan Circa	69.1	17	25.9	1.5	0.54	1.62	82.6	16	21.6	1.3	0.77	2.90
San José de Llanga	76.8	27	15.0	0.6	0.36	0.65	68.3	27	15.1	0.6	0.43	0.76
2007-08												
Kellhuiri	70.4	14	26.6	1.9	0.40	0.71	70.6	14	31.6	2.2	0.44	0.84
Vinto Coopani	76.7	15	24.4	1.6	0.41	1.35	69.2	23	14.8	0.6	0.36	2.06
San Juan Circa	70.7	14	23.3	1.6	0.39	2.24	75.3	18	22.5	1.3	0.32	0.63
San José de Llanga	81.6	22	19.3	0.9	0.34	1.24	75.1	22	16.9	0.8	0.26	1.10
Compost[§]	58.8	11	13	1.2	0.3	0.7						
Biofert[§]	87.9	4	38	10.1	0.2	0.4						

[†] D.M.= Dry matter

[‡] One replicate sample of sheep and one of cow manure was collected from the bulk manure used for planting potato in each community.

[§] One replicate sample collected from the bulk used for planting potato. Same compost and Biofert material was used for both growing seasons.

Table 4.7a. Selected soil properties of potato field trials under organic and inorganic fertilizers averaged for Kellhuiri, Vinto Coopani, San Juan Circa and San José de Llanga community. Samples collected at blooming time during 2006-07 and 2007-08 growing seasons.

Treatments	pH_s (0.01 *M* $CaCl_2$)	Soil test Bray 1 P	Exch. Ca	Exch. Mg	Inorganic N‡ 2006-07	Inorganic N‡ 2007-08	Total organic C	Total N	CEC
		---------------mg kg^{-1}	--------------	--------------	--------- mg kg^{-1}	--------	---------%	---------	$cmol_c$ kg^{-1}
T1	5.9	33.5	1190	147	3.5	10.4	0.76	0.05	9.0
T2	5.7	63.3	1234	154	32.8	20.9	0.85	0.06	9.6
T3	6.1	40.3	1237	152	8.4	14.8	0.83	0.06	9.2
T4	6.2	41.6	1234	151	8.9	13.5	0.80	0.06	9.1
T5	6.1	39.3	1233	154	8.6	14.3	0.86	0.07	9.1
T6	6.1	41.0	1302	160	8.8	12.4	0.81	0.06	9.4
T7	5.8	66.5	1180	149	38.7	21.4	0.86	0.07	9.1
T8	6.0	59.1	1261	159	37.6	20.6	0.80	0.06	9.5
T9	5.9	60.9	1251	153	38.2	20.5	0.84	0.06	9.5
T10	6.1	39.5	1240	150	8.7	13.2	0.82	0.06	9.0
T11	6.1	43.1	1202	150	8.8	15.2	0.81	0.06	9.0
T12	6.1	41.6	1237	153	9.0	14.5	0.85	0.06	9.2
$LSD_{(0.05)}$†	0.1	7.0	NS	NS	4.3	4.8	0.06	0.01	NS

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

pH_s= (0.01 M $CaCl_2$). Except for the soil test K (Table 4.7) and soil inorganic N, not significant interaction for the growing season and community and treatment, not for the growing season and treatment, and not for the community and treatment were detected; therefore, averaged treatments results across communities are presented.

‡ Significant interaction were found between growing seasons and treatments for soil inorganic N

† Least Significant Difference Test ($P < 0.05$); NS = not significant.

Table 4.7b. Soil test K content of potato field trials under organic and inorganic fertilizers for the four communities in Umala. Samples collected at blooming time during the 2006-07 and 2007-08 growing seasons.

Treatments	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
	----------------------------mg kg^{-1}	----------------------------		
T1	267	378	178	132
T2	203	331	200	139
T3	228	443	250	229
T4	251	408	289	275
T5	208	466	254	204
T6	207	345	178	152
T7	246	374	248	218
T8	246	363	370	178
T9	235	361	229	204
T10	204	379	224	205
T11	227	457	288	210
T12	256	369	228	205
$LSD_{(0,05)}$ †	NS	88	79	46

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test ($P < 0.05$); NS = not significant.

Significant interaction for the community and treatments was detected for soil test K and therefore treatments results are presented by community.

Table 4.8. Selected soil properties of quinoa field trials due to the residual effects of adding treatments to the previous potato crop. Samples collected prior to planting during the 2007-08 and 2008-09 growing seasons in Umala communities.

	2007-08‡					2008-09‡	
	Organic C	Total N	C:N Ratio	Inorganic N	Soil test Bray 1 P	Inorganic N	Soil test Bray 1 P
	---------- % ----------			--------- mg kg^{-1} ---------		--------- mg kg^{-1} ---------	
Treatments							
T1	0.51	0.05	15	5.1	33.6	8.0	82.1
T2	0.56	0.05	14	8.8	43.6	12.8	109.1
T3	0.56	0.05	14	7.0	35.3	9.0	83.4
T4	0.56	0.05	13	7.1	36.1	8.5	89.5
T5	0.56	0.05	13	7.4	39.5	8.8	81.4
T6	0.53	0.05	15	6.4	33.8	7.7	83.2
T7	0.55	0.06	12	9.9	46.1	13.1	96.2
T8	0.58	0.05	14	10.9	40.6	12.3	89.6
T9	0.53	0.05	13	9.4	41.9	13.2	114.0
T10	0.56	0.05	14	7.3	34.4	8.2	87.5
T11	0.56	0.05	14	7.7	34.2	9.6	97.4
T12	0.56	0.05	14	7.4	34.4	9.0	102.6
LSD$_{(0.05)}$ †	0.04	NS	NS	1.8	7.5	1.7	23.4

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

‡ No significant interaction for the community and treatment were detected in 2007-08 and 2008-09 growing seasons; therefore, averaged treatments results across communities are presented.

† Least Significant Difference Test ($P < 0.05$); NS = not significant.

Table 4.9. Cumulative CO_2-C and total inorganic N mineralized due to different rates of soil organic amendments in four Umala communities.

	Rate (Mg ha^{-1})					
	7.5		15		30	
Treatments	Inorg N	CO_2-C	Inorg N	CO_2-C	Inorg N	CO_2-C
	-mg kg^{-1}-	- µg g^{-1}-	-mg kg^{-1}-	- µg g^{-1}-	-mg kg^{-1}-	- µg g^{-1}-
Soil organic amendments						
Sheep manure (SM)	480	3268	543	4835	589	6957
Cow manure (CM)	477	3038	506	4286	576	6862
SM + Biofert	502	3157	576	4719	626	6559
CM + Biofert	466	3315	472	4779	554	6504
Compost	477	2697	495	3193	539	3671
LSD $_{(0.05)}$ †	NS	NS	71	537	66	1099

† Least Significant Difference Test ($P < 0.05$); NS = not significant.

Table 4.10. Soil bulk density of potato field trials in four communities in Umala. Samples were collected before planting and application of treatments during the 2006-07 and 2007-08 growing seasons.

Growing season	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
	---------------------------- g cm^{-3}	----------------------------	----------------------------	----------------------------
2006-07	1.42±0.06[†]	1.50±0.04	1.36±0.08	1.49±0.07
2007-08	1.39±0.03	1.49±0.07	1.42±0.04	1.48±0.02

[†] Values represent the average and ± standard deviation of 4 replicates

Table 4.11. Soil gravimetric water content during the 2006-07 growing season under organic and inorganic fertilizers applied in potato trials in three communities in Umala.

Days after planting (Dap) [‡]	104[§]	125	125			149	
Depth (cm)	0-15	0-15	15-30	15-30	15-30	0-15	15-30
Community			Kellhuiri	V. Coopani	S.J. Circa		
	----------	----------	----------	%	----------	----------	----------
Treatments							
T1	27.1	7.8	7.0	6.1	8.1	8.0	8.5
T2	28.4	8.8	8.2	7.0	8.8	8.5	9.0
T3	29.2	9.3	8.4	6.6	10.8	9.2	9.6
T4	29.4	10.9	7.8	7.9	12.8	9.9	9.0
T5	29.9	10.4	7.8	8.0	13.1	9.7	9.8
T6	29.7	10.2	7.7	7.0	13.0	9.3	9.8
T7	29.0	10.1	8.8	8.3	12.5	8.7	9.6
T8	29.3	10.4	8.8	7.4	11.6	8.7	9.0
T9	29.6	9.3	7.6	7.2	12.4	9.0	8.4
T10	30.3	10.0	8.5	7.5	12.2	9.4	9.2
T11	30.0	11.0	7.9	8.2	12.2	10.2	9.7
T12	30.0	10.0	8.6	8.0	13.1	9.3	10.0
$LSD_{(0,05)}$ [†]	NS	1.6	NS	1.0	2.4	NS	NS

T1= Control, T2= DAP (18% N – 46% $P_{2}0_{5}$ – 0% $K_{2}0$) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

[‡] Except for the 125 Dap at 15-30 cm depth, no significant interaction for the community and treatment factor was detected; therefore, averaged treatments results across communities are presented.

[§] Samples collected only at 0-15 cm depth

[†] Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 4.12. Soil gravimetric water content during the 2007-08 growing season under organic and inorganic fertilizers applied in potato trials. Averaged results for Kellhuiri, Vinto Coopani, San Juan Circa community.

Days after planting (Dap) ‡	41		60		83		104		125	
Depth (cm)	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
	---------- % ----------									
Treatments										
T1	12.5	11.9	17.5	15.8	11.0	11.5	10.2	9.8	7.8	7.4
T2	12.5	11.8	18.4	16.5	12.2	12.4	10.4	10.8	8.3	8.2
T3	13.4	12.1	19.0	17.2	13.0	13.1	11.0	10.4	9.3	9.5
T4	13.5	13.0	19.6	16.5	12.6	12.3	11.4	10.2	8.4	8.9
T5	12.5	12.9	18.9	16.4	12.9	13.5	11.1	10.7	9.4	9.1
T6	12.7	12.6	18.9	16.5	12.8	13.0	11.3	11.0	8.8	9.0
T7	13.6	12.2	19.1	16.8	12.6	13.1	11.0	10.5	8.8	8.5
T8	12.5	13.0	17.7	16.7	12.1	12.7	10.3	10.8	9.0	8.9
T9	13.2	12.5	18.7	16.5	12.5	13.3	11.5	11.1	9.6	9.5
T10	13.3	11.8	17.7	15.0	12.8	12.8	11.5	11.1	9.5	8.7
T11	12.6	13.8	17.8	16.7	12.3	12.8	11.0	10.8	8.4	9.5
T12	13.2	12.7	19.0	16.8	12.6	13.1	10.9	11.2	8.9	8.4
$LSD_{(0.05)}$ †	NS	NS	NS	NS	1.8	NS	NS	NS	1.4	1.7

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

‡ No significant interaction for the community and treatment factor was detected; therefore, averaged treatments results across communities are presented

† Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 4.13. Soil gravimetric water content in quinoa trials during the 2007-08 growing season due to the residual effects of organic and inorganic fertilizers applied to the previous potato crop in Umala communities.

Days after planting (Dap)[‡]	47		68		94		115	
Depth (cm)	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
	----------	----------	----------	----------	%	----------	----------	----------
Treatments								
T1	15.8	16.8	15.6	16.6	15.3	15.2	6.4	5.7
T2	16.6	17.7	16.4	17.8	16.6	16.2	7.1	6.2
T3	16.6	17.4	18.0	17.9	17.9	17.4	7.4	6.8
T4	17.6	19.8	17.6	18.4	18.6	17.9	7.8	7.4
T5	17.8	17.9	18.4	17.7	17.4	18.4	7.3	6.8
T6	17.4	17.8	17.8	17.9	17.4	17.9	7.6	7.2
T7	17.8	19.2	18.3	18.5	16.8	17.5	7.2	7.3
T8	18.3	17.7	18.0	18.4	17.4	17.5	7.6	6.8
T9	18.4	18.5	18.5	18.3	17.0	18.2	8.0	7.6
T10	17.4	18.1	18.0	18.2	17.5	16.2	7.9	6.9
T11	18.4	18.2	18.4	18.4	18.1	17.0	7.0	6.4
T12	17.6	18.0	17.5	18.1	16.9	16.8	7.1	6.6
$LSD_{(0.05)}$	1.7	NS	1.7	NS	1.4	1.7	NS	NS

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

[‡] No significant interaction for the community and treatment factor was detected; therefore, averaged treatments results across communities are presented

[†] Least Significant Difference Test ($P < 0.05$); NS = not significant

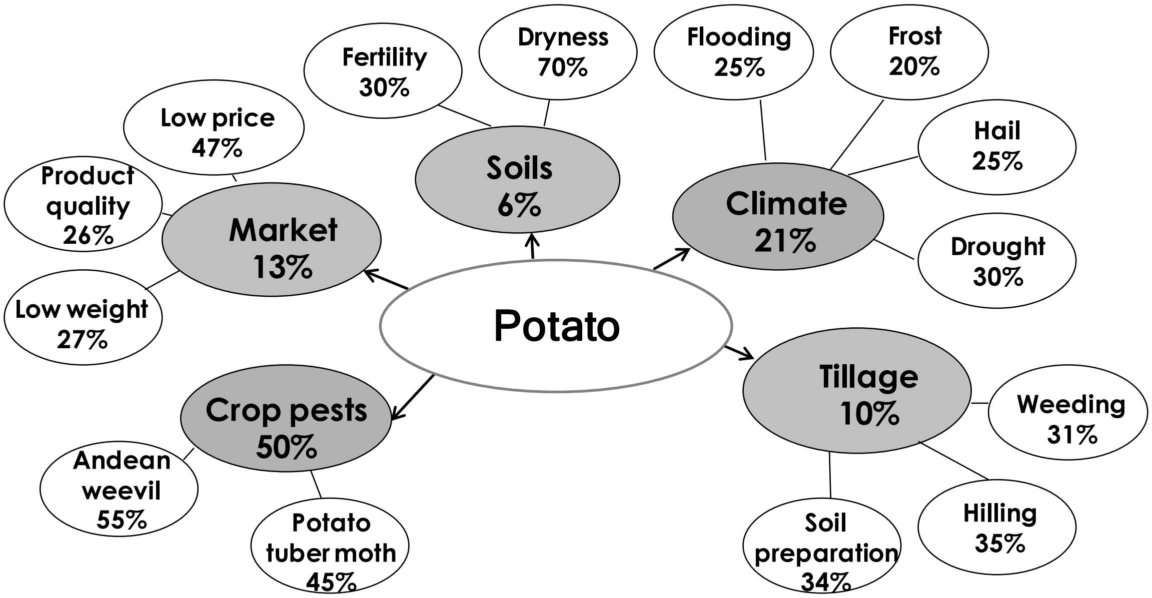

Figure 4.1. Potato production restrictions identified by farmers of San Juan Circa community through the tree problem methodology. Colored circles represent main restrictions and hollow circles represent specific information related to main restrictions. Main and specific restrictions are ranked by importance on a 0 to 100% scale.

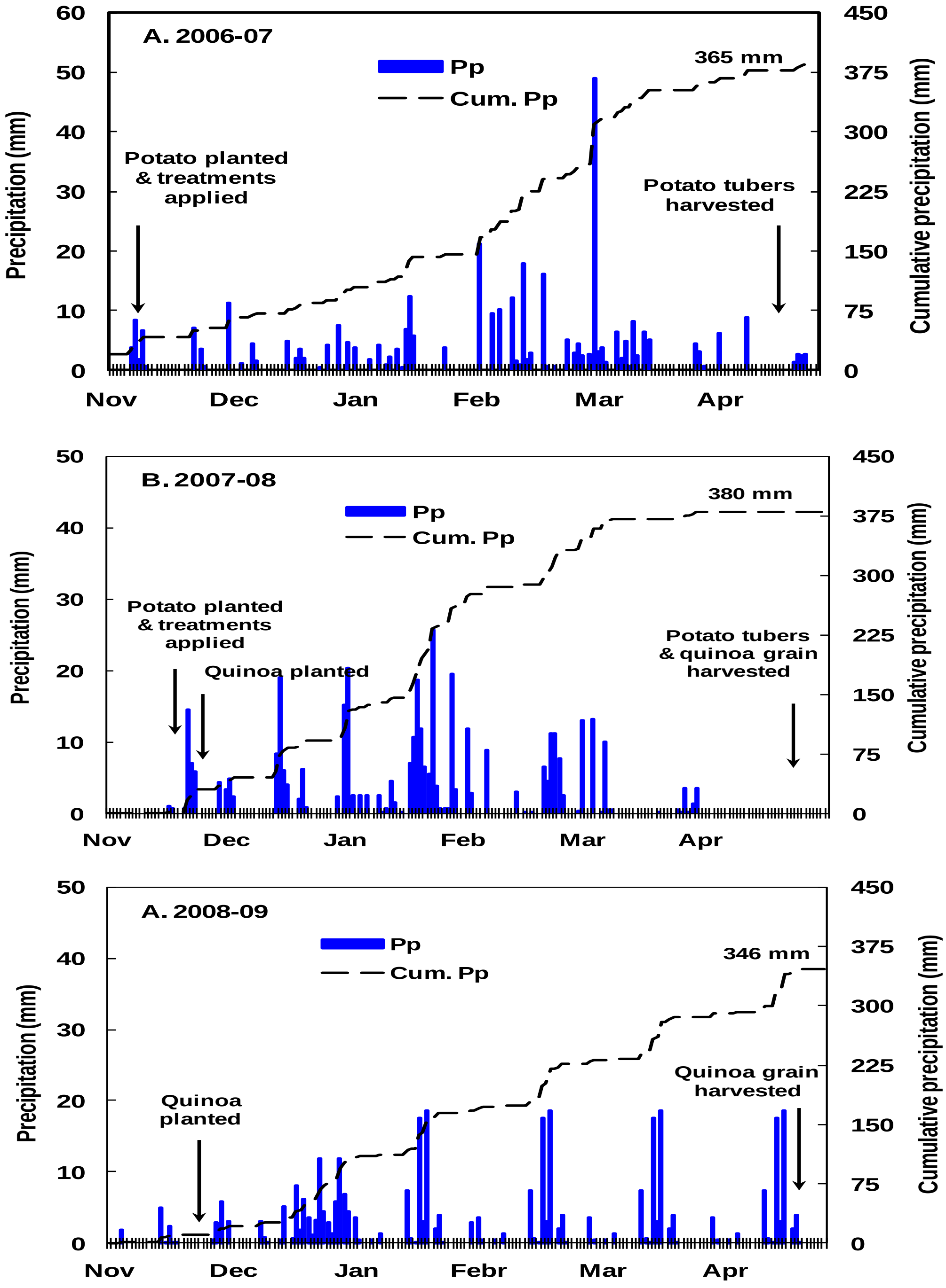

Fig. 4.2. Daily and cumulative precipitation during the 2006-2009 growing seasons in the Umala communities. The solid lines represent daily rainfall events. The dashed line represents the cumulative precipitation from the time of planting and application of treatments to harvest time.

