Initial and Residual Effects of Organic and Inorganic Amendments on Soil Properties in a Potato-Based Cropping System in the Bolivian Andean Highlands

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Authors’ contributions

This work was carried out in collaboration between all authors. Authors JA, PPM and CV designed the study and JA wrote the first draft of the manuscript. Authors JA and MAG coordinated the field trials and JA performed the statistical analysis with advisement from PPM. Authors JA and PPM managed the analyses of the study. All authors read and approved the final manuscript.

ABSTRACT

The objective of this study was to determine the effects of applications of organic and inorganic soil amendments on initial and residual soil chemical, physical and biological properties that may affect both short- and long-term soil fertility in a potato (Solanum tuberosum L.)-based cropping system of indigenous rural communities in the Bolivian Andean Highlands (Altiplano). Field experiments were conducted in four representative low and high elevation communities in the semi-arid Central Andean Region of Bolivia from 2006 to 2009. Treatments included a control, and applications of sheep and cow manure, a commercial household/urban compost product, a commercial biofertilizer soil amendment, urea and diammonium phosphate and combinations of these different treatments. Soil samples were taken from all the sites prior to application of treatments and planting of potatoes as well as during the growing season and prior to planting of a
subsequent crop of quinoa (*Chenopodium quinoa*, Willd). Soil pH, soil total organic C, and total N increased due to application of organic fertilizers with or without inorganic fertilizers. Soil inorganic N and Bray-1 P were increased by inorganic fertilizers alone or when combined with organic fertilizers. The residual effect of most of the analyzed soil nutrients was detected in the subsequent growing season. In addition, lower soil bulk density was observed after organic fertilizers were applied with or without inorganic fertilizers and this residual effect persisted for the quinoa crop. In a controlled laboratory incubation experiment, soil potentially mineralizable C and N increased as organic fertilizers application rates rose from 0 to 30 Mg ha\(^{-1}\). These results highlight the importance of a balanced soil fertilization program in this region with use of optimum rates of both inorganic and organic soil amendments to increase short- and long-term soil fertility.

**Keywords:** Andean highlands; potato; soil amendments; quinoa; residual soil fertility.

### 1. INTRODUCTION

Soil organic and inorganic fertilizers are important for agricultural sustainability because of their possible beneficial effects on soil properties and long-term 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 agronomic and environmental outcomes have been observed depending on the specific agroecosystem (Saha et al., 2008).

Some of the primary effects of use of organic fertilizers are increased soil organic matter (SOM) and improved 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. Over-reliance on use of chemical fertilizers 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 application rates of fertilizers and pesticide application (Singh, 2000).
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) which was mainly attributed to increased biomass production that 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 soil total 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 NO₃ 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 towards 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, intensive cultivation and overgrazing have caused drastic declines in soil productivity and increased risks of soil erosion (Kessler and Stroosnijder, 2006). 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. However, 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 objective of this study was to determine the effects of applications of organic and inorganic soil amendments on initial and residual soil chemical, physical and biological properties that may affect both short- and long-term soil fertility.

2. MATERIALS AND METHODS

2.1 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 (Fig. 1). 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 11ºC 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. Selected characteristics of each individual community are provided in Table 1. In general, communities at the higher elevations have a higher proportion of steep slopes and rocky areas with a predominance of animal-based tillage systems and sheep livestock. Because of the greater number of livestock, farmers in these higher elevation communities, use only manure as source of fertilizer, and have relatively small farm size (average 7 ha per household).

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. Community members use organic soil amendments for potato production although a few of them combine organic with inorganic fertilizers. Only around 250 m difference exists between the elevations of the low and high communities.
Fig. 1. Maps showing A) the location of the Bolivian Altiplano; B) the location of Umala in the Central Altiplano and C) the locations of the four communities in Umala

2.2 Experimental Design for the Field Trials

The experiment included 12 treatments representing organic and inorganic fertilizers used individually or in combination and at different rates (Table 2). The nutrient amendments used included four conventional and alternative organic fertilizers (i.e., composted cow manure, composted sheep manure, household compost, Biofert) and inorganic fertilizers
(i.e., urea + diammonium phosphate [DAP]). Farmers in this region normally apply local cow or sheep manure alone or combine both together but often at suboptimal rates (PROINPA 2005). Biofert (Biotop Company, Cochabamba, Bolivia) is a commercial solid biofertilizer 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 (http://www.biotopbolivia.org/). According to the manufacturer, the product contains *Bacillus subtilus* (1.1%) and *Glomus fasciculatum* (10.0%) microbes that make nutrient and moisture assimilation more efficient and promote plant growth (http://www.biotopbolivia.org/). The compost used in this research was produced commercially from household urban waste.

