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Impacts of Cultivation and Fallow Length on Soil Carbon and Nitrogen Availability in the Bolivian Andean Highland Region

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Inclusion of periods of unmanaged or natural fallowing is an important soil management practice in the potato-based cropping systems of the resource-poor Andean highland region (Altiplano) of Bolivia. However, in recent years the area in fallow and the fallow length are being reduced due to greater land use intensity and competing land uses. The objectives of this study were to determine the effects of the length of cropping and fallowing periods on soil degradation or soil restoration, and to compare the potential soil carbon and nitrogen mineralization from a range of cropped and fallow lands at different elevations. Four representative indigenous communities of the semiarid central Altiplano were selected, 2 at a relatively high elevation and 2 at a relatively low elevation. Soil samples were collected in 2006 and 2007 from fields at the first, second, and third year of crop rotation and from fields with 1, 10, 20, 30, and 40 years of fallow and analyzed for several soil properties. In general, the upper elevations had significantly higher soil organic carbon, total nitrogen, inorganic nitrogen, soil test phosphorus and potassium, exchangeable calcium and magnesium, and cation exchange capacity than the lower elevations. Cropping significantly decreased total and active soil organic carbon and total, inorganic, and active soil nitrogen. Fallowing was observed to restore total and active soil organic carbon and total and active soil nitrogen more rapidly in the higher communities than in the lower communities; this difference was mainly attributed to differences in initial soil properties, climate, and land management in cropped fields with elevation. Further research may be needed to determine which factor has the most influence on soil degradation and soil fertility restoration in this environment in order to assist farmers to improve soil fertility.

Keywords: *Fallow; elevation; Altiplano; active soil carbon and nitrogen; crop rotation.*

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Introduction

Importance of crop rotation

Systems of crop rotation vary in their duration and sequence, 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 causing higher soil water infiltration (Katsvairo et al 2002) and reduction in soil bulk density and penetrometer 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 carbon dioxide (CO_2) emissions compared to continuous crop production (Wilson and Al-Kaisi 2008).

Crop rotation can also result in increased soil nitrogen (N) and soil organic matter (SOM). In a 2-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 nitrate amounts and lower levels of soil test phosphorus (P) when compared with corn grown continuously (Riedell et al 1998). These results confirm the findings of many other studies of rotation effects that, for example, show an increase of soil nitrate in crop rotations, such as soybeans after sorghum (*Sorghum vulgare* Pers.) or soybeans after corn (Peterson and Varvel 1989) or when using red clover within the crop rotation (Raimbault and Vyn 1991). In general, crop rotation often results in higher crop yields and economic returns (Halvorson et al 2002).

Effects of fallow on soil properties

The inclusion of a fallow period in the crop rotation is an 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 or natural fallow is widespread in semiarid regions of Latin America, but little information on changes in soil properties, soil degradation, or natural rehabilitation due to this practice is available.

Type and length of fallow are also important for soil fertility restoration and improvement of soil properties. Five-year fallow fields recovered higher total porosity, macroporosity, and saturated hydraulic conductivity than fields with 2 years of fallow (Miranda et al 2009). Soil organic carbon (SOC) and soil nutrient (N, P, and potassium [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 10 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 their original levels, but this recovery level attained only 50% of that registered in undisturbed sites 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, 4 years of fallow in sandy soils in Senegal did not significantly increase SOM or soil nutrient concentrations (Masse et al 2004), and after 10 years of fallow there was no clear evidence of recovery of nutrient elements or any clear improvement in soil physical properties (eg bulk density) or chemical properties (eg SOC) with increasing natural fallow in the Bolivian Altiplano (Hervé 1994).

In the Andean highlands region of Bolivia, little research has been conducted (or at least published) on the effects of cropping and fallow length on soil restoration and soil characteristics. Moreover, few studies have sought to determine the optimum length of fallow to achieve desired soil restoration. In this region, crop rotations are often initiated with potato (*Solanum tuberosum* L.) followed by 2 to 3 years of cereal crops (eg quinoa [*Chenopodium quinoa* Willd.], barley [*Hordeum vulgare* L.], oats [*Avena sativa* L.]), and then an uncultivated fallow period that can last 1–15 years (de Queiroz et al 2001) or even 20 years (Hervé 1994; Motavalli et al 2009). These extended periods of natural fallow are expected to restore soil fertility mainly through the addition of organic matter due to the decomposition of both above- and below-ground plant biomass of native vegetation. The fallow period is also expected to control crop diseases and pests and to generate a mix of short evergreen shrubs (eg *thola* [*Parastrephia lepidophylla*]) and perennial bunch-grasses for grazing and for cooking fuel (Hervé 1994; de Queiroz et al 2001).