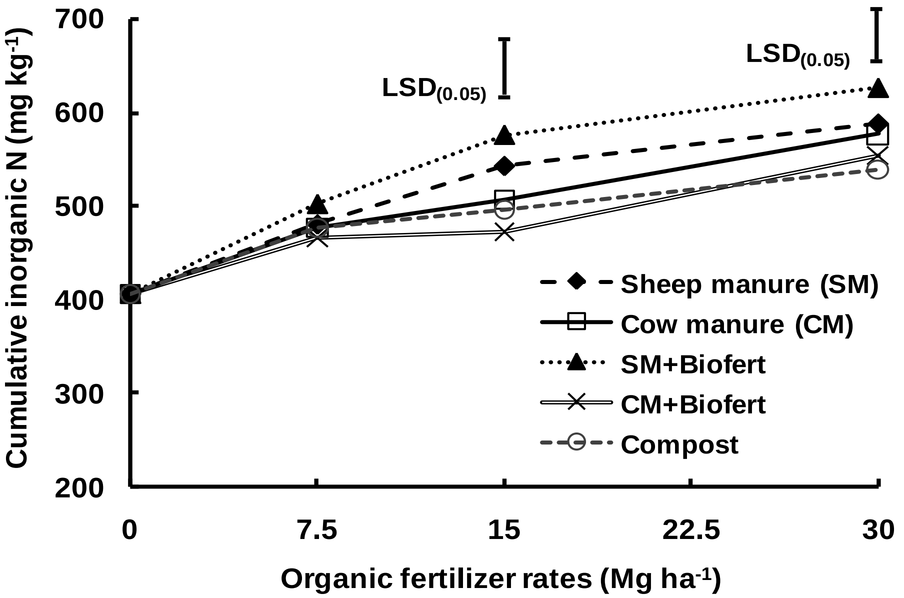

Figure 4.3. Cumulative soil inorganic N (NH_4^+ -N and NO_3^- -N) by effect of different rate of organic fertilizers.

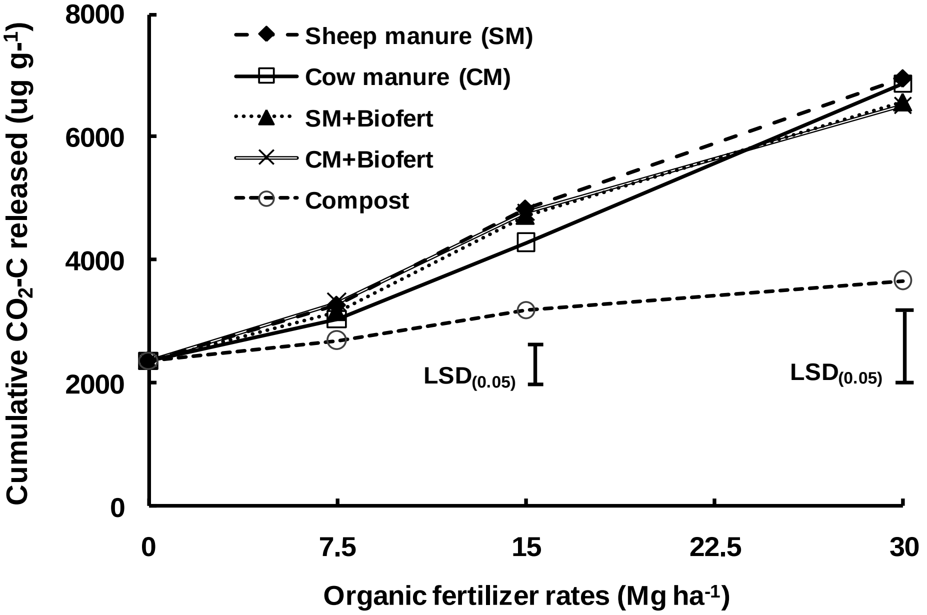

Figure 4.4. Cumulative soil CO_2-C generated by effect of different rates of organic fertilizers.

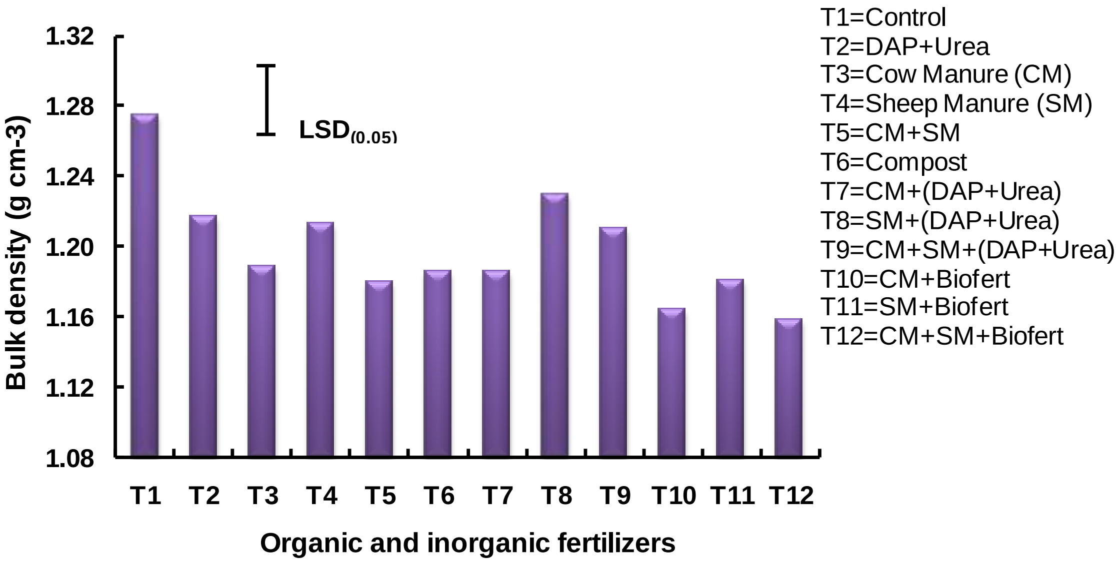

Figure 4.5. Soil bulk density of potato field trials under organic and inorganic fertilizers. Samples collected before harvest. Significant differences were only among treatments; therefore, data is presented averaged over growing seasons and communities of Umala municipality.

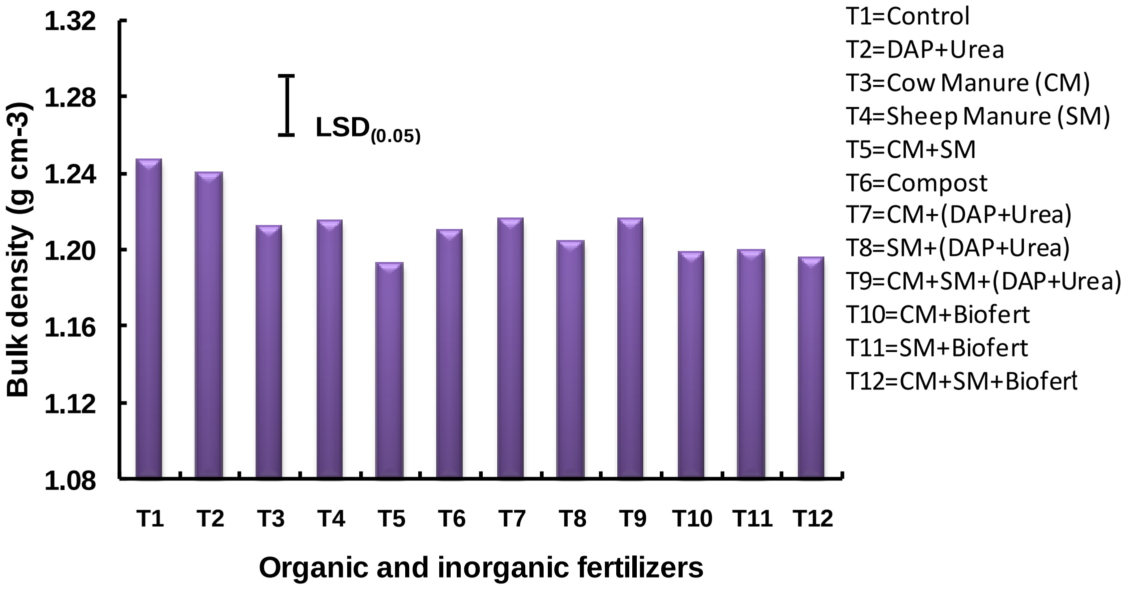

Figure 4.6. Soil bulk density of quinoa field trials established on harvested potato fields under organic and inorganic fertilizers. Samples collected before harvesting. Significant differences only among treatments; therefore, data is presented averaged for growing seasons and communities of Umala municipality.

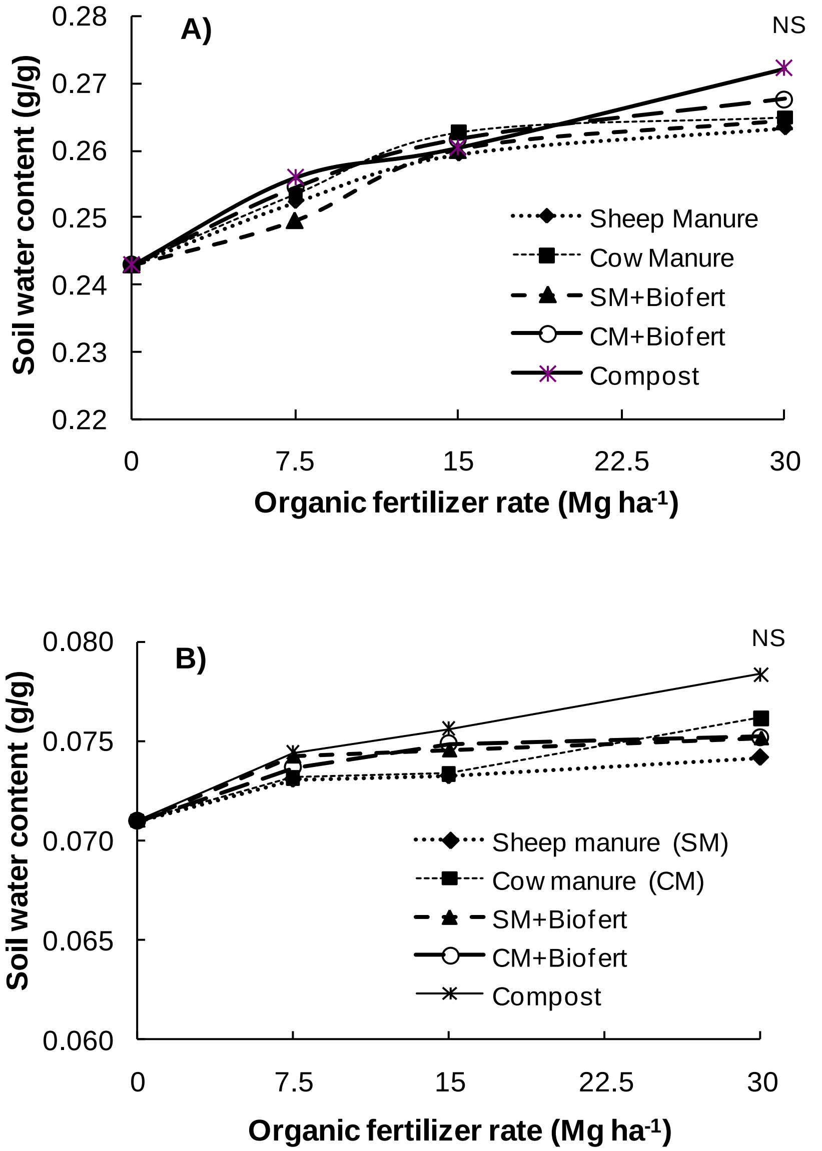

Figure 4.7. Soil of Uama at A) approximate field capacity (-10 kPa) and at B) wilting point (-1500 kPa) as result of different organic fertilizers and at different rates after 84 days of incubation. NS= Not significant.

CHAPTER 5

INITIAL AND RESIDUAL EFFECTS OF SOIL ORGANIC AND INORGANIC FERTILIZERS ON CROP PERFORMANCE IN A POTATO-BASED CROPPING SYSTEM IN THE BOLIVIAN ALTIPLANO

ABSTRACT

A study to determine the initial and residual effects of inorganic and organic fertilizers on potato (*Solanum tuberosum* L.) and subsequent quinoa (*Chenopodium quinoa*, Willd) crop performance was conducted in four indigenous communities in the central Andean highland (Altiplano) region of Bolivian during three growing seasons starting in 2006. On-farm trials using local crop management practices had an unfertilized control and separate and combined treatments of local and alternative organic sources (i.e., composted cow and sheep manure, household compost and Biofert, a solid biofertilizer), and inorganic fertilizer (diammonium phosphate+urea applied at 80 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 0 kg K_2O ha^{-1}). The manure treatments were applied at a rate of 10 Mg ha^{-1} (wet weight basis with an average dry matter of 73.1% across locations and years), the compost treatment was applied at a rate of 5 Mg ha^{-1} (wet weight basis with a DM of 58.8%, and the Biofert treatment was combined with the manure and compost and applied at an application rate of 0.2 Mg ha^{-1} (wet weight basis with a DM of 87.9%). The treatments were arranged in a randomized complete block (RCB) design with four replications. Treatments including inorganic fertilizer alone or combined with cow and sheep manure significantly increased potato and quinoa plant growth, total and marketable potato tuber size yield and total quinoa grain yield and the highest economic returns compared to that of control plots. These four treatments increased tuber yields

67, 68, 79 and 74% over the yield observed in the control plots. The residual effect of these treatments also increased quinoa grain yield 61, 58, 44 and 58% over that of the control. These results are possibly due to the more rapid nutrient availability of applied inorganic fertilizers compared to the application of organic amendments. The application of inorganic fertilizers also resulted in higher soil total inorganic N ($NO_3^- + NH_4^+$) and soil test P compared to the organic sources in the potato and in the subsequent quinoa crop trials. Farmer evaluation of relative crop growth at blooming and harvest time indicated a general preference for treatments combining inorganic and organic fertilizers. Application of household compost did not increase plant growth and tuber yields either in the initial or residual years of application which caused a negative economic return.

INTRODUCTION

Cropping and Nutrient Management Practices

In the Bolivian Altiplano, the rural indigenous population is predominantly engaged in small–scale rain-fed farming, where crops are planted only once a year most often during late spring or early summer (November/December). The production system normally initiates with potato followed by one or two years of small grains, such as quinoa, barley or oats and then succeeded by a relatively long fallow period (up to 10 years) or by perennial grasses (Hervé, 1994). This fallow practice is mainly utilized to restore soil fertility due to the accumulation of organic material through the re-growth of natural vegetation. The progressive and spontaneous re-growth of the natural vegetation increases soil microbial diversity and activity and stores mineralized nutrients in the plant biomass. After fields are tilled the biomass of the natural vegetation is incorporated into the soil and it decomposes providing nutrients and restoration of soil fertility (Pestalozzi, 2000).

In this region, potatoes are usually the only crop fertilized in the rotation due to its major importance as a source of food and income (PROINPA, 2005) and because of its high nutrient requirements during the growing season (Westermann, 2005). A certain portion of nutrients applied to the potato crop is expected to remain in the field after the crop is harvested for subsequent crops in the rotation. However, the amount of residual nutrients may depend on several factors, including the type and amount of fertilizers applied, plant requirements and utilization during the growing season, climate during the growing season, yield, crop residue management and soil characteristics (e.g., drainage, CEC).

There is strong evidence of residual effects of organic fertilizers that last for several years (Eghball et al., 2004). This residual effect of organic amendments improve long-term soil and crop productivity through the gradual release of soil nutrients over several growing seasons (Sharma et al., 1991**)**. There is also evidence of residual effects of inorganic fertilizers on soil and crop productivity (Condori et al., 1997), although their residual effects may last less time than organic fertilizers, especially for nutrients such as N.

In general, individuals of the Bolivian Altiplano continuously face low crop productivity due to several factors, including adverse climatic conditions, high incidence of pathogenic crop pests and diseases, and low soil fertility (PROINPA, 2005). Research in this region has reported low levels of soil N, P, and total organic C (less than 1%) (FAO and SNAG, 1995), although moderate to high levels of soil K were detected

(Hervé, 1994). Many authors have stated that nutrient management is important for enhancing short- and long-term soil fertility and for improving crop production or crop profitability (Lang et al., 1999). Selection of the appropriate source, timing, placement and application rate of plant nutrients is critical to optimize crop productivity while minimizing any potential negative environmental effects from excess nutrients entering into the environment (Westermann, 2005; IPNI, 2010).

Farmers of the Bolivian Altiplano perceive varied factors causing soil degradation of their agricultural lands. Among those factors, the rough topography of this region with the presence of steep slope areas apparently is inducing water runoff and soil erosion (Table 4.3, Chapter 4). The harsh climatic conditions of this region, such as the low temperature (average of 7 - 11°C) and low precipitation amounts (average of 300 - 500 mm) (FAO and SNAG, 1995, Garcia et al., 2007) and the erratic distribution of precipitation throughout the year, may restrict soil microbial diversity and activity (Sivila de Cary and Hervé, 1994). This decrease in soil microbial diversity and activity causes a decrease in the rate of soil C and nutrient mineralization (Sivila de Cary and Hervé, 2006). Moreover, the combined effect of water shortage due to low precipitation amounts with high rates of evapotranspiration and low water retention capacity of soils of this region are leading to reduced crop productivity (Garcia et al., 2003; Garcia et al., 2007), considering crop water requirements are in the order of 700 mm for potato (Vacher et al., 1988) and 500 mm for quinoa crops (Tapia, 1997; Garcia et al., 2003).

Many current soil and crop management practices practiced in the central Altiplano, such as the excessive use of tractors as primary tillage system, the little or no crop residue returned to the soils, the removal of native vegetation, and the inappropriate timing and use of suboptimal rates of inorganic and organic soil fertilizers, are causing reductions in the already low soil organic C content of agricultural soils in the region (FAO and SNAG, 1995; Bottner et al., 2006) thereby enhancing soil degradation. Moreover, due to the high price and low availability of manufactured fertilizers, farmers of this region generally rely on manure application as a main source of crop nutrients, although the limited availability of manure and the high labor requirement for loading and transporting manure to agricultural fields are limiting utilization of this nutrient source (Gilles et al., 2009).

In general, farmers of the Bolivian Altiplano apply low rates of composted sheep or cow manure alone or mixed both, and some farmers combine these organic fertilizers with low amounts of inorganic fertilizers (Gilles et al., 2009). Organic soil amendments used in this region primarily consist of composted sheep and dairy cow manure which are produced by livestock owned by the respective farm household, and the availability of these manures depends on the number and type of livestock and labor available for collection and transport (Gilles et al., 2009). Organic amendments are often less convenient to use due to the difficulty and extra labor requirements in the collection, handling and application of these low-analysis materials (FAO and SNAG, 1995). Moreover, in these semi-arid regions, several competing uses exist for manure resources such as fuel and construction demands, which reduces the availability of these materials for land application (Motavalli et al., 1994).

Importance of Potatoes in Bolivia

The potato has been cultivated in the Bolivian Andes region for thousands of years and is one of the most important food crops in Bolivia (FAO, 2008). Around

200,000 farmers of Bolivia, the majority of them small landholders, grow potato, mostly for household consumption, on approximately 135,000 hectares of land (FAOSTAT, 2008). Because of the high climatic risk for crop failure, most Andean farmers principally grow native potato varieties or introduced well-adapted varieties with good past performance in the region. In the past decade, potato production has increased in Bolivia due to a higher population demand and relatively better crop productivity, but the recent increase in importation of grains, such as wheat and rice, is generating strong competition for potato producers, especially in urban markets (FAOSTAT, 2008). In the Bolivian Andean region, farmers rely on potato as a source of food and income, especially for small landholder producers. Potatoes are consumed in higher proportion in the rural than the urban areas of Bolivia, either as a fresh or dehydrated product (PROINPA, 2005).