Results of previous individual community participatory workshops for the communities studied in this research indicated significant variation in application rates of organic (0.8 to 3.3 Mg ha\(^{-1}\) of manure) and inorganic (13 to 104 kg ha\(^{-1}\) of diammonium phosphate [DAP] and 13 to 42 kg ha\(^{-1}\) of urea) soil amendments among families (Gilles et al., 2009). However, for the field trials, recommended rates for both organic and inorganic fertilizers were applied as shown in Table 2. Recommended mineral fertilization rates for potato crops in the Altiplano region of 80 kg N, 120 kg P\(_{2}O_{5}\) and 0 kg K\(_{2}O\) ha\(^{-1}\), 261 kg ha\(^{-1}\) of DAP (18% N – 46% P\(_{2}O_{5}\) – 0% K\(_{2}O\)) were applied at planting and 72 kg ha\(^{-1}\) of urea (46% N) at hilling time based on Alvarez (1988) and Bellot (1991).

### Table 1. Selected characteristics of four rural communities in Umala in the Central Altiplano region of Bolivia in 2006.

| Characteristics                      | Kellhuiri | Vinto | Coopani | San Juan | San José de Llanga |
|--------------------------------------|-----------|-------|---------|----------|--------------------|
| Altitude (meters above sea level)    | 4,070     | 4,013 | 3,806   | 3,771    |
| *Demographics*                       |           |       |         |          |                    |
| 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 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 (No. of varieties) | 4.4       | 3.8   | 3.2     | 3.8      |
| Crops diversity (No. 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      |

*HH= Household; ha= Hectares  
Source: Valdivia et al (2007, 2010)*
Table 2. Annual application rates of soil organic and inorganic fertilizers and total N, P and K applied in the potato field trials in selected higher and lower Umala communities

| Treatment identification | Nutrient source and application rates | Total N  | Total P | Total K  |
|--------------------------|--------------------------------------|----------|---------|----------|
| 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
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 conducted over three growing seasons starting with potato as the first crop in the 2006-2007 season followed by quinoa in 2007-2008. A separate set of fields received initial fertility treatments for potato in the 2007-2008 season followed by quinoa in 2008-2009 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 Llianga. 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 organic and inorganic fertilizer 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.

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.

### 2.3 Soil and Organic Amendment Sampling and Analysis

Initial soil samples were taken from all the sites prior to application of treatments and before the planting of the potato crops. In addition, soil samples were taken at blooming time during the growing season planted to potato to assess relative differences in soil nutrient content and other soil properties due to the treatments. This sampling date was at approximately 110 days after planting (Dap) during the 2006-07 season and 105 Dap in the 2007-08 season. For assessment of residual treatment effects on soil properties, soil samples were also taken prior to planting of the quinoa crop in 2007-08 and 2008-09. Ten soil samples were collected to a depth of 20 cm within each plot using a trowel, mixed in a plastic bucket, and a composite sample was then removed and stored in a labeled plastic bag. When plants were
present, the soil samples were taken between the plants in the plant row.

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$_4$AOc 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 air-dried 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 4ºC 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 TruSpec® CN analyzer (LECO Corp., St. Joseph, MI). 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) with a core sampler with a 7.6 cm diameter core. 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 110ºC 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 using a TruSpec® CN analyzer (LECO Corp., St. Joseph, MI).

### 2.4 Soil C and N Mineralization Potential

To determine soil C and N mineralization potential with addition of organic amendments used in the field experiment, an aerobic leaching incubation experiment (Motavalli et al., 1995) was conducted in the laboratory. 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 showed that it contained an average (± std. dev.) of 1.0±0.1% total organic C and 0.09±0.01% total N (Table 3).

Treatments included in the laboratory incubation 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 25ºC 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) were 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 dry 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).

### 2.5 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 ≤ 0.05.
Table 3. Selected soil properties of the bulk soil from the Vinto Coopani community used for determination of soil C and N mineralization potential

|                       | 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 ± 1   |

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

3.1 Rainfall Distribution during the Growing Season

The cumulative precipitation across the different field trials during 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 (Fig. 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.

3.2 Initial Soil Analysis

Initial soil chemical and physical characteristics prior to treatment application in the field plots and of organic fertilizers are presented in Table 4. 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 elevation 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 5). 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 organic C and total N were observed either in cow and sheep manure at higher elevations (i.e., Kellhuiri and Vinto Coopani) than those at lower elevations (i.e., 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.