However, the increase in rural human population in this region and competing land uses are reducing 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 regrowth 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). Gomez-Montano et al (2013) recently found that longer fallow periods decreased soil fungal diversity in farm fields in the central Altiplano and lowered soil bacterial diversity in farm fields in the northern Altiplano. In that study, the presence of *thola* in agricultural fields during fallow periods increased the presence of some soil microbial genera, such as *Fusarium* and *Bradyrhizobium*, but did not have any significant effect on soil microbial diversity. Other researchers have found no significant change (Abreu et al 2009) or an increase in microbial biomass N (Jaimes 2000) with increased fallow years after cultivation in the high tropical Andes.

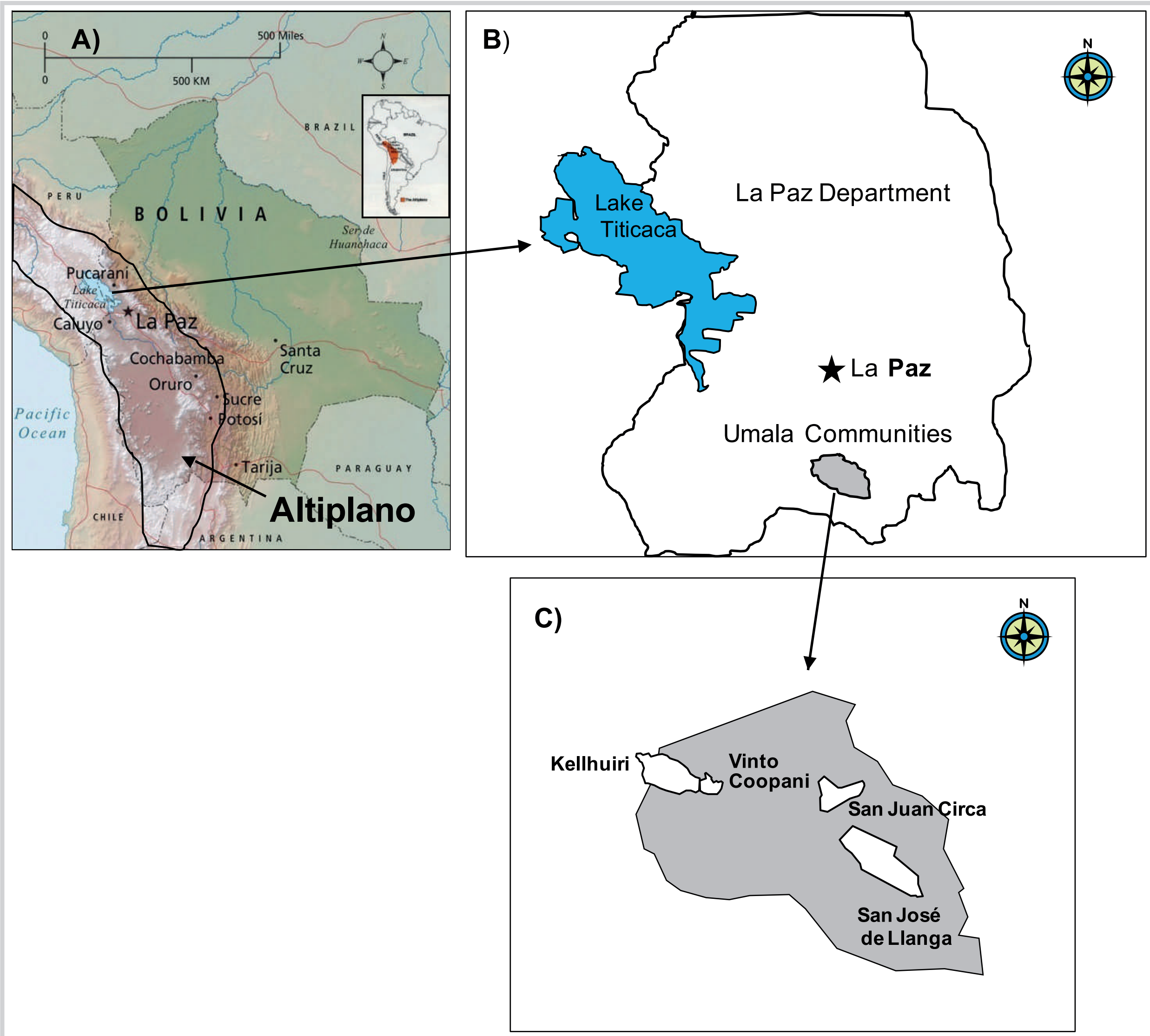
The objectives of this study were (1) to determine the effects of cultivation and fallowing periods on soil properties including soil carbon (C) and N and (2) to compare the potential soil C and N mineralization from a range of cropped and fallow lands at different elevations.