Potato is produced on relatively large amounts of land in Bolivia; however, average tuber yield is the lowest compared to rest of the Latin American countries (FAOSTAT, 2008). A recent agricultural production bulletin for Bolivia reported that a total of 754,851 Mg of fresh potato was produced on approximately 135,577 ha in 2007 with an average yield of 5.6 Mg ha^{-1}, which is below the Latin American (16.3 Mg ha^{-1}) and worldwide (16.8 Mg ha^{-1}) tuber yield (FAOSTAT, 2008). Among the several factors contributing to low potato crop productivity in the Bolivian Altiplano, include the farmers' lack of knowledge of soil fertility strategies may be significantly contributing to a low soil organic matter content (i.e., less than 2%) in most agricultural lands of this region (FAO and SNAG, 1995), leading to poor crop performance.

Optimum potato plant growth and production depends on several factors including adoption of effective nutrient management that is suitable for the local environmental conditions. Frequent occurrence of drought under the semi-arid climate of the Altiplano and frost damage due to the high altitude of this region and high incidence of insect pests are major limitations for potato growth in this region (PROINPA, 2005; Garcia et al., 2007). The potato crop requires relatively large amounts of nutrients mainly because of its shallow root system and short growing time; therefore, rapid availability of plant nutrients at critical vegetative and reproductive growth stages of potato is crucial for obtaining high tuber yield (Lang et al.1999; Westermann, 2005).

Reported nutrient removal due to potato harvest in the Altiplano varies considerably due to large variation in tuber yields in this region. The International Potato Center (CIP) reported that for a tuber yield of 10 Mg ha^{-1} removal of plant nutrients was approximately 160 kg N ha^{-1}, 17 kg P ha^{-1} and 154 kg K ha^{-1} (CIP, 1981), but Tocagni (1986) for the same expected tuber yield **(**10 Mg ha^{-1}) found an average nutrient extraction of 101 kg N ha^{-1}, 37 kg P ha^{-1} and 178 kg K ha^{-1}. Camara et al. (2007) cited several studies regarding potato plant nutrient extractions from soil based on crop yield. For a potato fresh yield ranging from 27 to 34 Mg ha^{-1} the nutrient extraction ranged from 125 to 140 kg N ha^{-1}, 50 to 56 kg P ha^{-1} and 246 to 263 kg K ha^{-1} and for a yield ranging from 53 to 57 Mg ha^{-1} the nutrient extraction ranged from 207 to 290 kg N ha^{-1}, 22 to 61 kg P ha^{-1} and 316 to 498 kg K ha^{-1}. In a large study performed in Bolivia, estimated nutrient removal by 1 Mg ha^{-1} of fresh tuber was 3.2 kg N ha^{-1}, 1.8 kg P_2O5 ha^{-1} and 6 kg K_2O (FAO and SNAG, 1995).

Numerous research studies have been conducted in the Bolivian Altiplano region on the effects of different rates of chemical and organic fertilizers on selected soil properties and on crop growth and production, but results of most of these studies were not published and this information is not easily accessible. For example, a combination of inorganic and organic (manure) soil fertilizers applied in potato plots showed 60% and 300% increased potato tuber yield compared to the inorganic fertilizer alone and the control plot respectively (FAO and SNAG, 1995), and the application of manure, compost or chemical fertilizer alone did not significantly increase tuber yield (Lorion, 2004). However, few studies have examined the residual effects of inorganic and organic fertilizers and have also included community participation in evaluating the agronomic and economic results of fertility treatments.

The objectives of this research were to: 1) identify local and alternative sources of organic fertilizers that improve potato growth and yields, 2) assess the residual effect of nutrient amendments applied to a previous crop on quinoa as a subsequent crop in the rotation, and 3) evaluate the relative performance of each fertility treatment based on economic return and local criteria determined by community members.

MATERIALS AND METHODS

Experimental Design

Description of the study area can be found in Chapter 2, the methodology of participatory workshops and selected characteristics of the potato and quinoa field trials and treatments used in this research are explained in detail in Chapter 4 of this thesis.

Agronomic Evaluations

Agronomic measurements in potato and quinoa experimental trials were performed during the 2006-2009 growing seasons. For the potato crop, plant emergence percentage, plant height, foliar cover and potato yields and grades were evaluated, and for the quinoa crop, plant emergence percentage, plant height, foliar area, and grain yields were determined.

In potato trials plant emergence was visually assessed after planting time by counting the number of plants emerged over the number of seeds planted at 29, 36, 43, and 50 days after planting (Dap). Plant height was measured in nine plants per plot at 57, 71, 85 and 115 Dap from the soil surface to the last apical leaf insertion on top of the plant canopy. Plant foliar cover or foliar growth of 9 plants per plot were evaluated at 44, 58, 85, and 100 Dap by using a 90 cm x 70 cm frame containing hundred squares of 9 x 7 cm. The methodology consisted of counting the number of squares covered by at least 50% foliage.

In the quinoa trials, plant emergence was visually assessed at 15 Dap, plant height was measured at 120 Dap in nine plants per plot at blooming time, where plants express major physiological activity, from the aboveground portion until the last apical seedhead on top of the plant canopy. Only in the 2007-08 growing season, foliar area of 10 quinoa leaves per plot was determined at 60, 90 and 120 Dap. Digital pictures of collected leaf samples along with a standard were taken and saved into a computer. The standard, a black piece of cardboard with a known dimension, was used as reference to scale pictures to a real area. Through the Microsoft Photo Editor and the ImageJ programs, pixels were converted to an equivalent real area and the number of pixels covering a leaf was counted to estimate the total leaf area.

Crop Yield

Potatoes were hand-harvested after plants and tubers reached physiological maturity on April of both 2007 and 2008 in 5 m length from three central rows of the five plot rows. Right after harvesting, potato tubers were hand graded by farmers and for this particular study, tubers were grouped into marketable (35 – 65 mm diameter) and non-marketable (> 65 mm or < 35 mm diameter) sizes and fresh-weighed. In San José de Llanga community, due to a sudden tuber pest infestation in 2007 and farmers' time availability in 2008, potatoes were harvested by the field owner and data for this trial could not be recovered.

By the third week of April 2008 and 2009, when the quinoa seedheads were sufficiently dry, at approximately 15 to 20% of moisture content as reported as standard moisture content of most quinoa varieties at harvesting time (Arce and Reyes, 1976), plants were hand harvested in 5 m length from six central rows of the ten plot rows by cutting the aboveground portion of the plant. Seedheads were stored until harvesting time was over and they were hand threshed to separate the grain from the seedhead. Subsequently, they were air-dried for about 2 days to reach a commercial moisture content ranging from 12 to 15% and total grain harvest per plot was then determined and yields expressed on a dry weight basis. According to Arce and Reyes (1976), there is a tight relationship between the air-dry period of time and the final quinoa grain moisture content that farmers of the Altiplano region are very familiar.

Participatory Evaluations

Participatory evaluations were used to evaluate the agronomic effectiveness and economic practicality of the fertility sources during and at the end of the growing season. Through the preference order technique, farmers assessed each treatment at flowering time and harvest using their local criteria which included plant color, plant height, plant biomass, uniformity, stem thickness, early maturation, and number and size of tubers. The preference order technique allows researchers to perceive and understand how farmers assess and compare technologies by setting a preference order for each technology evaluated (Ashby, 1991). This approach is relevant when technologies are being designed and tested at local conditions, and this methodology mostly tells researchers what features or characteristics of evaluated technologies are important and to identify reasons for farmer's preference or rejection (Ashby, 1991). In addition, production costs per treatment were analyzed to determine the treatments that economically fit to local agroeconomic conditions.

An average of eleven farmers from each community evaluated all treatments at blooming and harvesting time during the potato crop trials. In all cases, the preference order technique was used to identify treatments that farmers prefer more according to their local criteria. Evaluation was done at blooming time based on treatment effects on plant growth since farmer's evaluation criteria involve plant's and flower's color and plant architecture or vigor. To facilitate farmers' evaluation, the four best treatments were detected by farmers according to local criteria, and among them the first, second, third and fourth most preferred were identified. The control treatment was also included in the evaluation as a mean of comparison with other treatments.

Data Analysis

All data collected in experimental trials were analyzed using the SAS statistical program (SAS Institute, 2002-2003). The analysis of variance was performed by using PROC ANOVA and comparisons among treatments were tested through Fisher's Protected Least Significant Difference (LSD) Test and the test for statistical differences among the treatment means were at $p \leq 0.10$. Simple linear regression analyses were performed to determine the relationship of soil total N, soil total inorganic N, soil Bray1 P and soil total K with the total fresh tuber yield.

RESULTS AND DISCUSSION

Participatory Workshops

Participants in each community agreed that potato, quinoa and forage are the most important crops in the region in terms of their importance as food sources, as sources of economic revenue and in terms of largest proportion of agricultural land devoted to their cultivation. Based on the results of the participatory workshops, climate, crop pests and diseases and soil quality were considered to be the most important factors limiting production of these three crops in the Central Altiplano region (Table 5.1). On a 0 to 100% importance scale and averaged across crops and communities, drought, frost and hail were considered to be the most important factors limiting production (32% importance) and farmers stated that those factors are changing with climate variability which is affecting crop productivity.

In relation to climate variability, community members stated that they had observed changes in the time of rainfall initiation at the beginning of the growing season and the general overall rainfall distribution during the growing season. According to them, twenty or more years ago, rainfall used to start between the beginning to middle of October but now rainfall starts the beginning or middle of November, causing greater risk for crop failure. This greater potential for crop failure is because delayed planting in November exposes younger plants to frost occurrence in February or March when plants are not big enough to withstand these adverse climate events. Another perceived change in climate was a greater concentration of rainfall in fewer months, exposing crops to greater drought stress and subsequent yield reductions. The participants in the workshops also observed that agricultural soils have been degraded by wind and water erosion thereby reducing crop productivity.

Crop pests and diseases were mentioned as common limiting factors in this region (24% importance) that decrease the quantity and quality of most crop production thereby reducing food availability and marketing opportunities (Table 5.1). Farmers perceived that crop pests and disease incidence are changing due to increasing climate variability which is increasing yield losses.

Community members stated that soil-related problems are significantly affecting the crop productivity of this region (21% importance) (Table 5.1). They perceived that agricultural soils are getting less productive over time mainly due to low soil fertility and local soil management practices, such as use of conventional tillage systems, suboptimal use of organic and inorganic fertilizers and removal of native vegetation which represents an important source of soil organic material. Farmers have also perceived some socioeconomic factors that restrict adoption of innovative soil and crop management practices including the high cost and availability of inorganic fertilizers or alternative organic amendments, and the suitability of new alternatives to their traditional agroecosystem.

According to the results of community level surveys, individuals of this region do not have a well-defined soil fertility strategy and often use suboptimal rates of local organic fertilizers (between 0.8 to 3.3 Mg ha^{-1}) and alternative chemical fertilizers (between 13 to 104 kg ha^{-1} of DAP and 13 to 42 kg ha^{-1} of urea), and have poor fertilizer application timing (Table 4.4, Chapter 4). For instance in the community of San José de Llanga, around 33% of the surveyed population applies urea at planting and DAP at hilling time. Less than 25% of the surveyed population in San Juan Circa and San José de Llanga use manure as a source of organic fertilizer compared to the more than 90% of those surveyed in Kellhuiri and Vinto Coopani who apply organic fertilizers. In San Juan Circa, farmers do not even use chemical fertilizers to supply nutrients (Table 4.4, Chapter 4). The optimum timing of DAP and urea application to potato fields is at planting and hilling, respectively but around 33% of interviewed farmers in San José de Llanga community applied DAP at hilling and urea at planting.

Although most farmer participants were knowledgeable about the short-time benefits of inorganic fertilizers on crop production, they were not aware of the several benefits of organic fertilizers on soil properties, and that may be why some farmers prefer to sell manure to neighboring communities instead of applying it to their agricultural lands.

Temperature and Rainfall

To monitor daily changes in rainfall and temperature over the growing season, a portable Vantage Pro2 weather station (Davis Instruments, Vernon Hills, IL) was set up at the beginning of the 2006-07 growing season in the San Juan Circa community (lower elevation community). In 2007-08, an additional portable Vantage Pro2 weather station was also installed in Vinto Coopani (higher elevation community).

Temperature and rainfall registered in Vinto Coopani (higher) and San Juan Circa (lower) communities over the growing seasons showed no major differences between both elevations (Figs. 5.1a, and 5.1b). In San Juan Circa, the average temperature was similar among the seasons, although in 2008-09 there were higher temperatures recorded in November, December and March compared to those recorded for the same months in 2006-07 and in 2007-08. In 2007-08 there were also more below freezing temperatures at the beginning and the end of growing seasons in November, March and April compared to the other two seasons. In Vinto Coopani, higher temperatures were registered in February and lower in November, March and April, 2007-08 than in 2008-09. Potato and quinoa were planted in late November in 2007-08 when temperatures below freezing had already passed. Low temperatures were recorded in late March and during April causing frost damage to both potato and quinoa plants but yields were not significantly affected because crop plants had started the senescence period.

In San Juan Circa, the cumulative amounts of precipitation among the three seasons from potato or quinoa planting to harvest were not considerably different (i.e., 365 mm in 2006-07, 380 mm in 2007-08, and 346 mm in 2008-09). However, the distribution pattern differed among growing seasons with a high rainfall concentration in February and March 2007, almost even distribution from the end of November, 2007 to the middle of March, 2008, and almost even distribution from the end of December 2008 to the end of April 2009. In Vinto Coopani, cumulative precipitation was different between the 2007-08 and 2008-09 growing seasons (i.e., 401 mm in 2007-08 season and 503 mm in 2008-09). The distribution pattern also differed between both seasons with more rainfall concentrated in the middle of the season in 2007-08 compared to that of the 2008-09 season.

In general across communities and growing seasons, higher rainfall amounts and lower temperatures occurred in Vinto Coopani (high community elevation) compared to that of San Juan Circa (low community elevation), and these differences may have caused some variability in potato and quinoa crop performance in response to the soil fertility treatments. However, the rainfall distribution patterns were not considerably different between the two locations.

Crop Agronomic Performance

Plant emergence

No significant interactions among all factors (i.e., growing season, community and fertility treatments) were observed for the potato plant emergence (%), and it was not significantly affected by growing seasons, communities and treatments factors (Table 5.2). Apparently organic and inorganic fertilizers that were applied at planting time appatently did not have any significant influence on potato crop emergence.

For the quinoa crop, there was not a significant interaction among all factors (i.e., year, community and fertility treatments) affecting plant emergence but significant differences among treatments were found (Fig. 5.2). The residual effect of all treatments across communities promoted higher quinoa plant emergence than in the control plots.

Plant height

For the potato plots, plant height was not affected by growing season but it was significantly affected by the interaction between community and treatment factors (Tables 5.3a and 5.3b). In all communities, organic and inorganic fertilizers treatments promoted taller potato plants than the control plots. In Kellhuiri, only treatments containing chemical fertilizers (T2, T7, T8 and T9) promoted taller plants than the control. In Vinto Coopani and San Juan Circa, all treatments, except for T6 (compost), produced taller plants than the control. In San José de Llanga, all treatments generated taller plants than the control. The fact that treatments containing inorganic fertilizers promoted taller plants across communities and growing seasons could be attributed to effects of inorganic fertilizers supplying plants with rapidly available N and P. In Chapter 4 of this manuscript, higher soil total inorganic N (NO_3^- and NH_4^+) and soil test P were also detected during both growing seasons of potato which might have significantly contributed to better plant growth.

For the quinoa crop, there was no significant interaction among factors (i.e., growing season, community and treatment), but there were significant differences among treatments on plant height. Except for T6, T10, T11 and T12, the residual effects of treatments containing organic or inorganic fertilizers applied alone or combined together (T2, T3, T4, T5, T7, T8, and T9) generated taller plants than the control. In general, the residual effects of T2, T7, T8 and T9 application generated significantly taller plants compared to that of the control, and these results are also supported by the higher soil total inorganic N (NO_3^- and NH_4^+) and soil test P found for the same four treatments in soil samples collected in quinoa plots before planting. Sandy soils have relatively low water-holding capacity, high infiltration rates and a relatively high potential for nutrient leaching losses. However, the relatively low amount of rainfall observed during both growing seasons at both elevations probably did not induce significant amounts of leaching of plant nutrients.

Plant cover and foliar area

Plant cover measurements were performed for the potato crops trials in 2006-07 and 2007-08 growing seasons. There was no significant interaction between community and treatment factors but a significant interaction was found for growing seasons and treatments at all measuring times (Table 5.4). At the beginning of both growing seasons (at 44 and 58 Dap) , higher plant cover was found in 2006-07 than in-2007-08 but the opposite happened as the growing season moved on (85 and 100 Dap) where higher plant cover was registered in 2007-08 compared to that observed in 2006-07. Apparently the lower amount of precipitation received from the beginning of January to the end of February in 2007 compared to same months in 2008, especially in the low area communities (Fig. 5.1a) could have affected the average growth of the potato plants. In general, except for T6 (compost), all treatments generated greater potato plant cover than the control plots. Research has also found that the effect of inorganic fertilizer (Adhikari and Shrama, 2004) applied alone or combined with organic fertilizer (Linus and Irungu, 2004) resulted in higher potato plant growth compared to control plots.

Foliar area was measured for the quinoa crop trials only for the 2007-08 growing season and results area presented in Table 5.5. At 60 Dap, no significant interaction was found between communities and treatments but there were significant differences among treatments on quinoa foliar area. Averaged across communities, except for T10 and T12, the residual effect of all treatments promoted higher leaf area than the control plots. At 90 and 120 Dap there was significant interaction among communities and treatments. Except for T6 at 90 and 120 Dap and T12 at 120 Dap, residual effects of all treatments promoted higher foliar area in low elevation communities (i.e., San Juan Circa and San José de Llanga) than the control plots; whereas in the high elevation communities (i.e., Kellhuiri and Vinto Coopani) only the residual effects of T4, T5, T7, T8, T9 and T10 generated higher leaf area than the control plots.

Quinoa seedhead diameter

The quinoa seed head diameter was determined only in 2007-08 growing season and before harvesting time. There was significant interaction between communities and treatments on the seedhead diameter and treatments results are presented in Table 5.6. In Kellhuiri, the seedhead diameter was not affected by residual effect of treatments, but it was affected by T8, T9, T11 and T12 in Vinto Coopani, and by T4, T7 and T11 in San Juan Circa. In San José de Llanga, except for T6, the residual effects of all treatments generated greater seedhead diameter than the control plots.

Crop Yield

Significant differences between growing seasons and among treatments were found for both the potato and quinoa trials, but no significant interactions were detected for growing season, elevation and treatments. There was higher average potato tuber yield in 2007-08 (12.4 Mg ha^{-1}) than in the 2006-07 (9.0 Mg ha^{-1}) growing season and higher yield in Vinto Coopani (11.7 Mg ha^{-1}) than in San Juan Circa and Kellhuiri (10.4 and 10.0 Mg ha^{-1} respectively) communities. There was higher quinoa grain yields in 2007-08 (0.37 Mg ha^{-1}) than in 2008-09 (0.29 Mg ha^{-1}) and higher grain yield in San Juan

Circa (0.34 Mg ha^{-1}) than in higher Kellhuiri and Vinto Coopani (0.23 Mg ha^{-1}) communities. The higher average tuber yield along with taller potato plants and higher potato plant cover found in 2007-08 than in 2006-07 growing season are most likely due to better initial soil properties, such as higher total organic C, total N and total K, exchangeable Ca and Mg and higher CEC (Table 4.5. Chapter 4) and maybe the higher rainfall and uniform precipitation amount registered in 2007-08 than in 2006-07. These advantages although were not reflected in better quinoa crop yield in 2008-09 than in 2007-08 growing season.

