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Response of a Potato-Based Cropping System to Conventional and Alternative Fertilizers in the Andean Highlands

J. Aguilera[1], P. P. Motavalli[2*], M. A. Gonzales[1] and C. Valdivia[3]

[1]Andean Seed Project, FAO-Land and Rural Development Ministry, Av. Defensores del Chaco # 1997 (Zona Chasquipampa), La Paz, Bolivia.
[2]Department of Soil, Environmental and Atmospheric Sciences, University of Missouri, Columbia, Missouri, 65211 USA.
[3]Department of Agricultural and Applied Economics, University of Missouri, Columbia, Missouri, 65211 USA.

Authors' contributions

Authors JA, PPM and CV designed the study and Aguilera wrote the first draft of the manuscript. Authors JA and MAG coordinated the field trials and author JA performed the statistical analysis with advisement from author PPM. Authors JA and PPM managed the analyses of the study. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

A three-year study to determine the initial and residual effects of inorganic and organic fertilizers on potato (*Solanum tuberosum* L.) and subsequent quinoa (*Chenopodium quinoa*, Willd) crop performance was conducted in four indigenous communities in the central Bolivian Andean Highland region starting in 2006. The objectives of this research were to identify conventional and alternative fertilizers and combinations of those nutrient sources that improve potato growth and yields and to assess the residual effect of nutrient amendments applied to a previous crop on quinoa as a subsequent crop in the rotation. On-farm trials using local crop management practices had an unfertilized control and separate and combined treatments of local conventional and alternative organic sources (i.e., composted cow and sheep manure, household/urban compost and Biofert, a solid biofertilizer), and inorganic fertilizer (diammonium phosphate + urea). Treatments including inorganic fertilizer alone or combined with cow and sheep manure significantly

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**Corresponding author: E-mail: motavallip@missouri.edu;*

increased potato tuber yields 67, 68, 79 and 74% over the yield observed in the control plots. The residual effect of these treatments also increased quinoa grain yield 61, 58, 44 and 58% over that of the control. These results are possibly due to the more rapid nutrient availability of applied inorganic fertilizers compared to the application of organic amendments. Increased use of inorganic fertilizers in this region may be necessary because of the reduced availability of organic amendments and the need for improved crop production in both the initial potato crop and subsequent quinoa phase of the crop rotation that depends on residual soil fertility.

Keywords: Andean Highlands; potato; soil amendments; quinoa; residual soil fertility.

1. INTRODUCTION

In the Bolivian Altiplano, the rural indigenous population is predominantly engaged in small–scale rain-fed farming, where crops are planted only once a year most often during late spring or early summer (November/December). The production system normally initiates with potato followed by one or two years of small grains, such as quinoa, barley or oats and then succeeded by a relatively long fallow period (up to 10 years) or by perennial grasses [1]. This fallow practice is mainly utilized to restore soil fertility due to the accumulation of organic material through the re-growth of natural vegetation.

In this region, potatoes are usually the only crop fertilized in the rotation due to its major importance as a source of food and income [2] and because of its high nutrient requirements during the growing season [3]. A certain portion of nutrients applied to the potato crop is expected to remain in the field after the crop is harvested for subsequent crops in the rotation. However, the amount of residual nutrients may depend on several factors, including the type and amount of fertilizers applied, plant requirements and utilization during the growing season, climate during the growing season, yield, crop residue management and soil characteristics (e.g., drainage, CEC).

There is strong evidence for the residual effects of organic fertilizers that last for several years [4]. This residual effect of organic amendments improves long-term soil and crop productivity through the gradual release of soil nutrients over several growing seasons [5]. There is also evidence of residual effects of inorganic fertilizers on soil and crop productivity [6], although their residual effects may last less time than organic fertilizers, especially for nutrients such as N.

In general, individuals of the Bolivian Altiplano continuously face low crop productivity due to several factors, including adverse climatic conditions, high incidence of pathogenic crop pests and diseases, and low soil fertility [2]. Research in this region has reported low levels of soil N, P, and total organic C (less than 1%) [7], although moderate to high levels of soil K were detected [1]. Many authors have stated that nutrient management is important for enhancing short- and long-term soil fertility and for improving crop production or crop profitability [8]. Selection of the appropriate source, timing, placement and application rate of plant nutrients is critical to optimize crop productivity while minimizing any potential negative environmental effects from excess nutrients entering into the environment [3,9].