Material and methods

Area of study

This research was conducted during the 2006 and 2007 growing seasons in the Andean highland (Altiplano) region of Bolivia. Four representative communities (Kellhuiri, Vinto Coopani, San Juan Circa, and San José Llanga) in the central Altiplano were selected for this research (Figure 1). These communities are located in the Umala municipality (17°17′S, 68°08′W), approximately 28 km from the town of Patacamaya and 129 km from the capital city, La Paz. They were selected to represent traditional indigenous communities at relatively low and high elevations. Umala is a mostly semiarid region situated between 3750 and 4100 m above sea level (masl), with low rainfall (annual average 350 mm) distributed erratically during the growing season and an average

FIGURE 1 Maps showing (A) the location of the Bolivian Altiplano; (B) the location of Umala in the central Altiplano; (C) the locations of the 4 communities in Umala. (Map adapted from library.thinkquest.org and www.compassion.com).



annual air temperature of 11°C (PROINPA 2005). The potential agricultural productivity of this region is limited by several factors, including adverse climate (such as delays in rainfall in the early planting season), early frost, and hail and drought during the growing season (FAO and SNAG 1995; Garcia et al 2007). Other factors limiting growth are the presence of multiple pests and diseases, poor seed quality (PROINPA 2005), and soil limitations 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 higher elevations, and San Juan Circa and San José Llanga at lower elevations. Selected characteristics of each community are presented in Table 1 and highlight the differences in access to land and income from farming and nonfarming activities. In general, the lower-elevation communities had higher incomes and resources than those in the higher elevations (Valdivia et al 2007).

The altitude difference between higher- and lower-elevation communities is approximately 250 m. At the higher elevations, the land has more hills and steeper slopes, and soil tillage generally depends on animals. The soil at these elevations has a high proportion of rocks, and farmers do not use enough manure and manufactured fertilizers to optimize crop growth. The primary work for people in these communities is crop and sheep production, with potato production the major source of food and income (Table 1). 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

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TABLE 1 Selected characteristics of 4 rural communities in Umala in the central Altiplano region of Bolivia in 2006.[a)]

Characteristics	Community			
	High elevation		Low elevation	
	Kellhuiri	Vinto Coopani	San Juan Circa	San José de Llanga
Altitude (meters above sea level)	4070	4013	3806	3771
Demographics				
Population	108	55	179	395
Education, head of household (y)	5.2	4.4	5.3	7.1
Age, head of household (y)	52.4	50.4	48.6	49.3
Total household labor (adult equivalent)	3.2	3.8	3.3	3.4
Natural and agricultural resources				
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 (number of varieties)	4.4	3.8	3.2	3.8
Crop diversity (number of crops)	2.8	2.7	2.7	2.8
Livestock				
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
Off-farm employment	12.2	23.2	5.2	6.3
Others	5.7	4.8	2.3	3.2

[a)]Source: Valdivia et al (2007, 2010).

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 high wind frequency and intensity. Dairy production is a major economic activity at the lower elevations (Valdivia 2004), and there is greater access to schools and markets.

At both elevations, potato is the initial crop in the rotation, and barley is usually the last crop before farmers leave fields to natural fallow to recover soil fertility and then initiate a new cropping phase. The important native evergreen shrub *thola* (*P. lepidophylla*) is the most predominant evergreen vegetation that regrows in natural fallow lands and is considered an important soil cover for preventing soil erosion by water (in steep slope areas) or wind (in flat, uncovered areas); 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 a source of fuel, building material, and medicinal herb. More discussion of vegetative succession after disturbance in the high tropical Andes can be found in Sarmiento et al (2003).

Surveys of the study communities conducted in 2006 indicated that more than 90% of farmers in the high-elevation communities (Kellhuiri and Vinto Coopani) and fewer than the 25% of the farmers in the low-elevation communities (San Juan Circa and San José de Llanga) used manure (sheep, cow, or mixed) as a source of organic fertilizer (Aguilera 2010). Rates of manure application (average of 2.9 t ha^{-1} in high elevations and 0.8 t ha^{-1} in

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low elevations) were lower than the recommended rate for the area, which is 10 t ha^{-1} (FAO and SNAG 1995).