In the trials planted to potato and quinoa, all treatments generated higher total yields than the control (Figs. 5.4A and 5.4B). Higher total yields occurred when inorganic fertilizers were added alone (T2) or combined with manures (T7, T8 and T9). The same treatments also generated higher marketable tuber size but T3 (cow manure), T4 (sheep manure) and T7 (cow manure+DAP+urea) generated the highest non-marketable tuber size. In the potato trials, the T2, T7, T8 and T9 treatments generated 67, 68, 79 and 74% increase in total tuber yield and their residual effect on quinoa caused 61, 58, 44 and 58% increase in total grain yield over the control, respectively. Research has also shown greater potato tuber yield when inorganic fertilizer was applied alone or combined with organic fertilizer (Pervez et al., 2000; Romero-Lima et al., 2000; Hossain, 2003; Nyiraneza, 2007; CIP, 2008) or when half rates of inorganic fertilizers along with organic fertilizers were applied (Linus and Irungu, 2004). Under the rain-fed conditions of South America, Gandarillas (1982) mentioned by Johnson (1993) found significant quinoa production response to soil N.

Since soil N and P are limiting production factors in this region, addition of rapid plant available N and P through inorganic fertilizers, either alone or complemented by organic fertilizers had an important impact on potato and subsequent quinoa crop performance. Potato needs adequate amounts of N in its early growing stages to keep optimum shoot and tuber growth (Westermann, 2005), and adequate amounts of P to promote good root development and overall plant health (Lang et al., 1999). Tapia (1997) have reported a significant quinoa plant response to addition of N and P in agricultural Andean soils.

These results provide evidence of the existence of a residual effect of fertilizers, especially inorganic fertilizers, applied in potato on subsequent crops in this environment. Even though the soils studied in this soil had a high proportion of sand and would be vulnerable to nutrient leaching, significant amounts of residual soil total inorganic N was detected in quinoa plots before planting, which implies little inorganic N was lost. This effect could possibly be attributed to the low rainfall observed during and after each growing season. The same trend happened with soil test P (data presented in Chapter 4), where higher residual content in plots was observed where inorganic fertilizers had been applied (T2, T7, T8, and T9).

Compost did not significantly increase potato tuber or quinoa grain yield compared to the control plot because this organic fertilizer normally only gradually releases available N over time (Sullivan et al., 2002). Organic fertilizers combined with Biofert (T10, T11 and T12) also did not significantly affect potato plant height, plant cover and tuber yield compared to when the same organic fertilizers were applied alone (T3, T4 and T5).

As detected for plant height in both crops and similar trend for potato plant cover, the effects of sheep or cow manure alone or combined both together or any of these manures combined with inorganic fertilizers or with Biofert did not differ significantly on potato tuber and quinoa grain yield, therefore farmers of the highland areas of Bolivia can apply either of these manure types and can expect to have similar outcomes on crop performance.

Across communities and growing seasons and independently of specific treatment effects, a generally low (r^2=0.13, n=288; r^2=0.13 n=288; r^2=0.12 n=288; r^2=0.05 n=288) but significant positive linear relationship between the soil total N, soil total inorganic N, Soil Bray1 P, and soil total K with the total tuber potato yield was detected (Fig. 5.5). The stronger relationship between the soil total N, soil total inorganic N, and soil Bray1 P with the total tuber potato yield (r^2=0.13; r^2=0.13; r^2=0.12 respectively) than between the soil total K with the total tuber potato yield (r^2=0.05) probably reflects the importance of the addition of sources of N and P to the Umala soil that contains low levels of these minerals compared to the moderate to high levels of K (FAO and SNAG, 1995).

Participatory Evaluations of Crop Growth and Yield

Farmers evaluated the effects on plant growth of each soil fertility treatment at blooming and harvesting time during the potato trials. The local criteria for evaluating potato plants at blooming time was to evaluate the effects of treatments on plant and flower color and plant architecture and robustness. At harvest the local criteria was to observe effects of treatments on crop yield and marketable and non-marketable tuber size production. In both growing seasons and at each community, farmers showed different preference order among treatments either at blooming and at harvesting time as shown in

Table 5.7. Only the four best treatments selected by farmers at blooming and at harvest time and the control plots are presented. Across growing seasons and communities, T7, T8, and T9 were selected as the best treatments at blooming and at harvest time. Treatments T7, T8 and T9 are combination of manure and inorganic fertilizers, and those treatments along with T2 were the treatments that generated better plant height, plant cover and tuber yield. In general, farmers selected the mixed chemical fertilizer and manure treatments as their preferred treatment. At flowering time, a field day was held in which farmers from several communities in the region participated and heard talks from other farmers who presented information on their own experiences with the use of chemical fertilizers and organic soil amendments.

Cost Analysis

To determine the economic benefit of different fertilizer application, potato tuber yields of this study, total variable costs and average market price (1.24 Bs kg^{-1}) of different tuber sizes was used. Across growing season and communities, T2, T7, T8 and T9 generated the highest economic return in relation to the control (Table 5.8). These results indicate again the advantages of applying soil inorganic fertilizers with or without organic fertilizers. However, the complementary effects of organic fertilizers added in treatments T7, T8 and T9 may be seen over subsequent growing seasons as improving several soil properties.

CONCLUSIONS

Addition of the inorganic fertilizers, diammonium phosphate (DAP) and urea, at a fertilization rate of 80 kg N, 120 kg P_2O_5 and 0 kg K_2O per hectare either applied alone or combined with 10 Mg ha^{-1} (wet weight) of either cow or sheep manure or both mixed promotes important potato crop growth, produces higher total and marketable tuber yield and greater economic returns. The residual effects of these soil amendments significantly increase quinoa plant growth, foliar area and grain yield in higher and lower elevation communities of the Central Bolivian Altipano.

The early availability of nutrient supply (principally soil inorganic N and P) by the inorganic fertilizers either alone or combined with manure, may have promoted rapid initial potato plant growth which might have favoured crop performance throughout the growing season until the harvest.

All experimental trials where established in soils with a sandy loam textural class where inorganic N is more susceptible to leaching. However, the relatively low amount of precipitation received during the 2006-09 growing seasons (average of 399 mm) for both areas probably did not promote leaching of significant amounts of soil inorganic N and P, improving subsequent crop performance.

The higher potato and quinoa plant growth and potato tuber and quinoa grain yield with inorganic fertilizer application alone or combined with organic fertilizers compared to unfertilized plots and the other treatments is probably due to the higher soil total inorganic N (NO_3^- and NH_4^+) and soil test P detected during potato blooming and at pre-plant times prior to the quinoa trials. Andean crops in this region, such as potato and quinoa, are frequently grown under limited amount of soil nutrients mostly due to suboptimal rates of fertilizers applied by farmers; therefore, the addition of recommended rates of inorganic and organic fertilizers applied in both crop trials have significantly contributed to a better crop performance.

Farmers of Umala perceive that adverse climatic conditions, such as drought, for instance, significantly decrease crop productivity of this region and that further changes in climate can be detrimental for their cropping systems. However, the addition of recommended rates of inorganic fertilizer alone or combined with organic fertilizers could be promising alternatives to mitigate climate change effects since the direct and residual effects of these alternatives have shown good performance under low precipitation amounts received in both elevation communities during three growing seasons.

In the Umala communities, sheep or cow manure are applied in potato fields based on product and transport availability and they are applied almost in equal proportion, although some farmers prefer one over the another assuming better response. However, results of selected chemical properties analysis (Table 4.6, Chapter 4) and their effect on potato plant growth and tuber yield and subsequent quinoa crop performance did not significantly differ from each other. Therefore, farmers of higher or lower communities of Umala can use either of those manures as a source of soil organic fertilizers.

Applications of compost and the Biofert supplement did not show direct or residual effect on potato and subsequent quinoa plant growth and potato tuber or quinoa grain yield in higher and lower communities of Umala. This might be attributed in part to low rainfall amounts observed during the growing seasons influencing compost decomposition or N-mineralization. The relatively lower nutrient content of the compost and its possible slower release pattern may have also been a factor. The recommended rate of Biofert is relatively low (0.2 Mg ha^{-1}) and therefore its primary effect would possibly be with soil microbial activity but this effect was not measured and it did not affect observed agronomic performance. Among several components, Biofert contains *Mycorrhiza* fungi that make moisture and nutrient assimilation more efficient; especially of soil P which is not very mobile in soil solution and readily plant available; therefore, higher rates of application of this product may significantly improve the crop performance.

Farmers' criteria or preference on selecting best fertilizer alternatives varies between higher and lower communities and even within communities. In general, tuber production predominates over plant growth characteristics, and based on those criteria Umala's farmers selected the inorganic combined with organic fertilizers as a promising alternative soil fertility treatment for the region. Some Umala's farmers have being using a combination of inorganic and organic fertilizers for a long time, but with suboptimal rates and in some cases with an inappropriate application time which may reduce the fertilizers' effectiveness.

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Table 5.1. Important production limitation factors for selected crops perceived by farmers of four communities of Umala Municipality. Information gathered in participatory workshop conducted in each community. Potato, quinoa and forage are considered the most relevant crops in these communities.

	Kellhuiri			Vinto Coopani			San Juan Circa			San José de Llanga		
	Potato	Quinoa	Forage	Potato	Quinoa	Forage	Potato	Quinoa	Forage	Potato	Quinoa	Forage
	%											
<u>Climate</u>:	(20)[†]	(30)	(40)	(36)	(30)	(40)	(21)	(30)	(40)	(35)	(50)	(60)
Frost	25	20	-	20	20	-	20	30	-	50	10	20
Drought	40	30	100	38	40	50	30	15	70	30	40	70
Hail	20	-	-	30	30	37	25	45	30	20	10	10
Flooding	15	-	-	12	10	13	25	10	-	-	-	-
Late onset of raining	-	50	-	-	-	-	-	-	-	-	40	-
<u>Soils:</u>	(20)	(18)	(20)	(20)	(20)	(30)	(26)	(15)	(20)	(30)	(10)	(20)
Low fertility.	60	50	70	80	80	70	30	50	60	17	20	50
Rocky clayed	15	-	14	-	-	-	30	-	-	-	-	-
Local mgmt.	25	50	16	20	20	30	40	50	40	3	-	-
Salinity	-	-	-	-	-	-	-	-	-	80	80	50
Pests	(37)	(17)	(12)	(31)	(25)	(10)	(40)	(40)	(10)	(20)	(40)	(10)
Diseases	(10)	(15)	-	-	(20)	-	-	-	-	(15)	-	-
Others	(13)	(20)	(28)	(13)	(5)	(20)	(13)	(15)	(30)	-	-	(10)

[†] Data in parenthesis represent main problem and data without parenthesis represents the proportion of specific problem within a main problem. Sum of main problems per column or crop and sum of specific problems within a main problem total 100%. 54 farmers were interviewed among the four communities

Table 5.2. Potato plant emergence under organic and inorganic fertilizers effects averaged across growing seasons and across communities in Umala.

	Days after planting[‡]			
Treatments	29	36	43	50
	---------------------------- %		--------------------------	
T1	33	61	83	86
T2	37	61	83	86
T3	34	61	84	87
T4	36	61	81	86
T5	35	60	81	85
T6	38	64	85	88
T7	36	59	82	85
T8	36	61	84	86
T9	36	60	83	86
T10	37	64	85	88
T11	35	60	83	87
T12	36	63	84	88
$LSD_{(0.05)}$ [†]	NS	NS	NS	NS

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

[‡] Not significant interaction among factors (growing season, community and treatment) and among treatments was detected. Treatments results are presented averaged for growing seasons and communities.

[†] Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 5.3a. Potato plant height in two communities of the relatively high elevation area of Umala with application of organic and inorganic fertilizers averaged across growing seasons.

	Kellhuiri				Vinto Coopani			
	Days after planting							
Treatments	57	71	85	115	57	71	85	115
	------------------- cm ------------------				-------------------- cm ------------------			
T1	14.7	23.6	26.0	26.3	14.4	19.3	22.7	23.5
T2	17.4	29.2	33.3	36.2	20.3	28.5	33.3	36.3
T3	15.1	24.6	28.0	27.2	16.2	24.4	28.8	30.3
T4	14.9	23.9	27.7	28.7	15.2	21.9	25.3	28.5
T5	16.1	24.7	29.3	29.1	17.0	25.8	30.0	30.6
T6	15.5	24.3	26.9	26.2	15.7	20.7	24.1	24.8
T7	16.6	29.4	35.0	38.1	17.1	28.9	34.5	37.9
T8	16.4	30.4	37.7	39.0	18.1	32.7	39.6	42.4
T9	15.9	29.4	35.0	36.7	18.9	32.9	40.1	43.1
T10	15.3	25.4	28.8	29.2	15.8	24.5	28.7	30.6
T11	15.1	24.2	28.0	28.5	16.8	26.1	31.3	32.7
T12	14.7	24.6	28.4	28.9	15.8	25.0	30.5	32.5
$LSD_{(0.05)}$ †	1.6	2.9	3.2	3.5	2.4	2.9	3.4	3.4

T1= Control, T2= DAP (18% N – 46% P – 0% K) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test (P < 0.05); NS = not significant

Table 5.3b. Potato plant height in two communities of the relatively low elevation area of Umala with application of organic and inorganic fertilizers averaged across growing seasons.

	San Juan Circa				San José de Llanga			
	Days after planting							
Treatments	57	71	85	115	57	71	85	115
	-------------------- cm ------------------				--------------------- cm ------------------			
T1	21.4	29.7	32.8	32.7	22.9	29.3	31.4	32.4
T2	25.6	37.8	43.1	44.9	29.2	41.5	44.1	46.2
T3	22.0	30.0	33.1	33.5	25.8	33.4	35.9	36.6
T4	24.5	33.7	37.0	37.0	26.9	35.6	38.0	40.6
T5	23.2	32.8	36.5	36.6	24.5	32.8	35.7	36.6
T6	23.6	30.9	33.7	33.5	25.3	32.0	34.1	34.8
T7	25.5	36.7	40.7	41.8	28.7	41.0	44.4	46.8
T8	28.1	39.8	44.6	44.8	29.4	43.0	47.2	49.5
T9	25.3	37.3	43.1	44.5	28.8	42.2	45.7	48.1
T10	24.6	34.4	38.5	38.4	26.3	36.0	38.8	40.4
T11	24.5	35.7	41.0	42.1	26.6	36.4	39.1	41.0
T12	23.5	33.5	37.4	39.5	26.7	35.8	39.5	41.6
$LSD_{(0.05)}$ †	3.5	3.5	4.0	4.1	1.4	1.9	1.9	2.2

T1= Control, T2= DAP (18% N – 46% P – 0% K) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test (P < 0.05); NS = not significant

Table 5.4. Potato plant cover with application of organic and inorganic fertilizers in two growing seasons averaged across communities of Umala.

	Days after planting								
	44[‡]		58[‡]		85[‡]		100[‡]		120[§]
Treatments	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08	2007-08
	%								
T1	16.3	8.1	22.2	13.4	24.4	28.1	23.1	34.8	29.0
T2	27.4	10.9	44.9	20.0	50.2	54.2	49.3	70.7	65.1
T3	19.2	8.2	28.3	16.4	32.2	35.1	31.2	44.4	39.1
T4	22.1	9.1	30.2	16.5	33.7	33.7	33.7	45.2	39.4
T5	22.7	8.5	32.1	18.6	32.0	34.9	31.7	44.0	38.6
T6	19.7	7.1	27.1	13.5	27.2	31.7	27.0	37.7	32.4
T7	27.6	9.5	44.7	20.1	51.5	52.7	50.9	66.2	60.9
T8	34.4	9.5	51.2	21.8	57.7	60.8	54.2	67.1	61.9
T9	31.4	9.1	53.4	20.1	54.9	49.8	54.0	61.9	56.6
T10	23.9	8.0	36.6	16.6	38.2	38.3	36.7	50.8	45.5
T11	25.3	8.2	35.4	15.7	38.4	34.5	36.0	44.3	39.1
T12	23.8	8.0	32.5	16.5	35.3	33.0	35.2	41.1	37.0
LSD$_{(0.05)}$[†]	4.1	0.6	6.1	1.0	4.4	2.7	4.6	2.0	4.2

T1= Control, T2= DAP (18% N – 46% P – 0% K) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

[‡] Significant interaction between year and treatments

[§] Additional reading performed in 2007-08 growing season

[†] Least Significant Difference Test (P < 0.05); NS = not significant

Table 5.5. Foliar area of quinoa plants established on harvested potato fields with application of organic and inorganic fertilizers during the 2007-08 growing season in four communities of Umala.

	Days after planting								
	60[‡]	90[§]				120[§]			
Treatments		Kell	V.C.	S.J.Circa	S.J.Llanga.	Kell	V.C.	S.J.Circa	S.J.Llanga.
	cm^2								
T1	233	347	150	298	231	528	272	459	353
T2	273	416	279	618	301	580	467	784	463
T3	294	416	289	675	454	582	449	850	649
T4	290	439	324	656	393	609	518	829	576
T5	280	437	418	659	473	608	640	834	671
T6	272	348	184	515	301	501	311	671	465
T7	283	576	447	1029	573	763	679	1232	782
T8	289	514	227	518	401	694	404	628	584
T9	311	533	337	1144	513	718	545	1284	715
T10	259	519	339	937	446	699	542	1033	637
T11	284	373	195	912	263	532	328	1106	421
T12	263	378	216	602	281	513	359	774	442
LSD$_{(0.05)}$ [†]	34	104	193	279	112	121	246	323	136

T1= Control, T2= DAP (18% N – 46% P – 0% K) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

Kell= Kellhuiri; V.C.= Vinto Coopani; S.J.Circa= San Juan Circa; S.J.Llanga= San José de Llanga

[‡] Only significant differences among treatments;

[§] Significant interaction for the community and treatment factor

[†] Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 5.6. Seedhead diameter of quinoa plants established on harvested potato fields under organic and inorganic fertilizers. Measurements conducted before harvest (~140 days after planting) in the 2007-08 growing seasons in four communities of Umala.

Treatments	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
	-----	-----	cm	-----
T1	2.7	1.9	3.6	2.0
T2	3.7	2.5	3.7	2.7
T3	2.9	2.3	3.7	2.6
T4	2.8	2.1	4.4	2.7
T5	2.5	2.1	3.7	2.5
T6	3.0	2.1	3.6	2.3
T7	3.1	2.4	4.1	2.7
T8	3.0	2.9	3.9	2.8
T9	2.9	2.8	4.0	3.0
T10	2.5	2.4	3.6	2.6
T11	2.7	2.8	4.1	2.5
T12	2.8	2.7	3.5	2.5
LSD $_{(0.05)}$ †	NS	0.7	0.5	0.5

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 5.7. Preference order of treatments evaluated by farmers in potato plots at blooming and harvesting time in three communities of Umala in the 2006-07 and 2007-08 growing seasons.