3.3 Changes in Soil Properties

3.3.1 Soil chemical properties

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 6. 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).

Fig. 2. Daily and cumulative precipitation during the 2006-2009 growing seasons in the Umalá 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.
Table 4. 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 | Soil bulk density | Total org C | Total N | C:N ratio | pH$_{c}$ (0.01 M CaCl$_{2}$) | Soil test Bray1 P | Soil test K | Exch. Ca | Exch. Mg | CEC | EC |
|----------------|------------------|-------------|--------|-----------|----------------------------|------------------|------------|----------|----------|-----|----|
| 2006-07 Kellhuiri | 1.42 ± 0.06 | 0.9 ± 0.0 | 0.08 ± 0.01 | 12 ± 3 | 5.2 ± 0.1 | 35 ± 9 | 690 ± 33 | 74 ± 9 | 7.5 ± 0.1 | 0.4 ± 0.2 |
| 2006-07 Vinto Coopani | 1.50 ± 0.04 | 0.7 ± 0.0 | 0.07 ± 0.01 | 10 ± 1 | 5.1 ± 0.0 | 53 ± 5 | 520 ± 51 | 72 ± 7 | 6.5 ± 0.5 | 0.5 ± 0.1 |
| 2006-07 San Juan Circa | 1.36 ± 0.08 | 0.6 ± 0.0 | 0.05 ± 0.01 | 13 ± 3 | 5.7 ± 0.1 | 35 ± 2 | 686 ± 104 | 110 ± 13 | 5.9 ± 0.7 | 0.3 ± 0.1 |
| 2006-07 San José de Llanga | 1.49 ± 0.07 | 0.5 ± 0.1 | 0.04 ± 0.01 | 13 ± 5 | 5.4 ± 0.1 | 39 ± 8 | 298 ± 47 | 51 ± 5 | 3.4 ± 0.5 | 0.3 ± 0.1 |

| 2007-08 Kellhuiri | 1.39 ± 0.03 | 0.9 ± 0.2 | 0.09 ± 0.02 | 10 ± 0 | 5.9 ± 0.2 | 17 ± 2 | 199 ± 25 | 171 ± 22 | 12.6 ± 1.2 | 0.2 ± 0.1 |
| 2007-08 Vinto Coopani | 1.49 ± 0.07 | 0.9 ± 0.1 | 0.08 ± 0.01 | 12 ± 1 | 5.8 ± 0.1 | 101 ± 16 | 935 ± 106 | 137 ± 10 | 9.0 ± 0.5 | 0.2 ± 0.0 |
| 2007-08 San Juan Circa | 1.42 ± 0.04 | 0.6 ± 0.0 | 0.03 ± 0.00 | 17 ± 2 | 6.4 ± 0.2 | 27 ± 1 | 2312 ± 337 | 330 ± 47 | 15.5 ± 2.0 | 0.3 ± 0.1 |
| 2007-08 San José de Llanga | 1.48 ± 0.02 | 0.8 ± 0.1 | 0.08 ± 0.01 | 10 ± 1 | 7.6 ± 0.2 | 15 ± 1 | 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 5. Selected properties of the organic fertilizers used in the field trials during the 2006 to 2008 growing seasons in Umala