Use of inorganic fertilizers (diammonium phosphate and urea) was highest in the lower-elevation communities and less than 10% in the higher-elevation communities. Where inorganic fertilizers were applied, the average rate across the 4 communities was less than 105 kg ha^{-1} of diammonium phosphate and less than 45 kg ha^{-1} of urea. Recommended fertilization rates for potato crops in this region are 261 kg ha^{-1} of diammonium phosphate at planting and 72 kg ha^{-1} of urea at hilling time.

Soil sampling and analysis

Two to three replicate soil samples were taken just prior to the growing season in October 2007 from agricultural fields in the 4 communities, which were in traditional potato-based cropping systems and had different lengths of cropping and fallow. All the fields contained 1 soil type with a sandy loam texture, which is classified as sandy, mixed, frigid Typic Ustifluvents in US soil taxonomy (USDA 1999). This soil type is an important and common agricultural soil in the 4 communities and is locally called *ch'alla* soil.

Based on farmers' information on the cropping history of each field, researchers and farmers of the 4 communities collected 31 soil samples from cropped lands having 1, 2, or 3 years of crop rotation, and 50 soil samples from lands with 1, 10, 20, 30, or 40 years of fallow. Farmers of this region do not keep a written cropping history; therefore, we assumed that fallows described as lasting 20, 30, or 40 years might have ±2 years of variation. Land with 20 to 40 years of fallow is rare in Umala municipality, but some fields were identified and soil samples collected as a control for assessing the extent of SOM accumulation at different ages of fallow. Basic information was obtained on the cropping history of each field from which samples were collected, to supplement soil analysis results. Use of chronosequences for determination of changes in soil and plant properties over time, as was done in this research, has limitations (see Walker et al 2010) and was based on some assumptions, including that all sites had relatively homogenous initial conditions.

Soil samples were collected to a 20 cm depth using hand trowels; 15 to 20 subsamples were collected over the extent of each field (often 1 ha or less in size) and then composited. 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 TruSpec® C/N analyzer (LECO Corp., St. Joseph, MI, USA). 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 (nitrogen in the form of ammonium and nitrate [TIN]) was extracted by shaking 4 g soil samples in 40 mL of a 2 molar potassium chloride solution 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, 1993) recommended for the Lachat QuikChem automated ion analyzer (Lachat Instruments, Milwaukee, WI, USA). Other soil properties (soil pH_s [soil pH measured in 0.01 molar calcium chloride extract], soil test P [using the Bray 1 extracting solution] and K, exchangeable calcium [Ca] and magnesium [Mg], cation exchange capacity [CEC], and electrical conductivity [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). This procedure has been used to estimate the active fraction of soil organic C and N that is more rapidly mineralized (Motavalli et al 1994; 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 kilopascals soil moisture tension and a constant temperature of 25°C. 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 (1, 3, 7, 14, 21, 28, 42, 56, 70, and 84 days after initiation of the experiment), mineralized soil total inorganic N (MTIN) (nitrate and ammonium) 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 ammonium and nitrate were determined in the leachates using the Lachat QuikChem automated ion analyzer (Lachat Instruments, Milwaukee, WI, USA). For determining soil C mineralization, samples were periodically placed in sealed mason jars and the headspace swept with carbon dioxide [CO_2]-free air. The jars were then sealed for approximately 45 hours, and change in head space CO_2 concentration due to soil CO_2 evolution was then determined using a gas chromatograph (Buck Scientific, East Norwalk, CT, USA) fitted with a thermal conductivity detector.

Statistical analysis

Because the number of soil sample replications for years of fallow and cultivation were not balanced among communities, PROC GLM was used to compare the effect of years of cropping and fallow on soil pH, SOC, TN, TIN, 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 MTIN and C mineralization. Means

TABLE 2 Selected soil properties due to different cropping and fallow lengths in Umala communities at relatively high elevation. (Table 2 extended on next page.)