	Kellhuiri		Vinto Coopani		San Juan Circa	
Treatments	Blooming	Harvest.	Blooming	Harvest.	Blooming	Harvest.
	-----------------------	-----------------------	-----------------------%	-----------------------	-----------------------	-----------------------
2006-07						
T1	15	13	25	9	18	8
T2	74	75	58	79	92	75
T5	-	-	76	-	-	-
T7	100	99	88	88	-	80
T8	84		94	97	-	90
T9	91	85	-	-	100	100
T10	-	-	-	81	-	-
T11	-	-	-	-	74	-
T12	-	88	-	-	82	-
2007-08						
T1	24	20	20	32	30	20
T2	44	55	52	-	90	-
T6	-	69	-	-	-	-
T7	76	100	52	-	-	70
T8	92	-	100	100	-	40
T9	76	56	76	52	90	-
T10	-	-	-	52	45	80
T11	-	-	-	64	60	90

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}); T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert; T12= CM + SM + Biofert

Table 5.8. Averaged economic benefits of treatments applied to potato plots in 2006-07 and 2007-08 growing seasons and in four communities of Umala.

	Crop value	Total variable cost	Total net benefit	Increased benefit
	---------------------------	Bs ha^{-1}	---------------------------	
Treatments				
T1	9516	-	9516	-
T2	15862	1435	14427	4911
T3	11460	1280	10180	664
T4	11840	1280	10560	1045
T5	11179	1280	9899	383
T6†	10343	21530	-11187	-20703
T7	15947	2709	13238	3722
T8	17069	2709	14360	4844
T9	16566	2709	13857	4342
T10	12143	1901	10242	727
T11	13684	1901	11784	2268
T12	12407	1901	10507	991

T1= Control, T2= DAP (18% N – 46% P_20_5 – 0% K_20) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† High price of the urban commercial compost used in the research (4 Bs kg^{-1}) increased total variable cost of this treatment. Currency exchange rate between American dollars and Bolivians is approximately 1:7.

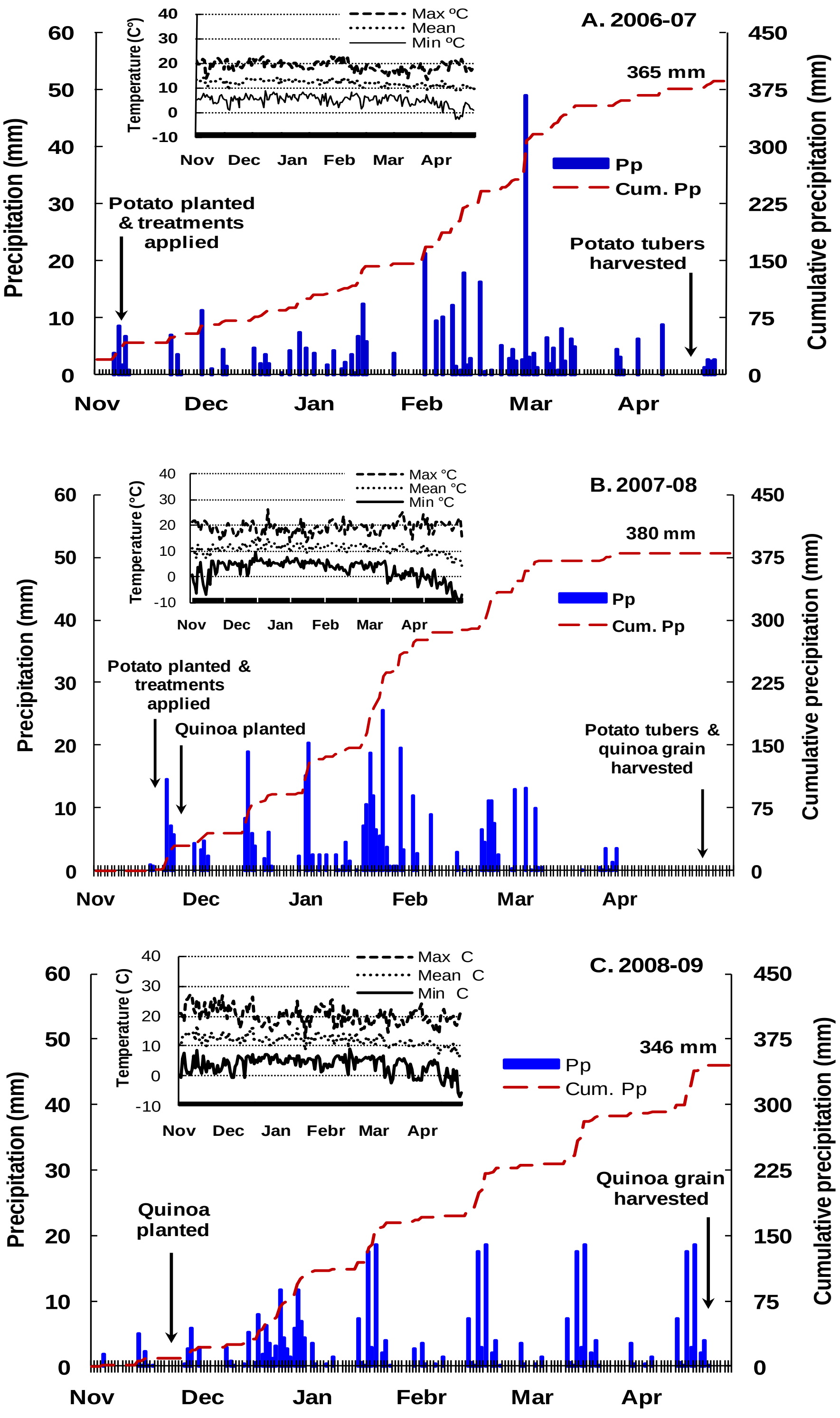

Figure 5.1a. Temperature and rainfall during the A) 2006-07, B) 2007-08 and C) 2008-09 growing seasons in the San Juan Circa lower elevation community of the Umala Municipality.

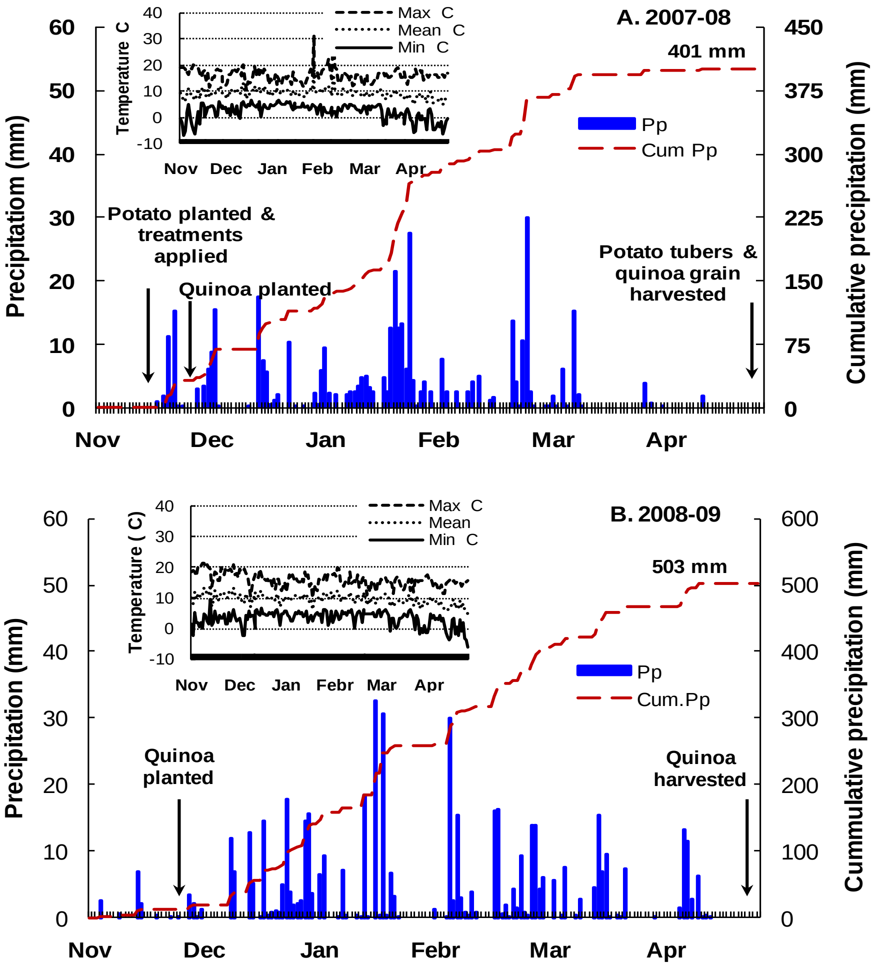

Figure 5.1b. Temperature and rainfall during the A) 2007-08 and B) 2008-09 growing seasons in the Vinto Coopani higher elevation community of the Umala Municipality.

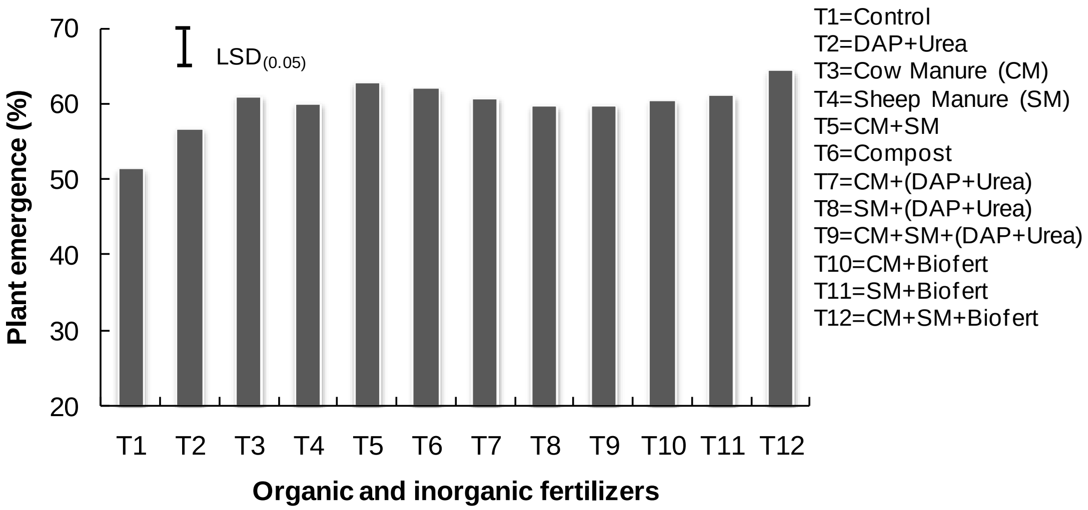

Figure 5.2. Effect of organic and inorganic fertilizers on quinoa plant emergence averaged across growing seasons and acrosscommunities of Umala. Vertical bar shows least significant difference at $p \leq 0.05$.

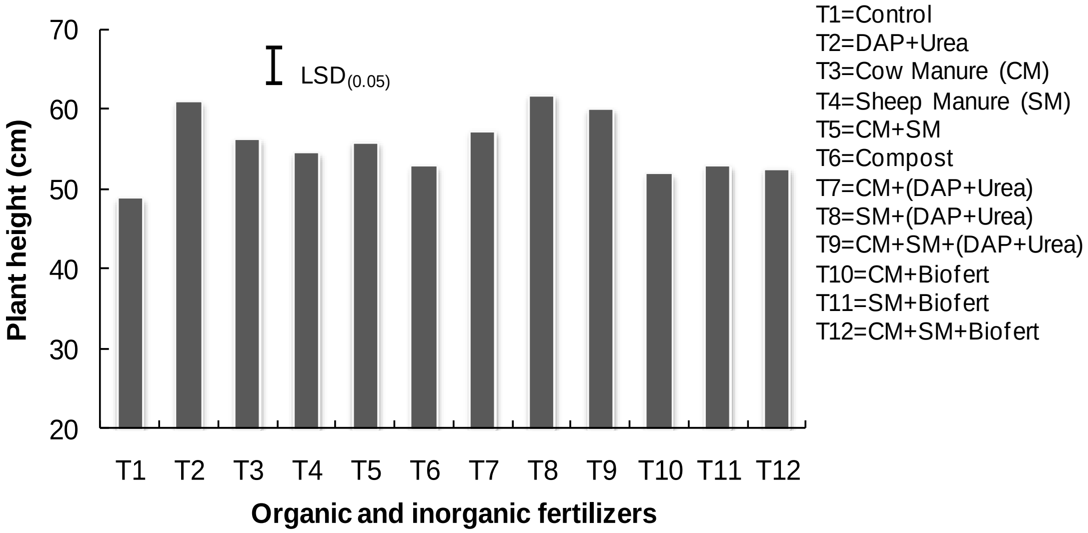

Figure 5.3. Quinoa plant height at blooming time averaged across growing seasons and across communities of Umala. Vertical bar shows least significant difference at $p \leq 0.05$.

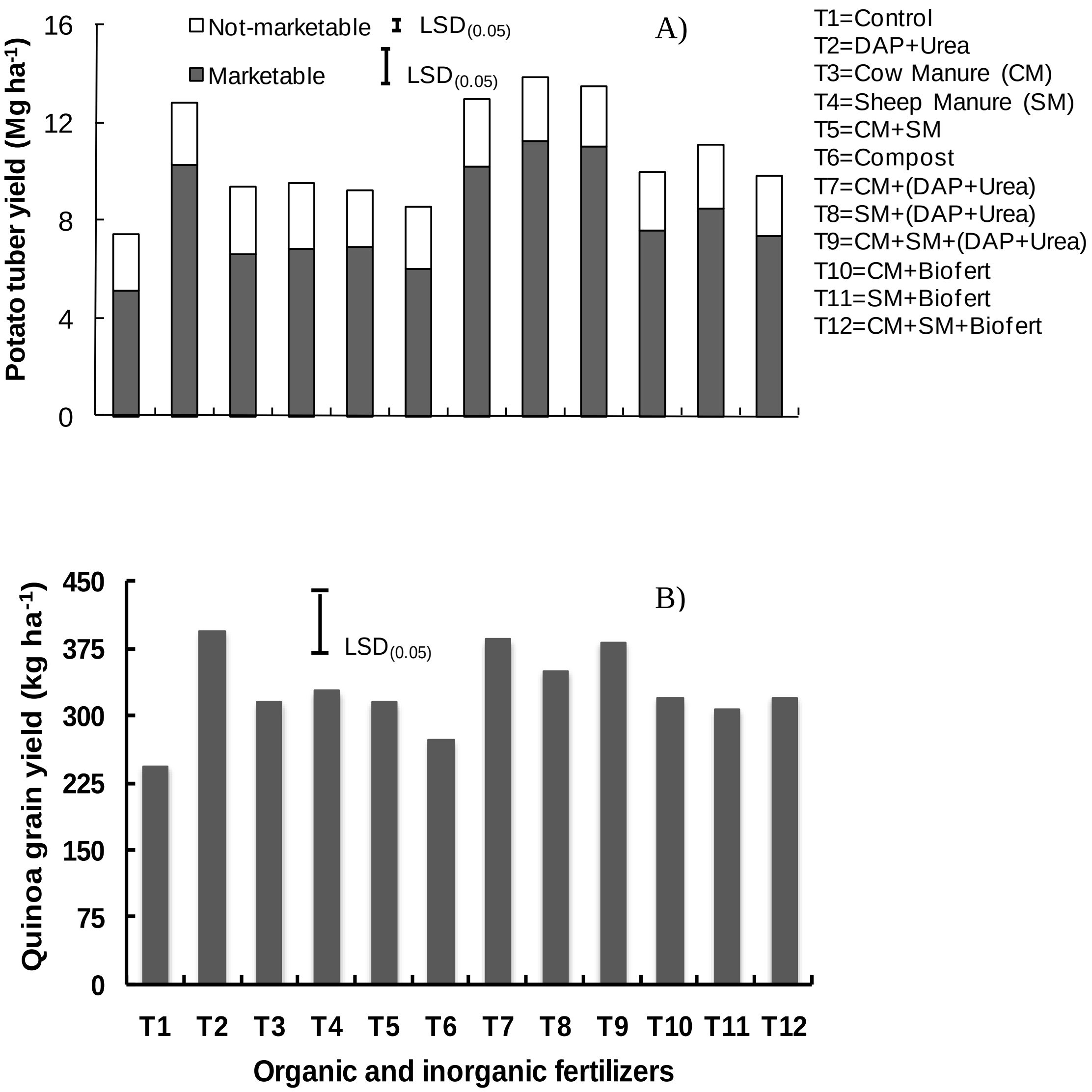

Figure 5.4. A) Potato tuber and B) quinoa grain yields by effect of organic and inorganic fertilizers applied in potato trials averaged across growing seasons and communities of Umala. Vertical bar shows least significant difference at $p \leq 0.05$.

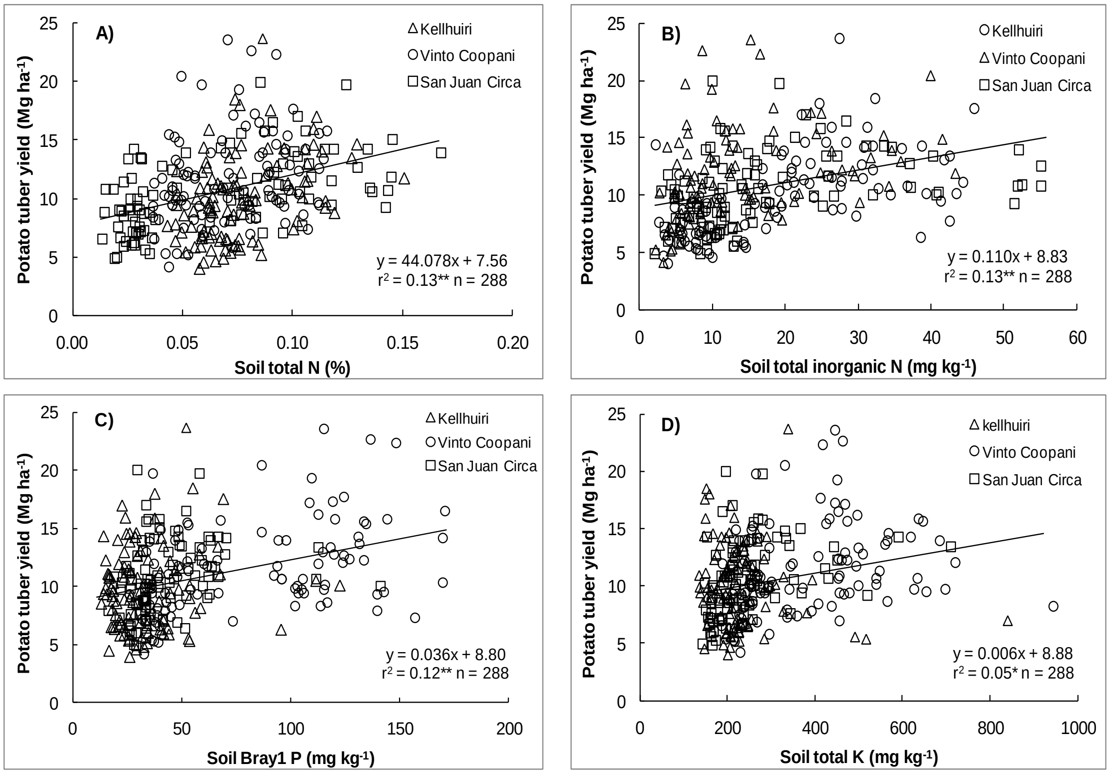

Fig. 5.5. Correlation between the A) soil total N, B) soil total inorganic N, C) soil Bray1 P, and D) soil total K and the fresh total tuber yield across communities and growing seasons *, **significant at $p \leq 0.05$ and $p \leq 0.01$, respectively.