| Organic material | Year/community | Analysis | C:N ratio | Total org. C | Total N | Total P | Total K |
|------------------|----------------|----------|-----------|-------------|--------|---------|---------|
| Sheep manure‡    | 2006-07        |          |           |             |        |         |         |
| Kellhuiri        | 71.6           | 26.4     | 1.5       | 0.34        | 2.00   |         |         |
| Vinto Coopani    | 68.1           | 18.6     | 1.1       | 0.45        | 0.97   |         |         |
| San Juan Circa   | 69.1           | 25.9     | 1.5       | 0.54        | 1.62   |         |         |
| San José de Llanga | 76.8          | 15.0     | 0.6       | 0.36        | 0.65   |         |         |
|                  | 2007-08        |          |           |             |        |         |         |
| Kellhuiri        | 70.4           | 26.6     | 1.9       | 0.40        | 0.71   |         |         |
| Vinto Coopani    | 76.7           | 24.4     | 1.6       | 0.41        | 1.35   |         |         |
| San Juan Circa   | 70.7           | 23.3     | 1.6       | 0.39        | 2.24   |         |         |
| San José de Llanga | 81.6         | 19.3     | 0.9       | 0.34        | 1.24   |         |         |
| Cow manure‡      | 2006-07        |          |           |             |        |         |         |
| Kellhuiri        | 69.3           | 26.1     | 1.4       | 0.34        | 1.86   |         |         |
| Vinto Coopani    | 71.9           | 23.9     | 1.7       | 0.41        | 0.73   |         |         |
| San Juan Circa   | 82.6           | 21.6     | 1.3       | 0.77        | 2.90   |         |         |
| San José de Llanga | 68.3          | 15.1     | 0.6       | 0.43        | 0.76   |         |         |
|                  | 2007-08        |          |           |             |        |         |         |
| Kellhuiri        | 70.6           | 31.6     | 2.2       | 0.44        | 0.84   |         |         |
| Vinto Coopani    | 69.2           | 14.8     | 0.6       | 0.36        | 2.06   |         |         |
| San Juan Circa   | 75.3           | 22.5     | 1.3       | 0.32        | 0.63   |         |         |
| San José de Llanga | 75.1         | 16.9     | 0.8       | 0.26        | 1.10   |         |         |
| Compost§         | All communities | 58.8     | 13        | 1.2         | 0.3    | 0.7     |         |
| Biofert§         | All communities | 87.9     | 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 amendment used for planting potato. Same compost and Biofert materials were used for all the communities and for both growing seasons.

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 test P 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) (NH₄⁺-N and NO₃⁻-N). In 2006-07 all treatments increased soil TIN, but in 2007-08 only treatments including inorganic fertilizers alone or combined with cow, sheep or both together significantly increased soil TIN. Differences in soil TIN in the control treatment (T1) between the two growing seasons is possibly partially due to the differences in initial soil properties among the new sites used to evaluate the first year effects of the treatments with potato including generally higher soil total N (Table 4) as well as differences in the pattern of rainfall during the growing season (Fig. 2).

A significant interaction was found for the effects of community and treatment on soil test K (Table 7). Soil test 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 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).

### 3.3.2 Soil bulk density

The bulk density in potato field trials before planting and treatment application showed no significant differences between growing seasons but it did among communities (Table 4). For instance, averaging over the 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).
Table 6. 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 approximately 105 to 110 days after planting during the 2006-07 and 2007-08 growing seasons.

| Treatments | pH<sub>s</sub> (0.01 M CaCl<sub>2</sub>) | Soil test Bray 1 P | Exch. Ca | Exch. Mg | Inorganic N‡ | Total organic C | Total N | CEC | cmol<sub>c</sub> kg<sup>1</sup> |
|------------|---------------------------------|----------------|---------|---------|-------------|----------------|--------|-----|-----------------|
| T1         | 5.9                             | 33.5           | 1190    | 147     | 3.5         | 0.76           | 0.05   | 9.0             |
| T2         | 5.7                             | 63.3           | 1234    | 154     | 32.8        | 0.85           | 0.06   | 9.6             |
| T3         | 6.1                             | 40.3           | 1237    | 152     | 8.4         | 0.83           | 0.06   | 9.2             |
| T4         | 6.2                             | 41.6           | 1234    | 151     | 8.9         | 0.80           | 0.06   | 9.1             |
| T5         | 6.1                             | 39.3           | 1233    | 154     | 8.6         | 0.86           | 0.07   | 9.1             |
| T6         | 6.1                             | 41.0           | 1302    | 160     | 8.8         | 0.81           | 0.06   | 9.4             |
| T7         | 5.8                             | 66.5           | 1180    | 149     | 38.7        | 0.86           | 0.07   | 9.1             |
| T8         | 6.0                             | 59.1           | 1261    | 159     | 37.6        | 0.80           | 0.06   | 9.5             |
| T9         | 5.9                             | 60.9           | 1251    | 153     | 38.2        | 0.84           | 0.06   | 9.5             |
| T10        | 6.1                             | 39.5           | 1240    | 150     | 8.7         | 0.82           | 0.06   | 9.0             |
| T11        | 6.1                             | 43.1           | 1202    | 150     | 8.8         | 0.81           | 0.06   | 9.0             |
| T12        | 6.1                             | 41.6           | 1237    | 153     | 9.0         | 0.95           | 0.06   | 9.2             |
| LSD<sub>0.05</sub> † | **0.1**             | **7.0**         | NS      | NS      | **4.3**     | **4.8**        | **0.06** | NS             |