Community/type of rotation	Length of rotation (y)	pH_s (0.01 M $CaCl_2$)	Total inorganic N (mg kg^{-1})	Soil test Bray 1 P (mg kg^{-1})
Kellhuiri				
Cropping	1	6.2	7.9	22
	2	5.3	5.8	39
	3	5.9	5.2	54
Fallow	1	5.5	4.9	49
	10	6.0	5.7	35
	20	5.8	6.4	15
	30	7.0	6.5	19
Tukey-Kramer[a)]		NS	1.7	NS
Vinto Coopani				
Cropping	1	6.1	9.9	55
	2	5.8	7.1	19
	3	5.8	6.0	34
Fallow	1	5.8	5.5	18
	10	5.9	5.9	26
	20	6.6	6.2	22
	30	7.6	7.0	28
	40	5.8	6.8	34
Tukey-Kramer [a)]		NS	1.9	NS

[a)]Tukey-Kramer minimum difference at $P \leq 0.05$; NS, not significant.

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 the relationship between years of cropping or years of fallow with TIN, SOC, TN, MTIN, and cumulative CO_2-C mineralized.

Results and discussion

No significant differences in soil pH, soil test P, or EC among treatments and in the 4 communities were detected (Tables 2 and 3). These results differ from those observed by Abadín et al (2002), who found an increase in soil acidity and soil test P with cultivation and after 1 year fallow in the Venezuelan Andes compared to selected sites in the Bolivian Andes. There was a significant difference in TIN in the 4 communities, with the highest content in the first year of cropping across communities (Tables 2 and 3). 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} 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 Llanga).

The soil TIN content was higher in the upper elevations than in the lower elevations at the first and second year of cropping, but at the third year it was the opposite (Tables 2 and 3). These results are due to the fact that inorganic fertilizers containing N are applied only to the first crop of the rotation (potato), and the potato crop utilizes a large proportion 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 that decays and adds organic N to the soil.

Except for the Vinto Coopani community, the cumulative MTIN determined by an 84-day incubation

TABLE 2 Extended. (First part of Table 2 on previous page.)

Community/type of rotation	Soil test K (mg kg^{-1})	Exchangeable Ca (mg kg^{-1})	Exchangeable Mg (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	EC (dS cm^{-1})
Kellhuiri					
Cropping	270	1154	151	9.0	0.3
	250	778	85	8.1	0.2
	316	1403	121	10.7	0.2
Fallow	242	1197	124	10.0	0.1
	316	1904	171	12.8	0.3
	250	1267	164	10.3	0.3
	162	1550	159	10.7	0.2
Tukey-Kramer[a)]	NS	NS	NS	NS	NS
Vinto Coopani					
Cropping	413	957	121	8.0	0.3
	145	1435	230	10.8	0.1
	181	1157	154	9.4	0.1
Fallow	155	1276	221	10.0	0.1
	294	1562	240	11.7	0.2
	243	3479	188	20.8	0.4
	173	3345	193	20.0	0.3
	238	1262	203	10.1	0.3
Tukey-Kramer [a)]	NS	NS	NS	NS	0.3

showed significant differences among years of cropping and years of fallow (Figure 2). In Kellhuiri, San Juan Circa, and San José Llanga, the amounts of MTIN decreased with years of cropping and increased with years of fallow. Across communities, high amounts of cumulative MTIN were observed for the first year of cropping, and Kellhuiri and Vinto Coopani (upper-elevation communities) had considerably higher amounts (467 and 418 mg kg^{-1}, respectively) than the lower communities of San Juan Circa and San José Llanga (304 and 119 mg kg^{-1}, respectively). When grouping higher and lower communities, the cumulative soil MTIN also showed similar differences between elevations as was observed for soil TIN content, indicating higher labile organic N in the upper elevations than in the lower elevations (Figure 2). The cumulative MTIN showed no significant relationship with years of cropping or with years of fallow for either the upper or lower communities, although a general decrease of cumulative MTIN was observed with years of cropping for both elevations (Figure 2).

The SOC content showed significant difference depending on years of cropping and fallow only in Vinto Coopani and San Juan Circa communities (Figure 3). 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%. In San Juan Circa, SOC showed a decrease with years of cropping (from 0.7% to 0.5%), and fallow showed a significant increase only at 40 years. In other highland regions, such as in forest and grassland sites in Africa, comparison of a chronosequence of cropped versus undisturbed native soils indicated over 85% losses of total SOC, especially during the first 4 years of cultivation, which was attributed to land use changes and human-induced land-cover changes affecting the active fraction of soil organic matter (Solomon et al 2007).