CHAPTER 6

EVALUATION OF A RAPID FIELD TEST METHOD FOR ASSESSING N STATUS IN POTATO PLANT TISSUE TO IMPROVE NITROGEN FERTILITY MANAGEMENT

ABSTRACT

The relatively poor accessibility, high costs, long turnaround time for analysis, and lack of information about soil and plant testing in the Andean highland region (Altiplano) of Bolivia has hampered timely nutrient management decisions for potato crops. The main objective of this study was to determine if the Cardy nitrate meter (Horiba Ltd., Kyoto, Japan), a low-cost, portable and rapid field test method, could be used to improve N fertility management in this environment. Fully matured leaf petioles were sampled at blooming time from potato trials established in three communities in 2006-2007 and 2007-2008 growing seasons. Those trials were comprised of twelve fertility treatments (i.e., an unfertilized control and different combinations of sheep and cow manure, inorganic fertilizer, household compost, and a commercial microbial activator soil amendment) arranged in a randomized complete block design with four replications. In general, in both growing seasons and in all communities, nitrate measured in the sap of leaf petioles by the Cardy meter had relatively low but significant correlations with leaf petiole total N (ranged from r^2=0.07 to r^2=0.60 across seasons and communities) and with total fresh tuber yield (ranged from r^2=0.11 to r^2=0.50 across seasons and communities). These results indicate that the Cardy ion meter might be an effective tool for potato growers or agricultural professionals working in the Altiplano of Bolivia if further research can be conducted to determine if the meter is consistent over

diverse sites in the Altiplano and is practical for the cultural and environmental conditions of the region.

INTRODUCTION

Plant Nutrient Assessment

Maintaining adequate plant nutrient availability for crop growth is important for optimizing soil productivity and increasing nutrient use efficiency. A major component of most soil fertility management programs is some means to assess nutrient availability either through soil or plant analysis (Lemaire et al., 2008). Both pre-season and in season soil analysis are considered an important practice to monitor initial soil nutrient availability that can predict potential nutrient limitations. The results of the soil analysis can be complemented by plant tissue analysis during the growing reason to diagnose and correct some possible nutrient deficiencies (Lang et al., 1999). Soil test reports combined with plant tissue analysis are useful information for growers to manage fertilization programs according to climate, specific soil and crop requirements (Fox et al., 1989).

Rural areas in many developing countries often have limited or no access to soil or plant testing laboratories and often have restricted financial resources to submit samples for analysis (Dierolf et al., 1997). Moreover, lack of adequate research- or experience-based interpretation tables and recommendations makes it difficult for growers to act upon any soil or plant test information them may receive. In some countries, suspicion of outside groups possibly associated with the government may also limit grower participation in soil and plant testing (FFTC, 2010). Therefore, it is critical to find alternative approaches to assess soil fertility, especially to assist farmers to make decisions during the growing season to solve potential plant nutrition problems that may arise due to the effects of climate or management practices. In this case, the turnaround time for when the sample is submitted and the results are returned may be inadequate for the grower to make timely management decisions during the growing season. To overcome this problem, significant research has been conducted recently to develop rapid tests focusing on in-field assessment of plant tissue to evaluate plant nutritional status and to detect potential nutritional deficiencies (Silveira et al., 2007).

Plant tissue analysis is currently considered an important component in soil or crop nutrient management programs, especially where soil testing has not been effective (Roth et al., 1989). Plant tissue analysis assesses the current plant nutrient status, which shows if soil nutrient supplies are adequate, detects unseen nutrient deficiencies or excess levels causing toxicity and assists growers to correct nutritional problems especially when analysis are done early in the growing season in young plants (Hochmuth et al., 1991).

Plant tissue analysis determines plant nutrient concentrations at a specific time of sampling or growth stage and from a particular plant part and it might be influenced by different factors, such as disease and pest incidence. Therefore, tissue analysis should be used with awareness of its drawbacks and in combination with soil analysis (Silveira et al., 2007). Most tissue nutrient assessments have shown significant correlations with crop yields such as with potatoes (Westcott et al., 1991; Majić et al., 2009), cotton (Sunderman et al., 1979), soft winter wheat (Ortuzar-Iragori et al., 2005) and corn (Rostami et al., 2008, Ziadi et al., 2008).

Plant Tissue Sampling and Analysis

It is crucial to select a representative plant part and a set growth stage for assessing plant nutrients status since nutrient concentration varies within most plants and over the growth cycle of the plant. For many vegetable and agronomic crops, the most recently fully matured leaf is considered a representative part to provide nutritional status of the plant. Sometimes only the petiole of a leaf is used for plant analysis because the petiole basically acts as a pathway for transferring nutrients to leaves (Hochmuth et al., 1991).

In potatoes, the leaf petiole is a standard representative plant part used for nutrient analysis of mature plants. The fourth or fifth fully-matured leaf from the top of the plant is commonly used to determine plant nutrient status and petiole sampling usually begins at tuber initiation (Stark et al., 2007). Petiole nutrient content is not uniform in the whole plant, therefore petioles of the same relative maturity (fourth or fifth fully-matured leaf from the top of the plant) should be sampled to avoid misinterpretation of nutrient content measured between sampling dates (Lang et al., 1999). Moreover, petiole nutrient analysis may include several essential nutrients, but normally only nitrate is determined (Stark et al., 2007).

Rapid Field Tests

Since N has a crucial role in most plant physiological activities, N deficiency is a very limiting factor for most crops and inefficient use of N can have negative environmental implications for water quality and generation of greenhouse gases. The amount of available soil N is critical for potato performance; deficiencies of soil N generally reduce plant growth and tuber yield (Westermann, 2005) and excessive soil N before or at tuberization period potentially delays tuber growth and reduces tuber specific gravity and total tuber yield (Lang et al., 1999). Traditional plant tissue nitrate analysis provides information on plant nitrate-N status but analytical results might be received too late for growers to make quick decisions, therefore development of quick on-site analysis might be more useful for growers to make timely management decisions (Brust, undated).

There are currently several tools or devices for determining rapid plant N status and with varied accuracy, price, availability and field operation procedures. Some of them are non-destructive, faster and easier to operate on-farm than others. For instance, the chlorophyll meter, a non-destructive tool, has gained a widespread acceptance for providing rapid information on leaf N concentrations and for its correlation with crop yield **(**Ortuzar-Iragorri et al., 2005; Rostami et al., 2008).

The Cardy nitrate-N meter (Horiba Ltd., Kyoto, Japan) is a portable battery-powered field device able to rapidly assess plant nitrate-N status. When used on a regular basis, the Cardy nitrate meter assesses the nitrate-N in fresh petiole sap sampled from new fully mature leaves helping to monitor the dynamics of crop N status throughout the growing season (Hochmuth, 1994). A study conducted by Hartz et al. (1993) found that the Horiba Cardy nitrate meter offered a quick and reliable way to measure crop NO_3-N status across a range of vegetable crops comparable to conventional dry tissue analysis in laboratories. According to the Horiba Company, the cost of this tool is $250 which is relatively affordable.

This portable equipment contains a nitrate-selective electrode and reference electrode combined into a replaceable sensor. Conventional nitrate selective electrodes are subject to interference by various anions, particularly Cl, HCO_3, and NO_2, (Meyers and Paul, 1968; Onken and Sunderman, 1970). Although, the Cardy meter may be considered a device easy to operate and maintain and an important tool to routinely assess the crop N status during varied stages of plant growth (Westerveld et al., 2007), some important factors should be considered with respect to sap analysis. For instance, the plant water status may significantly influence the nitrate status in the same way as the presence or absence of clouds, time of sampling and tissue portion to be sampled (Hartz et al., 1993; Hochmuth, 1994; Majić et al., 2009). Besides, the nitrate- selective electrode is sensitive to temperature fluctuations and the device may require at least two calibrations during a single reading time (Hartz et al,, 1993). The Cardy meter works better under traditional fertilizer programs where inorganic N is applied than in fields entirely fertilized with organic amendments (Brust, undated).

Farmers and consultants are starting to use this fresh sap test technology for fertilizer N management (Hochmuth, 1994) that helps not only to apply the right amount of N at the right time but also to prevent environmental contamination by reducing the potential for soil nitrate leaching (Westermann, 2005**)**. Studies conducted on the effectiveness of the Horiba Cardy nitrate-N meter for determining the plant N status or N requirements for the potato crop during the growing season found high correlation of the Cardy meter readings with the conventional laboratory measures of petiole dry matter nitrate (William and Maier, 1990; Westcott et al., 1993; Errebhi et al., 1998), and with tuber yield (Waterer, 1997; Errebhi et al., 1998). Waterer (1997) also found that plant nitrate status is highly variable among potato varieties irrespective of the N fertilizer rate applied. All authors concluded that the Cardy nitrate-N meter can be a quick and useful tool to assess potato N status.

Potato is the staple crop of the central Andean Altipano in Bolivia and it is considered one of the most important components of food security as well as a source of cash income (FAO and SNAG, 1995; PROINPA, 2005). Most inputs and labor are utilized for production of potato; however, tuber yields are generally very low (3.7 Mg ha^{-1}) (PROINPA, 2005) compared to the national yield (5.6 Mg ha^{-1}) (FAOSTAT, 2008**)**. Among several reasons for the low crop production in this region are limited knowledge of effective soil nutrient management and the inadequate supply and the relative high cost of soil nutrient amendments (FAO and SNAG, 1995; PROINPA, 2005; Gilles et al., 2009; Motavalli et al., 2009).

Traditionally potato growers of the Andean Altiplano region of Bolivia have relied on organic amendments, such as animal manures, as sources of nutrients for crop growth but manufactured fertilizers are utilized in some communities (Gilles et al., 2009). However, participation in soil and plant testing programs are very limited due to restricted access to soil and plant analysis laboratories which are basically located in main cities. Therefore, identification of an inexpensive and rapid field testing procedure for assessing plant N status might help potato growers of this region to establish better soil N fertility management programs. The main objective of this study was to determine if use of the Cardy nitrate meter among several communities in the central Altiplano could be used to improve N fertility management based on its relationship with leaf petiole total N determined in the laboratory and with potato tuber yield.

MATERIAL AND METHODS

Experimental Design

Description of the study area can be found in Chapter 2 and selected characteristics of the potato field trials and treatments used in this research are explained in detail in Chapter 4 of this thesis.

Potato Petiole Sampling

In both the higher (Kellhuiri and Vinto Coopani) and lower (San Juan Circa) communities during the 2006/2007 and 2007/2008 growing seasons, potato leaf petioles were collected to evaluate the effectiveness of the Cardy meter. Sampling was done at blooming time on relatively sunny days to avoid periods of cloudiness that might influence leaf nitrate-N content. The rate of conversion of nitrate into organic N compounds in the plant is reduced during cloudy days because this conversion process requires energy produced during photosynthesis (Hageman et al., 1961). At blooming, potato plants normally express maximum physiological activity and the blooming stage of growth may be considered an opportune period for analysing plant nutrient status (Lang et al., 1999). Twenty most recently fully mature leaves (fourth leaf from the top) were hand removed from randomly selected plants in each plot, leaflets of each leaf were stripped off the petioles, and the petioles were put into labeled paper bags, then placed into a cooler and transported to a processing place for sap extraction and analysis. In-field analysis of the Cardy meter was not practical for this research because of the large number of samples that had to be processed from the experimental fields and the intense solar radiation and windy conditions of the region which affected the readings. Therefore, all readings were done indoors.

Cardy Meter Nitrate-N Readings and Petiole Total N Analysis

Ten of the twenty leaf petioles samples per plot were designated for the Cardy meter nitrate-N test and ten for the leaf petiole total N analysis. All procedures to obtain petiole sap, initial and periodic calibration of the Cardy meter, and operational procedures were carried out as recommended by Hochmuth (1994) and Studstill et al. (2006). In summary, sap of a composite of ten petiole leaves was obtained using a manual garlic press and the sap was expressed into a small beaker. The Cardy meter was initially calibrated before analysis and periodically checked during the analysis using two nitrate standards (i.e., 20 and 450 mg NO_3^--N L^{-1}). An absorbent paper strip was placed over the sensors and several drops of sap were placed on the paper with a medicine dropper so the paper was saturated. Readings in mg NO_3^--N L^{-1} were recorded from the meter.

The remaining ten leaf petioles samples per plot were air-dried, ground and passed through a sieve with 1 mm openings and a representative 200 mg of each sample was analyzed for total N using a combustion procedure with a LECO TruSpec® C/N analyzer.

Tuber Yields

In April of both 2007 and 2008 season, potatoes were hand-harvested after plants and tubers reached physiological maturity in 5 m length from three central rows of the five plot rows. Right after harvesting, potato tubers were hand graded by farmers and tubers were grouped into marketable (35 – 65 mm diameter) and non-marketable (> 65 mm or < 35 mm diameter) sizes and fresh weight was recorded. In San José de Llanga community, due to a sudden tuber pest infestation in 2007 and farmers' time availability in 2008, potatoes were harvested by the field owner and the data were not recorded.

Data analysis

Data of both Cardy meter nitrate-N and leaf petiole total N were analyzed using the SAS statistical program (SAS Institute, 2002-2003). Analysis of variance (ANOVA) was performed by using PROC ANOVA and the multiple comparison test that was used was Fishers (Protected) Least Significant Difference (LSD) at $p \leq 0.05$. A simple linear regression analysis was performed to determine if there was a significant relationship between the tuber yield and the Cardy nitrate-N readings and a relationship of results from the Cardy meter nitrate-N with those of petiole total N.

RESULTS AND DISCUSSION

Leaf Petiole Total N and Petiole Sap Nitrate-N

There was a significant interaction for the year and treatment factors and among treatments for both leaf petiole total N and for Cardy meter nitrate-N, but no effect of community; however data are shown by community (Tables 6.1 and 6.2). For the leaf petiole total N analysis, higher leaf petiole total N concentrations were observed compared to those of the control when inorganic fertilizers were added alone (T2) or when combined with manures (T7, T8 and T9) in Kellhuiri and Vinto Coopani in 2006-07 and only in San Juan Circa in 2007-08 (Table 6.1).

For the Cardy meter nitrate-N test, in both growing seasons and across communities, there was a general trend of all fertilizer treatments to generate higher NO_3^--N concentration than the control plot (Table 6.2). In both growing seasons and in all communities, treatments T2, T7, T8 and T9 produced higher NO_3^--N concentrations than the control. Mahmoud et al. (2009) also detected higher plant nitrate-N under combined application of inorganic and organic fertilizers. Biofert supplementation of cow (T10), sheep (T11) and both manures combined (T12) also caused significantly higher leaf petiole nitrate-N compared to the control in Vinto Coopani and San Juan Circa in 2007-08, but no differences were observed for total N compared to the control in both seasons and for all communities. This result shows an apparent trend of a higher proportion of nitrate-N with respect to total N (Figs. 6.1A-B) that may be attributed to Biofert's total C and N content (Table 4.6 Chapter 4) and its supplementary effect on manure by stimulating higher microbial activity and, therefore, higher N mineralization. Selvamani et al. (2009) found an increase of N and other nutrients in banana plants at different growth stages when biofertilizers were applied combined with organic and inorganic fertilizers.

In the 2006-07 growing season, significant positive linear relationship between leaf petiole total N and the Cardy meter nitrate-N analysis was detected in all communities (i.e., Kellhuiri, Vinto Coopani and San Juan Circa) (r^2= 0.36 P < 0.0001; r^2= 0.60 P< 0.0001; r^2= 0.14 P< 0.009 respectively) (Fig. 6.1A). In 2007-08, a significant relationship between leaf petiole total N and the Cardy meter nitrate-N analysis was detected only in San Juan Circa (r^2= 0.20 P< 0.001) (Fig. 6.1B). Similar results were found when comparing on-site Cardy meter nitrate-N readings with soil nitrate-N (Sims et al., 1995), with petiole nitrate-N (Vitosh et al., 1994; Zhang et al., 1996; Errebhi et., 1998) and with leaf petiole total N **(**Majić et al., 2009) traditionally measured by laboratory procedures. This result means that determining leaf petiole nitrate-N content through the Cardy meter might be a rapid and reliable means to determine potato plant N status in this semiarid region where no soil and plant analysis laboratories exists or are difficult to access. Some research has found that the petiole sap nitrate-N measurement is more sensitive to N fertilizers and a better indicator of plant N status and crop yield than petiole total N measured in dried leaf petioles (Olsen et al., 1994).

Petiole Sap Nitrate-N and Tuber Yield

In both growing seasons, a significant linear relationship between the Cardy meter nitrate-N test report and total fresh tuber yield was also found in all communities (i.e., Kellhuiri, Vinto Coopani and San Juan Circa) (Figs. 6.2A-B). The pattern of the effects of treatments on petiole sap nitrate-N detected by the Cardy meter and on total fresh tuber yield, averaged across growing seasons and communities, was very similar (Fig. 6.3). These results show again the acceptable performance and potential usefulness of this rapid field device. Some studies have detected a good relationship between potato petiole sap nitrate-N concentration measured by the Horiba Cardy meter and the tuber yield when different N fertilizer rates have been applied (Waterer, 1996; Errebhi et al., 1998), but some have found no relationship between petiole sap nitrate-N and total tuber yield during vegetative stages of growth (Poljak et al., 2008).

These results indicate that this portable field device may be an interesting alternative tool to guide potato growers and development institutions working in the highlands areas of Bolivia to improve their soil nutrient management since there is limited access to soil and plant testing laboratories. However, comments from Bolivian agronomists who used the Cardy meter were that the major problems they encountered were instability in the readings between calibrations and difficulty in obtaining replacement sensors, reagents, and other materials needed for the analysis. Some of this instability in readings may be caused by the intense solar radiation and windy conditions of the region.

CONCLUSIONS

Results from testing the Cardy meter for determining potato N status under the environmental and cultural conditions in the Andean highlands of Bolivia suggest that this tool has some promise as a low cost alternative for conventional plant tissue testing. The Cardy meter device is relatively expensive for this resource poor region of Bolivia and use of this instrument may need to be initially targeted for agronomists working for governmental and non-governmental agencies in the region. Other restrictions for use of the instrument included the availability and cost of reagents and replacement parts and the relative instability of readings under the normal environmental conditions experienced in agricultural fields in this region.

Further studies assessing the effectiveness of the Cardy meter at different potato growth stages are needed as well as an examination of the source of the variability in the relationship between Cardy meter readings and plant tissue N and tuber yield. In addition, development of interpretation tables for the Cardy meter readings for native potato varieties is required. Finally, appropriate in-season management practices need to be developed for growers to be able to utilize the information they receive from the Cardy meter testing. In a region where availability of soil nutrient amendments is limited and fertilizers are relatively expensive for growers, several challenges still exist for increasing potato production.

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Table 6.1. Leaf petiole total N (conventional lab analysis) under organic and inorganic fertilizers in two growing seasons in three communities of Umala.