Farmers of the Bolivian Altiplano generally apply low rates of composted sheep or cow manure alone or mixed both, and some farmers combine these organic fertilizers with low amounts of inorganic fertilizers [10]. Organic soil amendments used in this region primarily consist of composted sheep and dairy cow manure which are produced by livestock owned by the respective farm household, and the availability of these manures depends on the number and type of livestock that the household has and the labor available for collection and transport [10]. Organic amendments are often less convenient to use due to the difficulty and extra labor requirements in the collection, handling and application of these low-analysis materials [7]. Moreover, in these semi-arid regions, several competing uses exist for manure resources such as fuel and construction demands, which reduce the availability of these materials for land application [11].

Numerous research studies have been conducted in the Bolivian Altiplano region on the effects of different rates of chemical and organic fertilizers on selected soil properties and on crop growth and production, but results of most of these studies were not published and this information is not easily accessible. For example, a combination of inorganic and organic (manure) soil fertilizers applied in potato plots showed 60% and 300% increased potato tuber yield compared to the inorganic fertilizer alone and the control plot respectively [7], and the application of manure, compost or chemical fertilizer alone did not significantly increase tuber yield [12]. Aguilera et al. [13] reported on the initial and residual effects of use of inorganic and organic fertilizers on soil properties in the Bolivian Altiplano indicating significant residual effects of these soil amendments. However, few studies have examined the residual effects of both conventional and alternative inorganic and organic fertilizers on agronomic performance in this region.

The objectives of this research were to: 1) evaluate conventional and alternative sources of organic and inorganic fertilizers and combinations of those nutrient sources that improve potato growth and yields, and 2) assess the residual effect of nutrient amendments applied to a previous crop on quinoa as a subsequent crop in the rotation.

2. MATERIALS AND METHODS

2.1 Experimental Site and Communities

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 11°C and an average annual precipitation of 350 mm. This region is exposed to frequent occurrences of frost and drought events during the growing season.

Four representative indigenous Aymara communities of the Umala municipality in the Central Altiplano region were selected for this study: Kellhuiri (4,070 m above sea level) and Vinto Coopani (4,013 m above sea level) at relatively higher elevations and San Juan Circa (3,806 m above sea level) and San José de Llanga (3,771 m above sea level) at relatively lower elevations. There were some important overall differences between the high and low elevation communities. The communities at the higher elevations generally had a higher proportion of steep slopes and rocky areas with a predominance of animal-based tillage systems and sheep livestock. Individuals in these communities use only manure as source of fertilizer, and have relatively small farm sizes (average 7 ha per household).

In contrast, the lower elevation communities were predominantly located on flat areas with high sand content and they mainly utilized tractor-based tillage and cows for livestock with most families involved in dairy production. This low elevation area has less native vegetation in fallow lands, possibly due to greater tractor-based tillage and the greater removal of native vegetation for fuel purposes compared to higher elevations. Only around 250 m difference exists between the elevations of the low and high elevation communities.