The SOC was significantly lower in soils collected from farm fields in the lower-elevation communities (San Juan Circa and San José Llanga) than in the upper-elevation communities (Kellhuiri and Vinto Coopani) (Figure 3). This difference may have been due to the generally higher sand content of the soils in the lower communities, the more intensive mechanized tillage used in those communities, and their higher temperatures, which may have contributed to a higher rate of SOC decomposition.

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TABLE 3 Selected soil properties due to different cropping and fallow lengths in Umala communities at relatively low elevation. (Table 3 extended on next page.)

Community/type of rotation	Time of rotation (y)	pH_s (0.01 M $CaCl_2$)	Total inorganic N (mg kg^{-1})	Soil test Bray 1 P (mg kg^{-1})
San Juan Circa				
Cropping	1	6.3	8.0	28
	2	5.9	7.1	23
	3	5.9	6.6	22
Fallow	1	5.7	5.0	23
	10	5.8	4.4	29
	20	6.3	4.6	22
	30	6.1	4.2	24
	40	5.9	4.5	22
Tukey-Kramer[a)]		NS	1.1	NS
San José de Llanga				
Cropping	1	6.1	6.5	25
	2	6.0	5.5	30
	3	7.4	5.2	20
Fallow	1	5.7	3.3	22
	10	5.6	3.7	29
	20	6.0	2.3	20
	30	6.3	2.6	25
	40	6.2	2.5	21
Tukey-Kramer[a)]		NS	1.0	NS

[a)]Tukey-Kramer minimum difference at $P \leq 0.05$; NS, not significant.

No significant linear or polynomial relationship was determined between SOC and years of cropping in either elevation (Figure 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 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 than in those from lower elevations (Figure 3). The fitted polynomial curve determined in both elevations showed a consistent increase of SOC with years of fallow; generally, a maximum accumulation was reached at higher elevations after approximately 20 to 30 years of fallow and continued to accumulate in the lower elevations over 40 years of fallow (Figure 3). These results are consistent with findings by Pestalozzi (2000), who detected, in the high Andes of Bolivia (4000–5000 masl), 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 southwestern 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 10th year of fallow. On the other hand, evaluations by Hervé et al (1994) in the central Bolivian Altiplano found no clear evidence of recovery of nutrient elements even after 10 years of fallow.

The soil 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 C mineralized showed significant differences among years of cropping and years of fallow (Figure 4). In Kellhuiri, San Juan Circa, and San José Llanga, the amount of C mineralized decreased with

TABLE 3 Extended. (First part of Table 3 on previous page.)

Community/type of rotation	Soil test K (mg kg^{-1})	Exchangeable Ca (mg kg^{-1})	Exchangeable Mg (mg kg^{-1})	CEC (cmol$_c$ kg^{-1})	EC (dS cm^{-1})
San Juan Circa					
Cropping	184	1846	300	13.9	0.2
	131	1007	136	7.4	0.1
	133	912	133	7.0	0.1
Fallow	142	844	153	6.9	0.2
	169	710	119	6.0	0.1
	129	1061	143	7.6	0.2
	138	675	113	5.3	0.1
	193	1387	220	10.1	0.1
Tukey-Kramer[a)]	62	905	180	5.9	NS
San José de Llanga					
Cropping	111	443	68	4.3	0.2
	108	465	68	4.7	0.2
	90	722	65	5.1	0.2
Fallow	114	317	49	2.9	0.1
	150	285	42	3.1	0.1
	128	319	49	3.0	0.2
	163	727	87	5.3	0.1
	134	386	57	3.3	0.1
Tukey-Kramer[a)]	70	NS	39	NS	NS

increasing years of cropping and increased with increasing years of fallow. High amounts of C mineralized were observed in the first year of cropping, and Kellhuiri and Vinto Coopani (upper communities) obtained higher amounts (2923 and 3427 mg kg^{-1} respectively) than did San Juan Circa and San José Llanga (lower communities) (2087 and 1464 mg kg^{-1} respectively).

When grouping higher and lower communities, the cumulative soil C mineralized showed similar differences between elevations (Figure 4) as was observed for SOC (Figure 3). The SOC content was considerably larger in the higher elevations than in the lower elevations during both 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 (Figure 3). Others have observed in the Andes in Venezuela that the maximum level of active C accumulation occurred after 8 years of fallow (Cabaneiro et al 2008).

Soil TN content was significantly different among treatments in all communities except San José Llanga (Figure 5). 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 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-year fallow period, which had a significant increase (from 0.05 to 0.08%).