	Kellhuiri		Vinto Coopani		San Juan Circa	
Treatments	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08
	------	------	------	%	------	------
T1	1.1	1.1	1.2	0.7	1.4	0.8
T2	1.4	1.2	2.0	0.7	1.7	1.2
T3	1.4	0.9	1.1	0.7	1.4	0.8
T4	1.2	0.9	1.4	0.5	1.3	1.1
T5	1.3	1.0	1.0	0.7	1.2	0.9
T6	1.2	1.0	1.0	0.7	1.3	0.8
T7	1.6	1.0	2.6	0.8	1.7	1.2
T8	1.7	1.0	2.1	0.7	1.6	1.4
T9	1.5	0.8	2.0	0.7	1.6	1.4
T10	1.2	0.9	1.2	0.7	1.3	0.7
T11	1.2	1.0	1.3	0.7	1.2	0.9
T12	1.1	1.2	1.3	0.7	1.3	0.9
$LSD_{(0.05)}$ †	0.4	NS	0.4	NS	NS	0.3

T1= Control, T2= DAP (18% N – 46% P_2O_5 – 0% K_2O) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test ($P < 0.05$); NS = not significant

Table 6.2. Cardy meter nitrate-N concentrations under organic and inorganic fertilizers in two growing seasons in three communities of Umala.

Treatments	Kellhuiri 2006-07	Kellhuiri 2007-08	Vinto Coopani 2006-07	Vinto Coopani 2007-08	San Juan Circa 2006-07	San Juan Circa 2007-08
	---mg L^{-1}---					
T1	318	285	225	318	218	133
T2	801	513	813	593	798	464
T3	417	383	317	323	351	151
T4	400	353	280	365	307	290
T5	370	342	297	420	393	144
T6	372	366	368	365	418	260
T7	897	814	804	678	805	552
T8	853	873	859	759	861	863
T9	914	835	896	651	811	849
T10	423	383	278	506	349	289
T11	370	345	339	445	343	443
T12	412	404	294	499	356	408
$LSD_{(0.05)}$ †	182	226	159	168	217	164

T1= Control, T2= DAP (18% N – 46% P_2O_5 – 0% K_2O) + Urea (46% N), T3= Cow manure (CM) (10 Mg ha^{-1}), T4= Sheep manure (SM) (10 Mg ha^{-1}), T5= CM (5 Mg ha^{-1}) + SM (5 Mg ha^{-1}), T6= Compost (5 Mg ha^{-1}), T7= CM + DAP + Urea , T8= SM + DAP + Urea, T9= CM + SM + DAP + Urea, T10= CM + Biofert (0.2 Mg ha^{-1}), T11= SM + Biofert, T12= CM + SM + Biofert

† Least Significant Difference Test ($P < 0.05$); NS = not significant

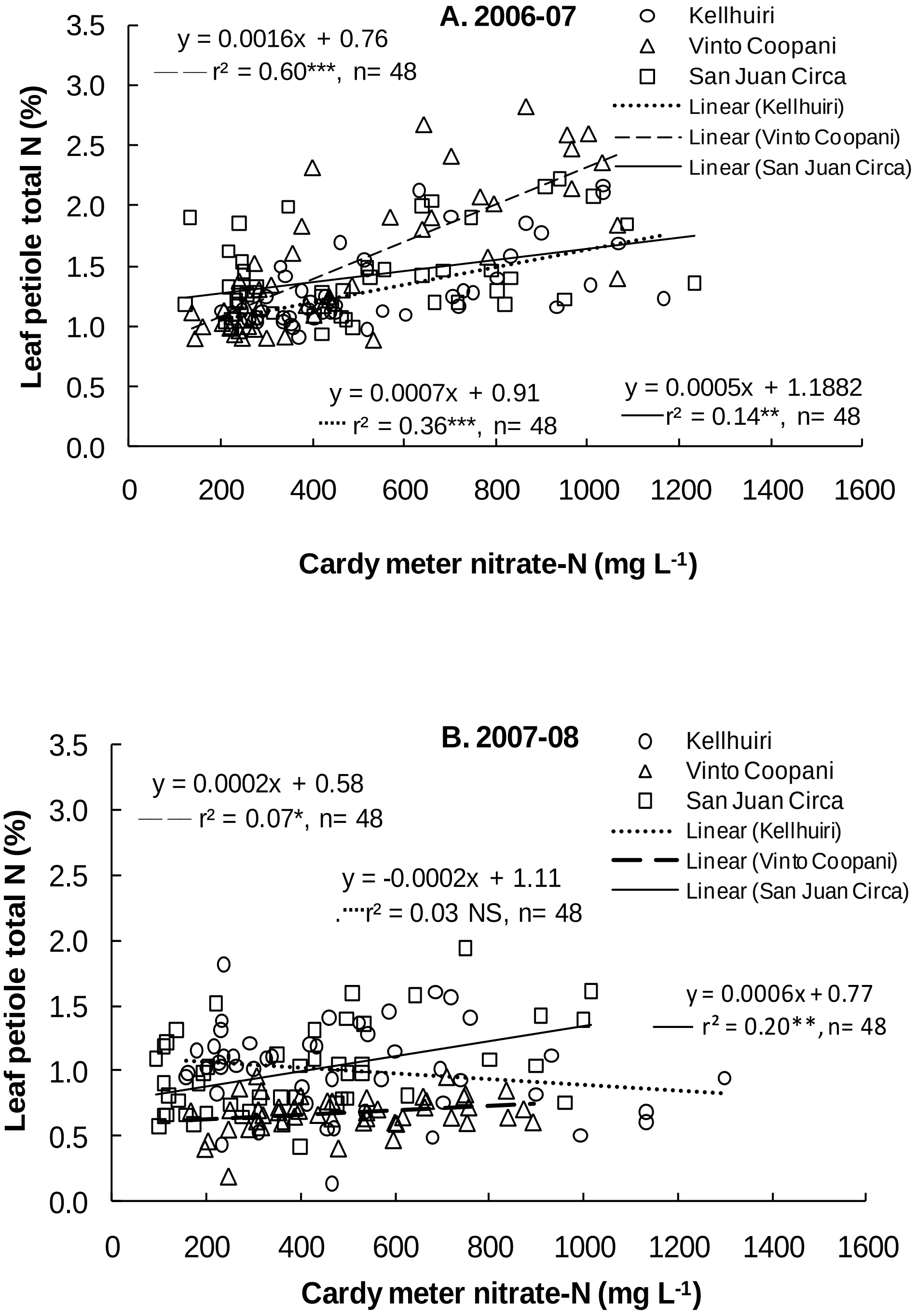

Figure 6.1. Linear regression between the leaf petiole total N obtained with laboratory procedures and petiole sap nitrate-N measured with the Cardy meter at blooming in three communities of Umala in A) 2006-07 and B) 2007-08 growing seasons. *, **, * significant at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively; NS = not significant.**

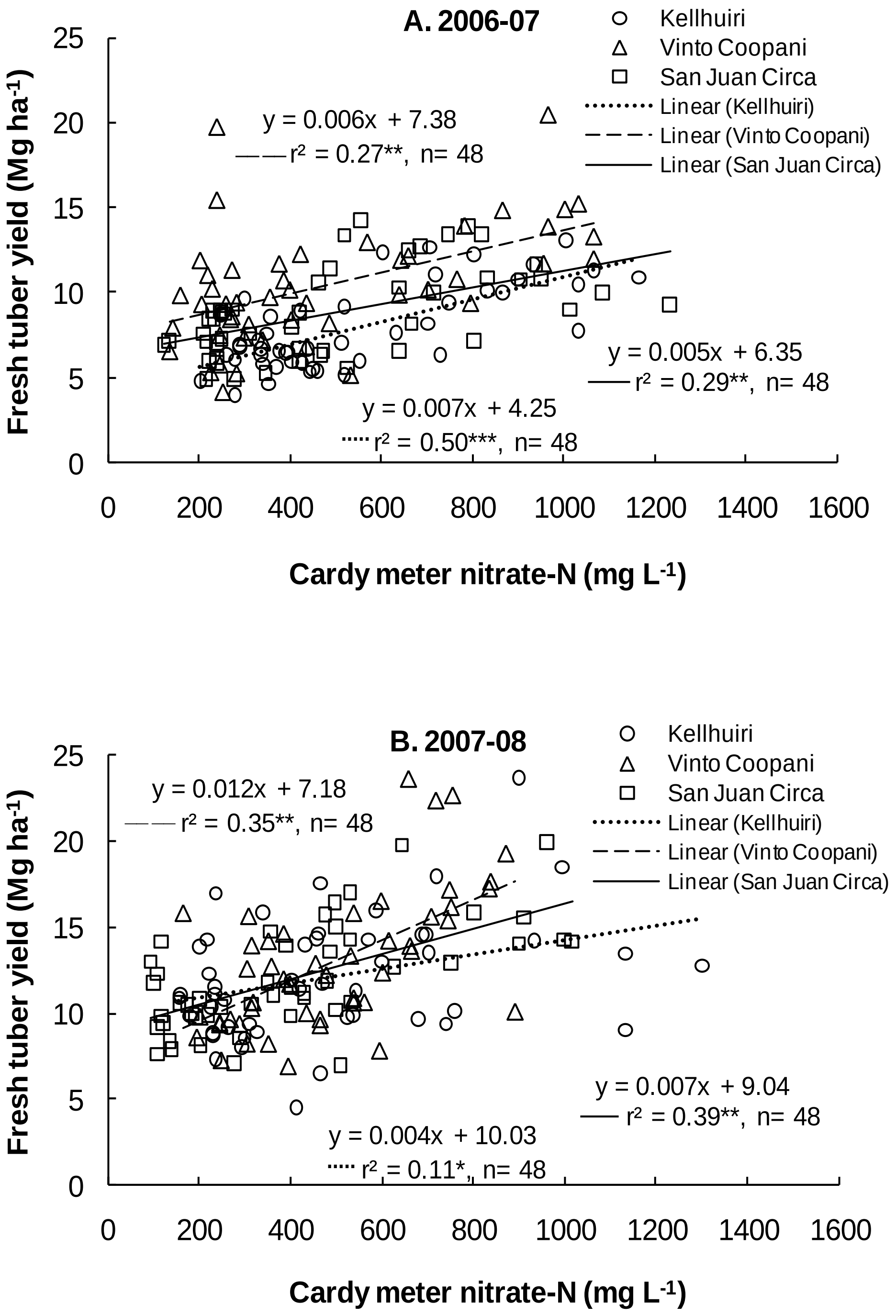

Figure 6.2. Linear regression between the petiole sap nitrate-N measured with the Cardy meter and fresh total tuber yield in three communities of Umala in A) 2006-07and B) 2007-08 growing seasons. *, **significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; NS = not significant.

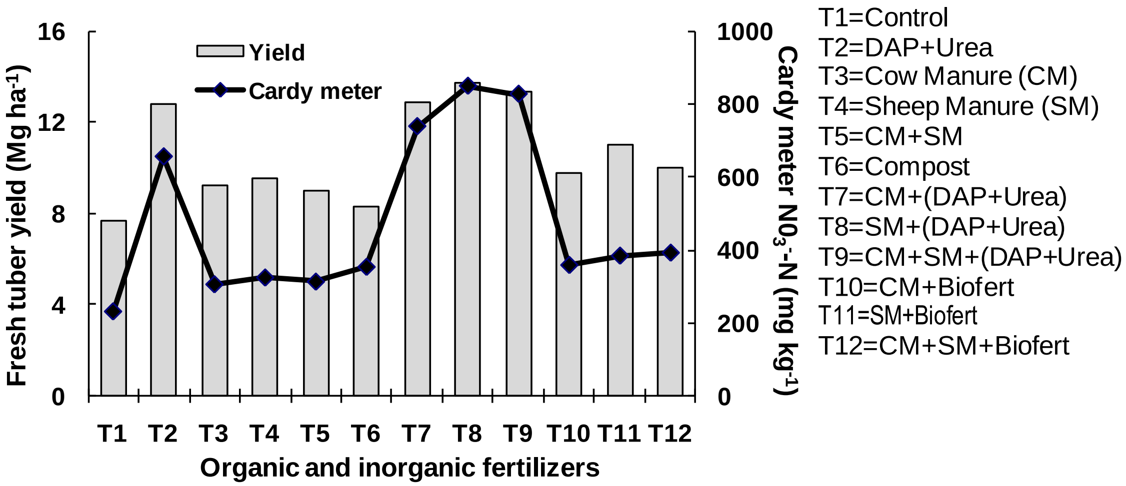

Figure 6.3. Relationship between petiole sap nitrate-N measured with the Cardy meter at blooming and the fresh tuber yield under the effects of organic and inorganic fertilizer treatments averaged across communities and growing seasons.

CHAPTER 7

GENERAL CONCLUSIONS

This research combined community level surveys with on-farm field trials in representative indigenous Aymara communities in the central Altiplano region of Bolivia in order to determine the impact of climate and socioeconomic changes on soil fertility management practices in the traditional potato-based cropping system in this region. In addition, it examined the use of inorganic and organic amendments as a possible practice to overcome soil degradation and increase soil productivity and crop performance during the crop rotation. Finally, one possible low-cost field assessment tool was tested to determine if it could provide valuable information for more effective potato N management in a region where access to soil and plant tissue testing is limited or too expensive for indigenous farmers of this region to utilize in soil fertility management.

Farmers in this region had well-developed indigenous soil classification systems which were largely based on differences in soil texture, color, the presence of stones, depth of the plow layer and crop productivity. A general change perceived by community members in most cropped lands was the increase in soil erosion and the consequent reduction in soil productivity. These changes were primarily attributed to increased frequency and intensity of wind, seasonal concentration of rainfall in fewer months and an increase in air temperature. Except for few exceptions, all the different soil types identified by farmers in the selected communities had relatively low SOM (average of 1.5% across soil types) and none of the different soil types appeared to have cropping limitations due to salinity or soil test K. The results of this study highlight the need for a detailed soil survey of this region which captures both native and scientific-based soil classification. Without soil survey information, effective management of the soil resources in this region will be limited.

Some important differences in soil management practices were observed between communities located at relatively lower elevations compared to those located at higher elevations. For example, animal traction is primarily used for tillage at higher elevation communities while in the lower communities, tractor-based tillage systems have been utilized which may be causing lower native vegetation re-growth in fallow lands and a decline in SOM.

Farmers also perceived a decrease in the length of the fallow period over the past 25 years, and the reduction of this practice is considered one factor that contributes to reduction in soil quality and other soil characteristics. One reason mentioned for the shortening of the fallow periods has been the switch from agricultural cropping lands planted to annual row crops to land planted to forages since livestock and/or dairy activity has rapidly increased in the region over the last ten years. An investigation into the effects of cropping and fallow on soil fertility restoration indicated that cropping generally decreased total and active SOC, and total, inorganic and active soil N and soil inorganic N. In contrast, the practice of fallowing restored total and active SOC and total and active soil N more rapidly in the upper communities than was observed in the lower communities. This difference was mainly attributed to differences in soil properties and land management in cropped fields at both elevations. One possible future area of research could be to examine the use of managed fallow areas in which multi-purpose plants could be planted during the fallow period to reduce potential soil erosion, restore soil fertility, and provide needed forage. In addition, a better understanding of the effects of agricultural management practices on native vegetation is needed to better conserve this resource.

One possible strategy to overcome soil degradation in this environment is the use of inorganic fertilizers and/or traditional (i.e., sheep and cow manures) and alternative (i.e., household compost and a biofertilizer) organic fertilizers. The effects of these soil amendments on first year potato crop response and residual quinoa crop response were investigated over three years in community level field trials with grower participation in evaluating crop response. Organic fertilizers, such as cow and sheep manure combined with inorganic fertilizers significantly affected initial and residual soil properties, such as pH, soil test P, soil TN, soil TIN and SOC, soil gravimetric water content and bulk density in all communities. These treatments also significantly increased the potato and subsequent quinoa crop's growth and yields and also increased economic returns with the potato crop. The combination of inorganic and organic fertilizers was the preferred fertility treatment among farmers involved in the participatory evaluation.

The greater early season availability of nutrients (principally soil TIN and soil test P) by inorganic fertilizer either applied alone or combined with manure, apparently promoted rapid initial potato plant growth which might have improved crop performance throughout the growing season up to harvest. Because of the relatively low amount of precipitation received during the course of the research, leaching losses were probably minimal reducing potential losses of soil TIN and soil test P and improving subsequent crop performance.

In general, applications of cow manure and sheep manure did not differ from each other in their effects on most soil chemical and physical properties and on crop growth and yield. Therefore, either manure can be applied by farmers of the Altiplano as an effective soil amendment, but survey results indicate that these manures are being applied at relatively low rates in the central Altiplano due to several constraints related to labor availability and transport costs. Further research is needed to develop methods to increase the effective rate of application of these organic materials since this research indicated that relatively high rates are needed to increase soil properties, such as water-holding capacity and potentially mineralizable C and N.

Based on the results of this research which had limited application rates, the alternative organic soil amendments (i.e., household compost and Biofert) were not effective in increasing soil fertility and potato and quinoa crop growth. Further research is needed possibly using higher rates of application to evaluate whether these soil amendments and other possible organic sources can be effective in this environment since low soil organic matter levels and low soil N and P are primary restrictions for improved crop growth.

A final investigation was conducted to determine whether the use of a rapid and relatively low cost field test could be effective in providing farmers with useful information on N status in potatoes in a region where soil and plant testing laboratories are expensive or inaccessible. Petiole sap nitrate-N measured by the Cardy nitrate meter had a good relationship with the leaf petiole total-N measured with laboratory procedures and with the total fresh tuber yield, suggesting that this tool has some promise as a low cost alternative for conventional tissue testing for potatoes in the Andean highlands of Bolivia. However, further studies assessing the tool at different potato growth stages and in different native potato varieties are needed to develop reliable interpretation information and recommendations for farmers. It is also recommended that this research compare the Cardy meter with other tools (e.g., the chlorophyll meter) and obtain feedback from farmers and agricultural professionals whether the tool would provide useful and timely information for them to improve their crop management. An approach for using the Cardy meter confidently in the field conditions is also needed.

APPENDICES

Appendix 1. P>F values from the ANOVA for selected soil properties due to different cropping and fallow length in four Umala communities.

Source	pH (0.01 *M* $CaCl_2$)	Inorganic N	Organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	----------	----------	----------	----------	P > F	----------	----------	----------	----------	----------
Location (L)	0.07	0.0001	0.0001	0.0001	0.42	0.03	0.0001	0.0001	0.0001	0.03
Rep (L)	0.98	0.77	0.88	0.82	0.06	0.09	0.98	0.76	0.98	0.45
Treatm. (T)	0.005	0.0001	0.0001	0.0001	0.02	0.30	0.45	0.81	0.50	0.04
L*T	0.28	0.0001	0.04	0.04	0.09	0.42	0.14	0.12	0.02	0.15

Appendix 2. P>F values from the ANOVA for selected soil properties due to different cropping and fallow length in Kellhuiri community.

Source	pH (0.01 *M* $CaCl_2$)	Inorganic N	Organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	----------	----------	----------	----------	P > F	----------	----------	----------	----------	----------
Rep	0.48	0.94	0.74	0.15	0.23	0.22	0.59	0.51	0.51	0.30
Treatment	0.08	0.003	0.63	0.002	0.08	0.56	0.81	0.63	0.84	0.64

Appendix 3. P>F values from the ANOVA for selected soil properties due to different cropping and fallow length in Vinto Coopani community.

Source	pH (0.01 M CaCl$_2$)	Inorganic N	Organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
					P > F					
Rep	0.81	0.55	0.65	0.98	0.07	0.18	0.95	0.56	0.98	0.47
Treatment	0.26	0.001	0.005	0.05	0.43	0.32	0.26	0.63	0.16	0.05

Appendix 4. P>F values from the ANOVA for selected soil properties due to different cropping and fallow length in San Juan Circa community.