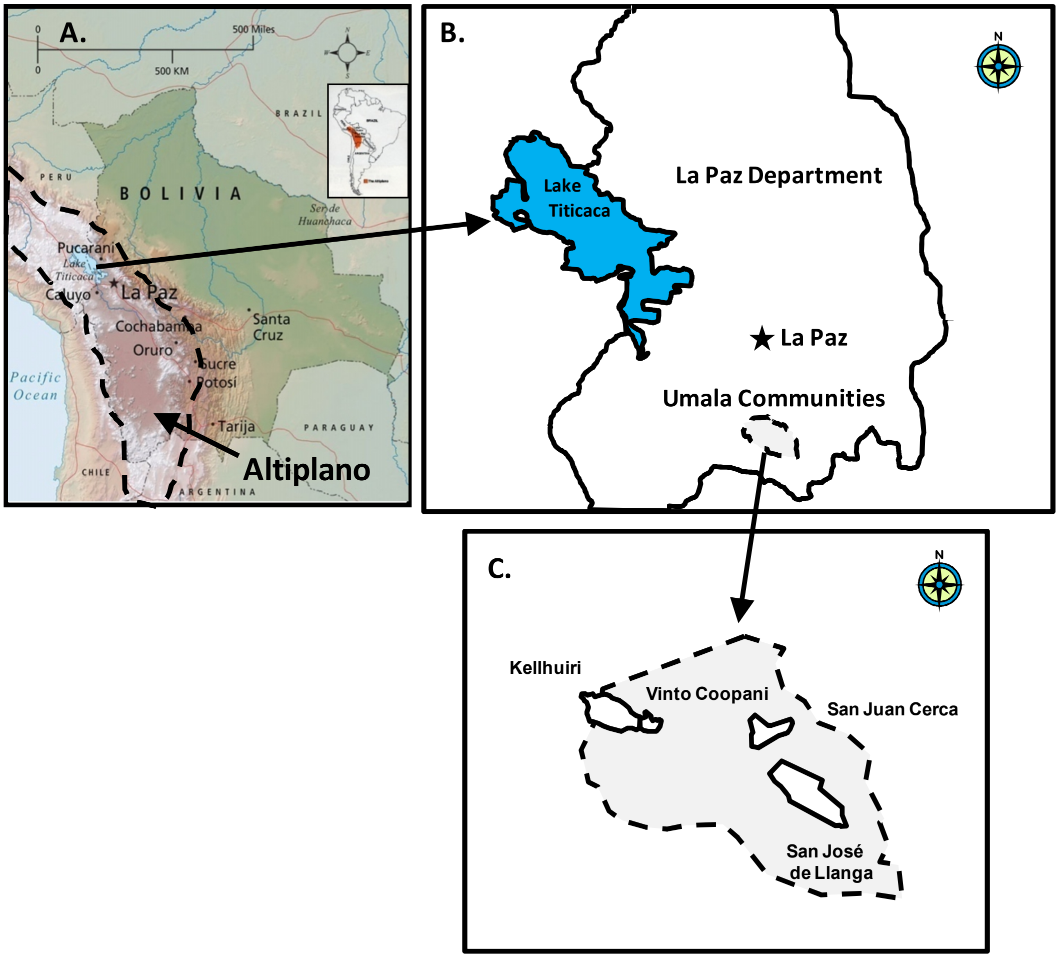

Fig. 1. Maps showing A) the location of the Bolivian Altiplano; B) the location of Umala in the Central Altiplano, and C) the locations of the four communities in Umala. (Map adapted from library.thinkquest.org and www.compassion.com).

2.2 Experimental Design for Field Trials

The field trials were initiated in 2006 and included four conventional and alternative organic nutrient amendments (i.e., composted cow manure, composted sheep manure, household compost, Biofert) alone or combined with inorganic fertilizer (i.e., urea + diammonium phosphate [DAP]) making a total of 12 treatments (Table 1). Farmers in this region normally apply local cow or sheep manure alone or combine both together but often at suboptimal rates [2]. Both household/urban compost and Biofert are alternative soil amendments that

Table 1. Fertility treatments applied in potato field trials in selected higher and lower elevation Umala communities

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

are not commonly used in this region. Biofert is a solid biofertilizer that is designed to be a supplement for organic fertilizers and is being tested by a local non-governmental organization, Promotion and Investigation of Andean Products Foundation (PROINPA). It contains a source of organic N which the manufacturer claims enhances soil microbial activity. In addition, the product literature says it contains Mycorrhiza fungi that make nutrient and moisture assimilation more efficient, and Bacillus bacteria that promote plant growth [2]. The compost used in this research was produced commercially from household urban waste consisting primarily of food waste, composted in piles and then bagged for sale.

Results of community participatory workshops conducted prior to 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 of diammonium phosphate [DAP] and 13 to 42 kg ha^{-1} of urea) soil amendments among the different communities [10]. However, for this research, both organic and inorganic fertilizers were applied at rates recommended by [14] and [15] and PROINPA (Table 1). To reach the recommended mineral fertilization rate for potato crops in the Altiplano region, 80 kg N, 120 kg P_2O_5 and 0 kg K_2O ha^{-1}, 261 kg ha^{-1} of DAP (18% N – 46% P_2O_5 – 0% K_2O) were applied at planting and 72 kg ha^{-1} of urea (46% N) at hilling time.