Soil TN was significantly lower in soils collected from both cropping and fallow fields in the lower-elevation communities than in the upper-elevation communities (Figure 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 that of Barrios et al (2005), who found, in a study of Andean hillsides in Colombia, a consistent increase in TN across time of fallow.

The differences in SOC, soil TN, and soil TIN between the upper and lower communities may have been due to lower regrowth of native vegetation (eg *thola*), as observed

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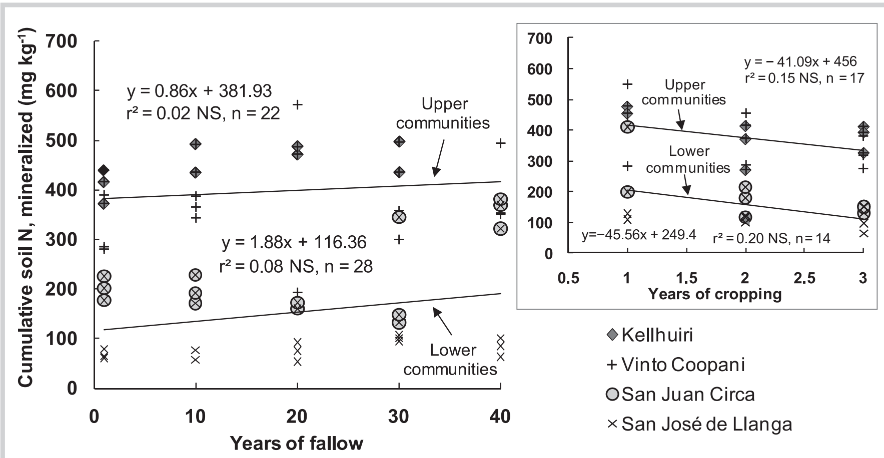
FIGURE 2 Cumulative soil N mineralized after 84 days of incubation of samples collected from different years of cropping and fallow in the upper and lower Umala communities.



by community members (Aguilera 2010), causing fewer 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.

Soil test K was significantly different among treatments only in San Juan Circa and San José Llanga (the lower communities) (Tables 2 and 3). 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}). The exchangeable Ca differed significantly among treatments only in Vinto Coopani and San Juan Circa. In Vinto Coopani, it 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 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 mg kg^{-1}, respectively). Among all communities, San José 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}) but showed a comeback at 40 years of fallow (10.1 cmol$_c$ kg^{-1}). These results suggest that cultivation generally decreased and fallowing generally increased certain characteristics of

FIGURE 3 Soil total organic C content under different years of cropping and fallow in the upper and lower Umala communities.

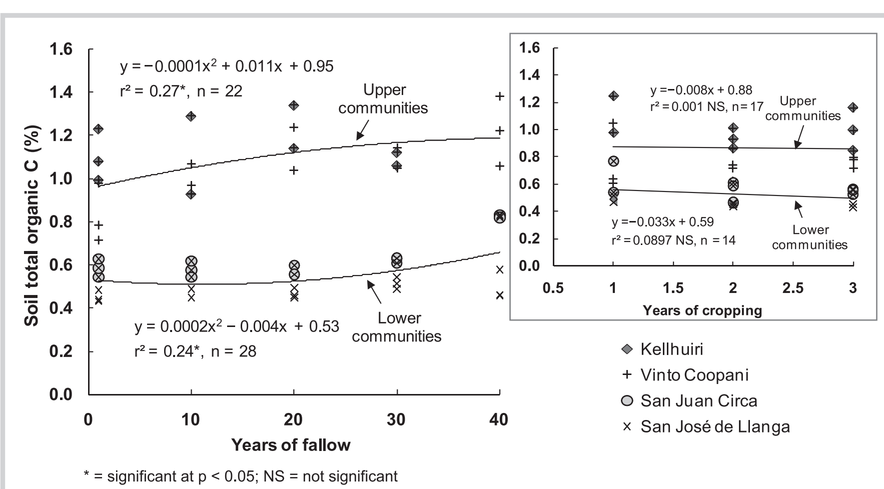
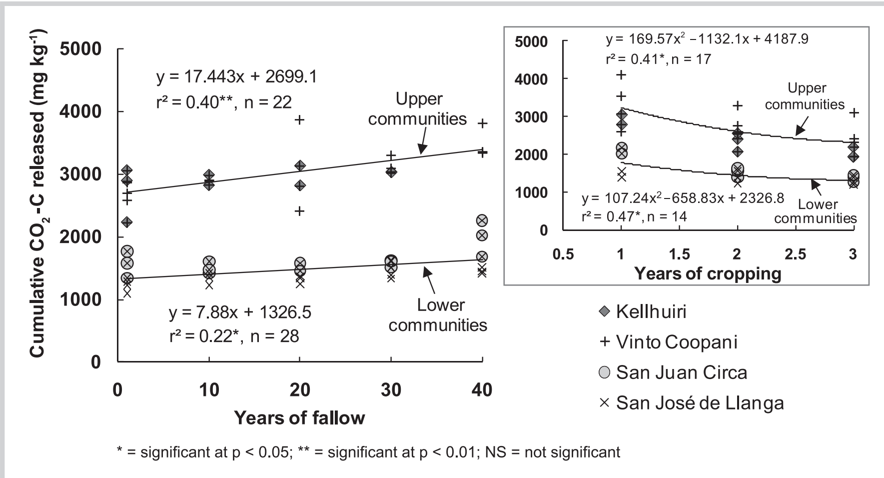