T1 = Control, T2 = DAP (18% N – 46% P<sub>2</sub>O<sub>5</sub> – 0% K<sub>2</sub>O) + Urea (46% N), T3 = Cow manure (CM) (10 Mg ha<sup>1</sup>), T4 = Sheep manure (SM) (10 Mg ha<sup>1</sup>), T5 = CM (5 Mg ha<sup>1</sup>) + SM (5 Mg ha<sup>1</sup>), T6 = Compost (5 Mg ha<sup>1</sup>), T7 = CM + DAP + Urea, T8 = SM + DAP + Urea, T9 = CM + SM + DAP + Urea, T10 = CM + Biofert (0.2 Mg ha<sup>1</sup>), T11 = SM + Biofert, T12 = CM + SM + Biofert pH<sub>s</sub> = (0.01 M CaCl<sub>2</sub>).

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

† Least Significant Difference Test (P < 0.05); NS = not significant.
Table 7. Soil test K content of potato field trials under organic and inorganic fertilizers for the four communities in Umala averaged over the 2006-07 and 2007-08 growing seasons. Samples collected at blooming time approximately 105 to 110 days after planting during the 2006-07 and 2007-08 growing seasons.

| Treatments | Kellhui | Coopani | San Juan | San José de Llanga |
|------------|---------|---------|----------|--------------------|
| 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 †      | NS      | 88      | 79       | 46                 |

T1 = Control, T2 = DAP (18% N – 46% P2O5 – 0% K2O) + 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.

Statistical analysis of the effects of treatments, communities and season on soil bulk density at harvest time showed significant differences among the treatments and with the control (Fig. 3). Soil bulk density of the control treatment measured prior to potato harvest appeared to be higher than was measured for untreated soil at the beginning of the growing season (Table 4) possibly due to the effects of hilling during the growing season. 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 growing seasons but significant differences among treatments were observed (Fig. 4). 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. Sarkar 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.
Table 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

| Treatments | 2007-08‡ | | | | 2008-09‡ | | | |
|-------------|----------|----------|----------|----------|----------|----------|----------|----------|
|             | Organic | Total | C:N | Inorganic | Soil test | Inorganic | Soil test |
|             | C | N | Ratio | N | Bray 1 P | % | mg kg⁻¹ | Bray 1 P | % | mg kg⁻¹ |
| 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% P2O5 – 0% K2O) + 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
Fig. 3. Soil bulk density of potato field trials under organic and inorganic fertilizers. Samples collected just prior to harvest. Significant differences were only among treatments; therefore, data is presented averaged over growing seasons and communities.

Fig. 4. Soil bulk density of quinoa field trials established on harvested potato fields under organic and inorganic fertilizers. Samples collected just prior to harvest. Significant differences only among treatments; therefore, data is presented averaged over growing seasons and communities.
3.4 Soil Potential C and N Mineralization in Incubation Experiment

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 (Figs. 5 and 6). 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$^{-1}$. 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 with application of organic fertilizers at a rate of 10 Mg ha$^{-1}$ 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. 5). For the cumulative soil CO$_2$-C mineralized, no significant differences among treatments at 7.5 Mg ha$^{-1}$ was detected. Compared to the compost treatment, 15 and 30 Mg ha$^{-1}$ of sheep and cow alone and combined with Biofert showed significantly higher accumulation. 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 soil 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).

![Fig. 5. Cumulative soil inorganic N (NH$_4^+$-N and NO$_3^-$-N) due to the effects of different rates of organic fertilizers](image-url)
Soil properties, such as pH, soil test P, soil TN, soil TIN and soil organic C and bulk density, of agricultural lands in the Central Bolivian Andean Highlands were highly influenced both during the first and subsequent cropping seasons after application of conventional and alternative organic amendments either applied alone or in combination with inorganic fertilizers. Increases of soil organic C due to application of organic amendments may have also influenced the improvement of other soil properties, such as soil bulk density during the initial and subsequent growing seasons 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 based on cumulative soil CO$_2$-C mineralization measurements compared to the cow and sheep manure tested in the research. Therefore, compost does not appear to be a promising alternative for this region if animal manures are available or it may need to be tested for periods beyond two growing seasons.

Biofert combined with cow or sheep alone or with both together improved initial and residual soil chemical and physical properties compared to those of the control, but its effect was not significantly better than compared to soil properties when manure was 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 was higher as rate of organic fertilizers increased from 0 to 30 Mg ha⁻¹. The observed rise in CO₂-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 CO₂ is also an indicator 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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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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