The manure treatments were applied at a rate of 10 Mg ha^{-1} (wet weight basis with an average dry matter of 73.1% across locations and years), the compost treatment was applied at a rate of 5 Mg ha^{-1} (wet weight basis with a DM of 58.8%, and the Biofert treatment was combined with the manure and compost and applied at an application rate of 0.2 Mg ha^{-1} (wet weight basis with a DM of 87.9%).

The study was set up over three growing seasons starting with potato as the first crop followed by quinoa. A separate set of fields received initial fertility treatments for potato in the first year so that there would be two seasons of initial fertilization of potato and two seasons of residual effects in quinoa. All practices for the establishment and management of the trials followed were based on commonly used local practices including land preparation, hand-seeding and placement of fertility treatments in the side of the hill. All the trials contained one soil type with a sandy loam textural class which was classified in the U.S. Soil Taxonomy as a sandy, mixed, frigid Typic Ustifluvents. Clay content of this soil ranged from 5 to 10%.

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

400 mL ha^{-1} (52.5 mL ha^{-1}a.i.). Potatoes were hand harvested in 5 m lengths from three central rows of the five plot rows after plants and tubers reached physiological maturity in April of both 2007 and 2008.

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

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

2.3 Soil and Organic Amendments Sampling and Analysis

Initial soil samples were taken from all the sites prior to application of treatments and before the planting of potato and quinoa crops. Ten soil samples were collected to a depth of 20 cm within each plot, mixed in a plastic bucket, and a composite sample was then removed and stored in a labeled plastic bag. The soil samples were subsequently air-dried, ground using a mortar and pestle, and then passed through a sieve with 2 mm openings. All the samples were then analyzed for soil pH (0.01 M $CaCl_2$), neutralizable acidity [N.A.], total organic carbon [SOC], total nitrogen [N], inorganic N (NH_4^+-N + NO_3^--N), exchangeable calcium [Ca] and magnesium [Mg], soil test phosphorus [Bray P1], soil test potassium [1 M NH_4AOc at pH 7], effective cation exchange capacity [CEC], electrical conductivity [EC] and soil physical (bulk density and soil gravimetric water content) analyses. Soil chemical analyses (except for total inorganic N, total organic C and total N) were determined using standard methods for the University of Missouri Soil and Plant Testing Laboratory [16].

Total inorganic N (NH_4^+-N and NO_3^--N) was extracted by shaking 4-g soil in 40 mL of 2 M KCl solution at approximately 180 rpm for 1 hour and filtering soil and extracting solution through Whatman no. 2 filter paper. The extracts were then stored in sealed plastic scintillation vials at 1 to 4 ºC in a refrigerator prior to analysis. Ammonium-N and NO_3^--N were determined colorimetrically using a flow injection analyzer ([17,18]. 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).

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 placed in labeled plastic bags. Organic amendments were then 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 [16]. Total organic C and N were determined by combustion of approximately 0.100 g samples using a TruSpec® CN analyzer (LECO Corp., St. Joseph, MI).

The results of soil property changes due to the application of inorganic and organic fertilizers in this research are presented and extensively discussed in Aguilera et al. [13].

2.4 Agronomic Evaluations

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

In potato trials, plant height was measured in nine plants per plot at 57, 71, 85 and 115 days after planting (Dap) from the soil surface to the last apical leaf insertion on top of the plant canopy. Plant foliar cover or foliar growth of 9 plants per plot were evaluated at 44, 58, 85, and 100 Dap by using a 90 cm x 70 cm frame containing hundred squares of 9 x 7 cm. The methodology consisted of counting the number of squares covered by at least 50% foliage [19].

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

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

By the third week of April 2008 and 2009, when the quinoa seed heads were sufficiently dry, at approximately 15 to 20% of moisture content as reported as the standard moisture content of most quinoa varieties at harvesting time [20], plants were hand harvested in 5 m length from six central rows of the ten plot rows by cutting the aboveground portion of the plant. Seed heads were stored until harvesting time was over and they were hand threshed to separate the grain from the seed head. Subsequently, they were air-dried for about 2 days to reach a commercial moisture content ranging from 12 to 15% and total grain harvest per plot was then determined and yields expressed on a dry weight basis.

2.5 Statistical Analysis

All research data collected in the experimental trials conducted for this study were analyzed using the SAS statistical program [21]. The analysis of variance was performed by using PROC ANOVA and comparisons among treatments were tested through Fisher's Protected Least Significant Difference (LSD) Test and the test for statistical differences among the treatment means were at $P = 0.05$.