FIGURE 4 Soil cumulative C (as carbon dioxide [CO_2]) released after 84 days of incubation of samples collected from different years of cropping and fallow in the upper and lower Umala communities.



soil fertility, but the effects of cultivation and fallowing were not consistent across all communities that were included in this study.

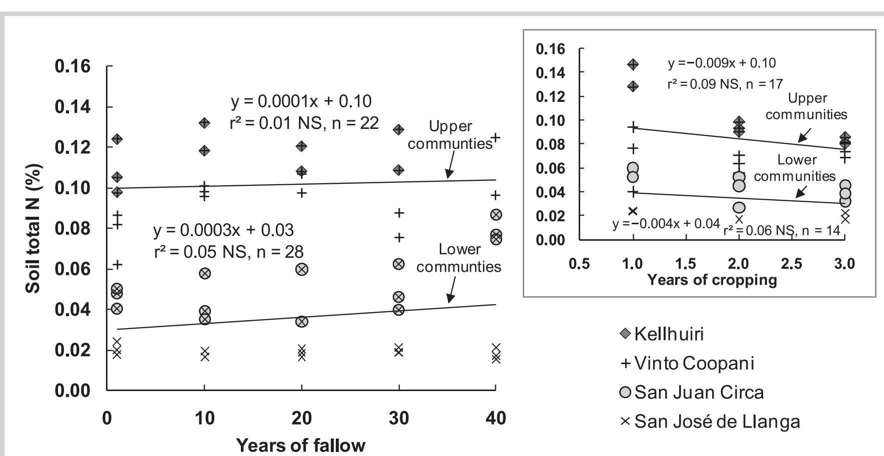
Subsequent research in the same communities by Aguilera et al (2012) indicated that combined use of inorganic and organic fertilizers (eg manure) in the potato-based cropping system practiced in this region also generally improved soil fertility both in the year of application and in the subsequent year. Increased use of these fertilizers may also be needed if traditional fallowing and other soil restoration practices are decreased.

Conclusions

The upper-elevation communities in Umala municipality examined in this study had higher initial soil fertility status than the lower communities, as evidenced by higher soil total organic C, total N, TIN, soil test P and K, exchangeable Ca and Mg, and CEC. This difference may be due to greater soil degradation in lower-elevation communities caused by diverse factors, including changing climate (eg increased wind frequency and intensity that leads to increased soil erosion) and inappropriate soil management practices, such as the excessive use of tractors for 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 Llanga communities, although this effect varied among soil properties and among the four communities. Years of cropping had an impact on more

FIGURE 5 Soil total N content under different years of cropping and fallow in the upper and lower Umala communities. NS, not significant.



soil properties in the low-elevation communities (San Juan Circa and San José de Llanga) than in the high-elevation communities (Kellhuiri and Vinto Coopani). Years of cropping have also been shown to decrease active organic C and N at both elevations.

Fallow increased soil chemical properties in agricultural lands of the 4 communities. 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 communities. This trend may be associated with soil management practices in lower communities such as use of the conventional tillage system, scarce use of soil organic fertilizers, higher *thola* removal, and overgrazing of fallow lands. The soil restoration detected in these communities suggests that 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 increased active organic C and N in all communities.

The decreasing length of the fallow period and reduction in native vegetation caused by greater land use intensity and mechanized tillage may be removing an important mechanism by which total and active soil organic C and general soil fertility are restored in potato-based cropping systems in this region. Some communities may be affected more than others due to differences in elevation, which affects initial environmental conditions, management practices, and the subsequent rate of soil degradation.

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