Source	pH (0.01 M CaCl$_2$)	Inorganic N	Organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
					P > F					
Rep	0.89	0.35	0.46	0.54	0.95	0.46	0.33	0.54	0.55	0.16
Treatment	0.56	0.0001	0.002	0.02	0.24	0.03	0.02	0.05	0.01	0.40

Appendix 5. P>F values from the ANOVA for selected soil properties due to different cropping and fallow length in San José de Llanga community.

Source	pH (0.01 *M* $CaCl_2$)	Inorganic N	Organic C	Total N	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	----------	----------	----------	----------	P > F	----------	----------	----------	----------	----------
Rep	0.92	0.36	0.32	0.24	0.96	0.34	0.38	0.21	0.48	0.74
Treatment	0.29	0.0001	0.37	0.54	0.63	0.05	0.50	0.05	0.20	0.63

Appendix 6. P>F values from the ANOVA for cumulative soil potential N and C mineralization due to different cropping and fallow length in four Umala communities.

Source	CO_2-C released	Inorganic N
	----------- P > F	----------
Location (L)	0.0001	0.0001
Rep (L)	0.70	0.50
Treatm. (T)	0.0001	0.02
L*T	0.67	0.79

Appendix 7. P>F values from the ANOVA for the cumulative soil potential N and C mineralization due to different cropping and fallow length in four Umala communities.

	Kellhuiri		Vinto Coopani		San Juan Circa		San José de Llanga	
Source	CO_2	Inorganic N	CO_2	Inorganic N	CO_2	Inorganic N	CO_2	Inorganic N
	---------- P > F ----------							
Rep	0.57	0.21	0.51	0.36	0.35	0.63	0.52	0.67
Treatment	0.04	0.05	0.32	0.89	0.002	0.04	0.04	0.05

Appendix 8. P>F values from the ANOVA for the for selected soil properties of potato field trials due to organic and inorganic fertilizers in four communities of Umala. Samples collected at blooming time.

Source	pH (0.01 *M* $CaCl_2$)	Soil test Bray1 P	Total N	Organic C	Inorganic N	Soil test K	Exch. Ca	Exch. Mg	CEC
	---------- P > F ----------								
Year (Y)	0.0001	0.0001	0.0001	0.0001	0.05	0.0001	0.0001	0.0001	0.0001
Location (L)	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001
Y*L	0.0001	0.0001	0.0001	0.0003	0.0001	0.0001	0.0001	0.0001	0.0001
Rep (Y*L)	0.006	0.0001	0.0001	0.0001	0.08	0.0001	0.0001	0.0001	0.0001
Treatm. (T)	0.0001	0.0001	0.03	0.04	0.0001	0.56	0.52	0.89	0.56
Y*T	0.33	0.99	0.27	0.40	0.0001	0.37	0.08	0.59	0.37
L*T	0.12	0.98	0.61	0.74	0.90	0.32	0.17	0.98	0.32
Y*L*T	0.009	0.33	0.33	0.18	0.69	0.82	0.23	0.99	0.82

Appendix 9. P>F values from the ANOVA for the for the soil pH of potato field trials due to fertilizers applied in two growing season and in four communities of Umala. Samples collected at blooming time.

	2006-07				2007-08			
Source	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
	--- P > F ---							
Rep	0.12	0.001	0.30	0.03	0.32	0.12	0.46	0.07
Treatment	0.49	0.001	0.79	0.001	0.02	0.07	0.03	0.008

Appendix 10. P>F values from the ANOVA for the soil inorganic N of potato field trials due to fertilizers applied in two growing seasons and in four communities of Umala.

Source	2006-07	2007-08
	----------- P > F ----------	
Location (L)	0.0002	0.002
Rep (L)	0.87	0.15
Treatm. (T)	0.0001	0.0001
L*T	0.59	0.92

Appendix 11. P>F values from the ANOVA for the soil test K of potato field trials due to organic and inorganic fertilizers in four communities of Umala. Samples collected at blooming time.

Source	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
	---------------------------- P > F	---------------------------		
Year (Y)	0.08	0.0002	0.03	0.06
Rep (Y)	0.0001	0.02	0.19	0.003
Treatm. (T)	0.72	0.04	0.0004	0.0001
Y*T	0.45	0.62	0.40	0.28

Appendix 12. P>F values from the ANOVA for the for the selected soil properties of quinoa field trials due to the residual effects of adding treatments to the previous potato crop in four communities of Umala. Samples collected prior to planting in two growing seasons.

	2007-08					2008-09	
Source	Organic C	Total N	C:N	Inorganic N	Soil test Bray1 P	Inorganic N	Soil test Bray1 P
	-- P > F	--					
Location (L)	0.0001	0.0001	0.0001	0.0005	0.009	0.03	0.0001
Rep (L)	0.004	0.0002	0.02	0.0001	0.10	0.0001	0.0001
Treatm. (T)	0.03	0.35	0.21	0.0001	0.005	0.0001	0.005
L*T	0.58	0.41	0.06	0.69	0.71	0.89	0.14

Appendix 13. **P>F values from the ANOVA for the cumulative soil potential N and C mineralization due to different rates of soil organic amendments in four Umala communities.**

	7.5 Mg ha^{-1}		15 Mg ha^{-1}		30 Mg ha^{-1}	
Source	CO_2	Inorganic N	CO_2	Inorganic N	CO_2	Inorganic N
	----------	----------	---------- P > F	----------	----------	----------
Rep	0.26	0.58	0.11	0.44	0.93	0.39
Treatment	0.25	0.21	0.005	0.05	0.006	0.04

Appendix 14. **P>F values from the ANOVA for the soil gravimetric water content during the 2006-07 growing season under soil fertilizers applied in potato trials in three communities in Umala.**

Days after planting	104	125		149	
Depth (cm)	0-15	0-15	15-30	0-15	15-30
Source					
	----------	----------	P > F	----------	----------
Location (L)	0.004	0.0001	0.0001	0.01	0.002
Rep (L)	0.07	0.81	0.003	0.33	0.0005
Treatm. (T)	0.26	0.004	0.0001	0.29	0.59
L*T	0.99	0.92	0.04	0.99	0.98

Appendix 15. **P>F values from the ANOVA for the soil gravimetric water content during the 2006-07 at 125 days after planting under soil fertilizers applied in potato trials in three communities in Umala.**

Source	Kellhuiri	Vinto Coopani	San Juan Circa
	------------------------	P > F	----------------------
Rep	0.11	0.40	0.02
Treatment	0.44	0.002	0.001

Appendix 16. **P>F values from the ANOVA for the soil gravimetric water content during the 2007-08 growing season under soil fertilizers applied in potato trials in three communities in Umala.**

Days after planting	41		60		83		104		125	
Depth (cm) Source	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
	---				P > F					---
Location (L)	0.02	0.0001	0.07	0.04	0.14	0.20	0.0001	0.0001	0.05	0.22
Rep (L)	0.12	0.04	0.001	0.0001	0.003	0.004	0.07	0.005	0.0001	0.0001
Treatm. (T)	0.96	0.64	0.86	0.97	0.08	0.88	0.89	0.97	0.04	0.04
L*T	0.99	0.98	0.99	0.97	0.99	0.98	0.98	0.90	0.98	0.89

Appendix 17. P>F values from the ANOVA for the soil gravimetric water content during the 2007-08 growing season due to residual effects of fertilizers applied to the previous potato trials in four communities in Umala.

Days after planting	47		68		94		115	
Depth (cm)	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
Source								
	-- P > F --							
Location (L)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.25	0.09
Rep (L)	0.008	0.09	0.0001	0.02	0.0001	0.02	0.0001	0.0001
Treatm. (T)	0.07	0.25	0.03	0.70	0.002	0.009	0.57	0.17
L*T	0.99	0.99	0.93	0.98	0.87	0.85	0.97	0.99

Appendix 18. P>F values from the ANOVA for the soil bulk density of potato field trials and the subsequent quinoa trials due to fertilizers applied in two growing seasons and in four communities of Umala.

Source	Potato	Quinoa
	----------- P > F	----------
Year (Y)	0.12	0.0001
Location (L)	0.0007	0.92
Y*L	0.04	0.70
Rep (Y*L)	0.0001	0.06
Treatm. (T)	0.0001	0.0001
Y*T	0.09	0.08
L*T	0.31	0.44
Y*L*T	0.66	0.92

Appendix 19. **P>F values from the ANOVA for the soil at approximately field capacity (-10 kPa) and wilting point (-1500 kPa) as result of different organic fertilizers and at different rates in Umala.**

Rate	7.5 Mg ha^{-1}		15 Mg ha^{-1}		30 Mg ha^{-1}	
Source	-10 kPa	-1500 kPa	-10 kPa	-1500 kPa	-10 kPa	-1500 kPa
	---------- P > F ----------					
Rep	0.62	0.65	0.12	0.20	0.54	0.60
Treatment	0.80	0.95	0.99	0.56	0.85	0.29

Appendix 20. **P>F values from the ANOVA for the potato plant emergence due to organic and inorganic fertilizers in four communities of Umala.**

Days after planting Source	29	36	43	50
	---------- P > F ----------			
Year (Y)	0.0001	0.0001	0.0001	0.0001
Location (L)	0.0001	0.004	0.001	0.010
Y*L	0.23	0.0002	0.006	0.0002
Rep (Y*L)	0.0001	0.0001	0.0001	0.0001
Treatm. (T)	0.84	0.56	0.24	0.59
Y*T	0.98	0.95	0.86	0.94
L*T	0.99	0.99	0.98	0.99
Y*L*T	0.99	0.97	0.99	0.99

Appendix 21. P>F values from the ANOVA for the potato plant height due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	57	71	85	115
	------------------------------	P > F	------------------------------	
Year (Y)	0.0001	0.0001	0.0001	0.0001
Location (L)	0.0001	0.0001	0.0001	0.0001
Y*L	0.007	0.10	0.53	0.08
Rep (Y*L)	0.0001	0.0001	0.0001	0.0001
Treatm. (T)	0.0001	0.0001	0.0001	0.0001
Y*T	0.11	0.07	0.77	0.99
L*T	0.24	0.002	0.01	0.002
Y*L*T	0.52	0.003	0.09	0.09

Appendix 22. P>F values from the ANOVA for the potato plant height in Kellhuiri due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	57	71	85	115
	------------------------------	P > F	------------------------------	
Year (Y)	0.0001	0.0001	0.0001	0.0001
Rep (Y)	0.25	0.46	0.21	0.15
Treatm. (T)	0.02	0.0001	0.0001	0.0001
Y*T	0.40	0.06	0.22	0.58

Appendix 23. P>F values from the ANOVA for the potato plant height in Vinto Coopani due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	57	71	85	115
	------------------------------	P > F	------------------------------	
Year (Y)	0.0001	0.0001	0.0001	0.0001
Rep (Y)	0.0003	0.004	0.18	0.16
Treatm. (T)	0.0003	0.0001	0.0001	0.0001
Y*T	0.22	0.003	0.129	0.20

Appendix 24. P>F values from the ANOVA for the potato plant height in San Juan Circa due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	57	71	85	115
	------------------------------ P > F		-----------------------------	
Year (Y)	0.003	0.002	0.002	0.0009
Rep (Y)	0.0002	0.0001	0.0001	0.0001
Treatm. (T)	0.03	0.0001	0.0001	0.0001
Y*T	0.65	0.29	0.41	0.55

Appendix 25. P>F values from the ANOVA for the potato plant height in San José de Llanga due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	57	71	85	115
	------------------------------ P > F		-----------------------------	
Location (L)	0.0001	0.0001	0.0001	0.0001
Rep (L)	0.17	0.02	0.01	0.31
Treatm. (T)	0.0001	0.0001	0.0001	0.0001
L*T	0.01	0.002	0.130	0.12

Appendix 26. P>F values from the ANOVA for the potato plant cover due to organic and inorganic fertilizers in four communities of Umala.

Days after planting Source	44	58	85	100
	------------------------------ P > F		-----------------------------	
Year (Y)	0.0001	0.0001	0.16	0.0001
Location (L)	0.0001	0.0001	0.006	0.0001
Y*L	0.0001	0.0001	0.0001	0.0001
Rep (Y*L)	0.0002	0.02	0.07	0.0001
Treatm. (T)	0.0001	0.0001	0.0001	0.0001
Y*T	0.0001	0.0001	0.008	0.0001
L*T	0.21	0.60	0.79	0.58
Y*L*T	0.01	0.62	0.80	0.82

Appendix 27. P>F values from the ANOVA for the foliar area (cm^2) and seedhead diameter (cm) of quinoa plants established on harvested potato fields with application of fertilizers during the 2007-08 growing season in four communities of Umala.

Days after planting Source	60	90	120	Seedhead diameter
	-------------------------------	---------- P > F ----------	-------------------------------	
Year (Y)	0.0001	0.0001	0.0001	0.006
Rep (Y)	0.0002	0.60	0.08	0.0001
Treatm. (T)	0.003	0.0001	0.0001	0.0005
Y*T	0.34	0.0001	0.007	0.12

Appendix 28. P>F values from the ANOVA for the foliar area (cm^2) of quinoa plants established on harvested potato fields with application of fertilizers during the 2007-08 growing season in two high elevation communities of Umala.

	Kellhuiri			Vinto Coopani		
Days after planting	60	90	120	60	90	120
Source						
	-- P > F --					
Rep	0.24	0.09	0.03	0.0001	0.95	0.40
Treatment	0.07	0.0004	0.0004	0.06	0.07	0.03

Appendix 29. P>F values from the ANOVA for the foliar area (cm^2) of quinoa plants established on harvested potato fields with application of fertilizers during the 2007-08 growing season in two low elevation communities of Umala.

	San Juan Circa			San José de Llanga		
Days after planting	60	90	120	60	90	120
Source						
	-- P > F --					
Rep	0.14	0.90	0.67	0.009	0.003	0.0002
Treatment	0.13	0.0001	0.0002	0.63	0.0001	0.0001

Appendix 30. P>F values from the ANOVA for the quinoa plant emergence (%), plant height (cm) and grain yield (kg ha^{-1}) established on harvested potato fields with application of fertilizers in communities of Umala.

Source	Plant emergence	Plant height	Grain yield
	-------------------------	P > F	------------------------
Year (Y)	0.88	0.04	0.01
Location (L)	0.0001	0.0001	0.0001
Y*L	0.0002	0.0001	0.0001
Rep (Y*L)	0.0001	0.0001	0.0001
Treatm. (T)	0.001	0.0001	0.007
Y*T	0.26	0.47	0.54
L*T	0.25	0.45	0.78
Y*L*T	0.95	0.46	0.99

Appendix 31. P>F values from the ANOVA for the fresh potato yield (Mg ha^{-1}) by effect of inorganic and organic fertilizers in communities of Umala.

Source	Marketable size	No-marketable size	Total yield
	-------------------------	P > F	------------------------
Year (Y)	0.0004	0.0001	0.0001
Location (L)	0.03	0.0001	0.01
Y*L	0.03	0.0001	0.32
Rep (Y*L)	0.006	0.31	0.005
Treatm. (T)	0.0001	0.040	0.0001
Y*T	0.63	0.004	0.75
L*T	0.41	0.0001	0.90
Y*L*T	0.65	0.001	0.93

Appendix 32. P>F values from the ANOVA for the leaf petiole total N (%) and the sap petiole nitrate-N (mg L^{-1}) measured by the Cardy meter under the effects of inorganic and organic fertilizers in communities of Umala.

Source	Cardy NO_3^--N meter	Leaf petiole Total N
	----------- P > F ----------	
Year (Y)	0.29	0.0001
Location (L)	0.46	0.40
Y*L	0.58	0.01
Rep (Y*L)	0.0001	0.0001
Treatm. (T)	0.0001	0.0001
Y*T	0.0001	0.0001
L*T	0.82	0.09
Y*L*T	0.27	0.0001

Appendix 33. **P>F values from the ANOVA for the leaf petiole total N (%) and the sap petiole nitrate-N (mg L^{-1}) measured by the Cardy meter under the effects of inorganic and organic fertilizers applied in two growing seasons in three communities of Umala.**

	Kellhuiri				Vinto Coopani				San Juan Circa			
	2006-07		2007-08		2006-07		2007-08		2006-07		2007-08	
Source	Cardy meter	Total N	Cardy meter	Total N	Cardy meter	Total N	Cardy meter	Total N	Cardy meter	Total N	Cardy meter	Total N
	---------- P > F ----------											
Rep	0.14	0.04	0.0001	0.0001	0.001	0.08	0.0001	0.57	0.0006	0.05	0.13	0.002
Treatment	0.0001	0.02	0.0001	0.53	0.0001	0.0001	0.0001	0.90	0.0001	0.15	0.0001	0.002

Appendix 34. Major cultural practices performed in the potato field trials during the 2006-08 growing seasons in four communities in Umala.

	Kellhuiri		Vinto Coopani		San Juan Circa		San José de Llanga	
Activities	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08	2006-07	2007-08
	--Schedule --							
Treatment application and planting	11/06/06	11/27/07	11/08/06	11/13/07	11/09/06	11/15/07	11/07/06	11/13/07
Urea application and hilling	12/26/06	01/04/08	12/28/06	01/03/08	12/29/06	01/07/08	12/27/06	01/12/08
Pesticide application	01/24/07	02/09/08	01/24/07	02/08/08	01/25/07	02/14/08	01/26/07	02/12/08
Harvesting	04/18/07	04/24/08	04/20/07	04/22/08	04/19/07	04/17/08	-	-

Appendix 35. Major cultural practices performed in the quinoa field trials during the 2007-09 growing seasons in four communities in Umala.

	Kellhuiri		Vinto Coopani		San Juan Circa		San José de Llanga	
Activities	2007-08	2008-09	2007-08	2008-09	2007-08	2008-09	2007-08	2008-09
	--Schedule --							
Planting	11/27/07	11/04/08	11/21/07	11/12/08	11/23/07	12/03/08	11/22/07	-
Pesticide application	02/13/08	02/20/09	02/15/08	02/20/09	02/07/08	02/21/09	02/05/08	-
Harvesting	04/28/08	04/09[†]	04/27/08	04/09[†]	04/29/08	04/09[†]	04/27/08	-

[†] Harvested the last week of April, 2009.

VITA

Javier Aguilera Alcón was born on May 26, 1965 in La Paz Bolivia. He is the son of Luis Aguilera and Lucy Alcón. In 1990, he obtained his B.S. in Agronomy from the San Simón Major University in Bolivia. In November 1989, he initiated his career in the Promotion and Investigation of Andean Products (PROINPA) Foundation as a junior researcher in the Potato Seed Production Program, where he gained important experience in conducting research. He was promoted to become the Head of this Program in 1994. In 1998, he obtained his M.S. degree in Horticulture at the University of Madison-Wisconsin in the United States. Once he returned to Bolivia, he assumed important responsibilities with PROINPA in conducting field research and technology transfer in the Central Andean Highland region of Bolivia. The goal of his work was improving crop productivity of Andean crops and training poor farmers of this region mostly in integrated crop management practices.

Between 1998 and 2006, he was responsible for designing and conducting several national and international agricultural research projects. In 2001, he married Cecilia Salinas and they had two boys, Santiago and Joaquín Aguilera Salinas. In 2006, as a part of an international project in which he was involved, he had the opportunity to improve his academic education and he moved, along with his family, to Missouri in the United States to pursue a Ph.D. degree in Soil, Environmental & Atmospheric Sciences at the University of Columbia-Missouri. After almost three and half years of continuous learning and enjoying the beauty of Columbia, MO, he is finally graduating on May 15, 2010 and he will be returning to Bolivia to continue his agricultural research activities.