3. RESULTS AND DISCUSSION

3.1 Temperature and Rainfall

Temperature and rainfall registered in Vinto Coopani (higher) and San Juan Circa (lower) community over the growing seasons showed no major differences between both elevations (Figs. 2-3). In San Juan Circa, the average temperature was similar among the seasons, although in 2008-09 there were higher temperatures recorded in November, December and March compared to those recorded for the same months in 2006-07 and in 2007-08 (Fig. 2). In 2007-08 there were also more below freezing temperatures at the beginning and the end of growing seasons in November, March and April compared to the other two seasons (Fig. 2). In Vinto Coopani, higher temperatures were registered in February and lower in November, March and April, 2007-08 than in 2008-09 (Fig. 3). Potato and quinoa were planted in late November in 2007-08 when temperatures below freezing had already passed. Low temperatures were recorded in late March and during April causing frost damage to both potato and quinoa plants but yields were not significantly affected because crop plants had started the senescence period.

In San Juan Circa, the cumulative amounts of precipitation among the three seasons from potato or quinoa planting to harvest were not considerably different (i.e., 365 mm in 2006-07, 380 mm in 2007-08, and 346 mm in 2008-09) (Fig. 2). However, the distribution pattern differed among growing seasons with a high rainfall concentration in February and March 2007, almost even distribution from the end of November, 2007 to the middle of March, 2008, and almost even distribution from the end of December 2008 to the end of April 2009. In Vinto Coopani, cumulative precipitation was different between the 2007-08 and 2008-09 growing seasons (i.e., 401 mm in 2007-08 season and 503 mm in 2008-09) (Fig. 3). The distribution pattern also differed between both seasons with more rainfall concentrated in the middle of the season in 2007-08 compared to that of the 2008-09 season.

In general across communities and growing seasons, higher rainfall amounts and lower temperatures occurred in Vinto Coopani (high community elevation) compared to that of San Juan Circa (low community elevation), and these differences may have caused some variability in potato and quinoa crop performance in response to the soil fertility treatments.

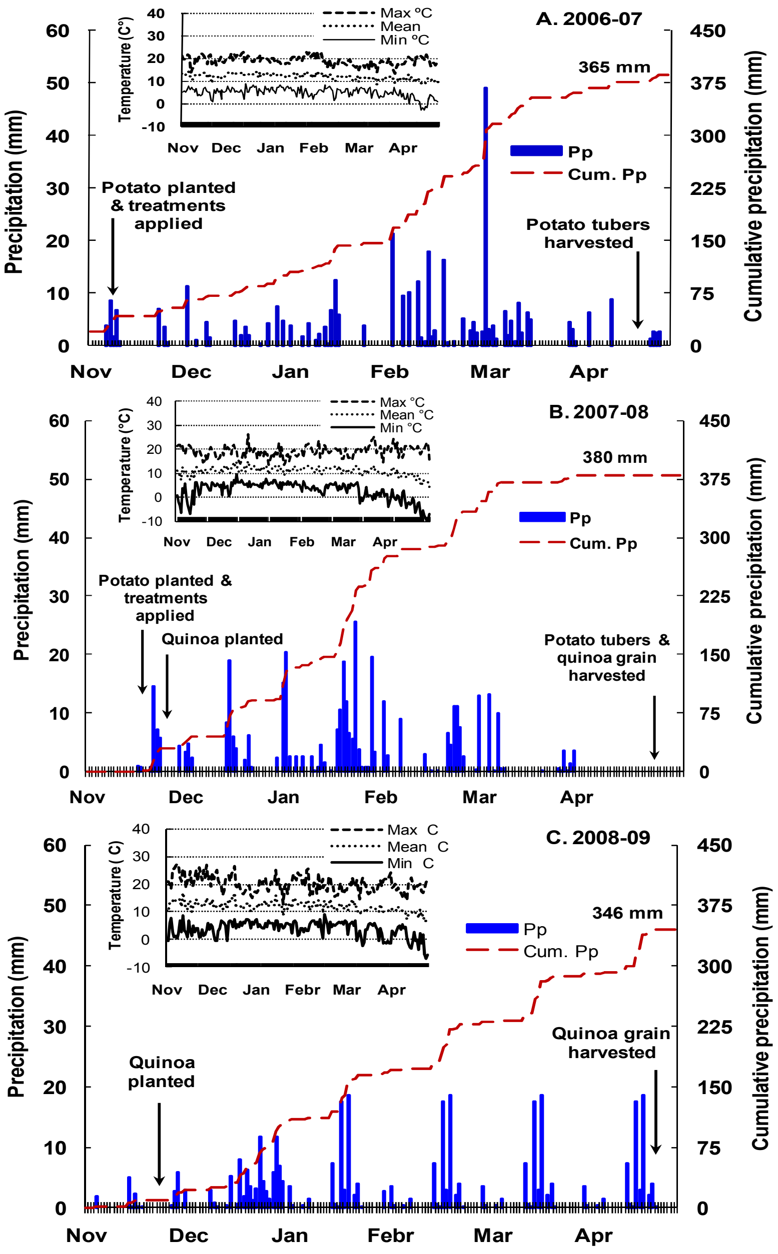

Fig. 2. Temperature and rainfall during the A) 2006-07, B) 2007-08 and C) 2008-09 growing seasons in the San Juan Circa lower elevation community of the Umala Municipality.

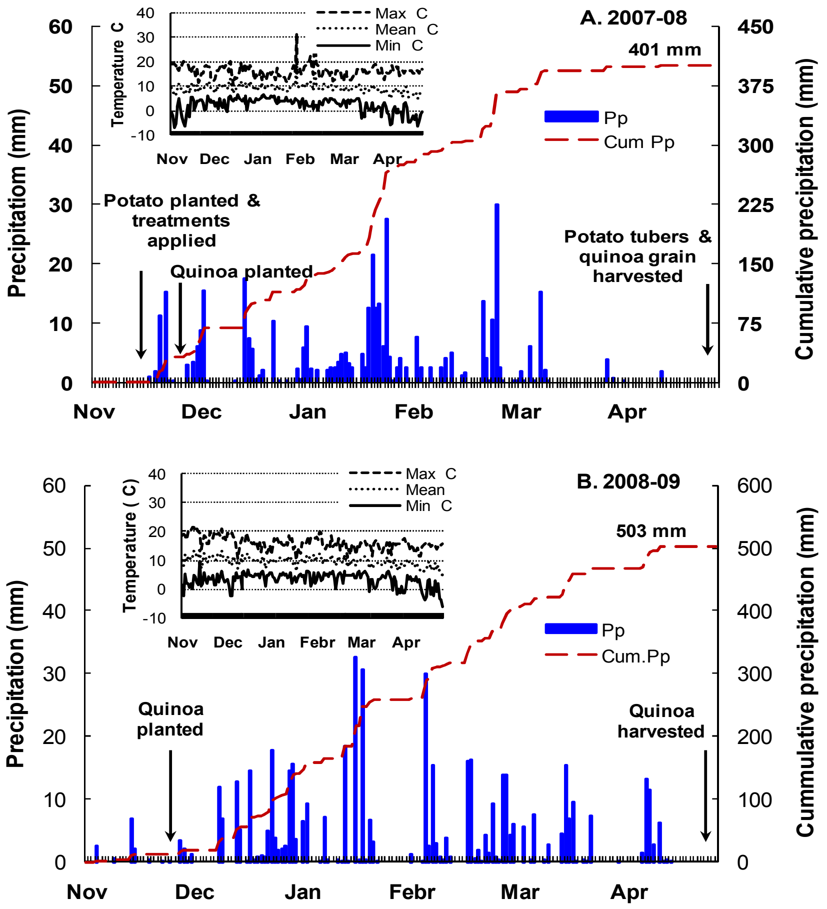

Fig. 3. Temperature and rainfall during the A) 2007-08 and B) 2008-09 growing seasons in the Vinto Coopani higher elevation community of the Umala Municipality.

3.2 Selected Properties of Initial Soil and Organic Amendments

Chemical characteristics of soil in the field plots prior to the initiation of the experiment are presented in Table 2. 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 [22]. 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 [3]. The lower content of some mineral nutrients in lower communities could possibly be attributed to the relatively greater use of tractor-based tillage, the presence of sandier soils and greater soil erosion caused mainly by wind.

No major differences were found among cow and sheep manure amendments used for the field trials among the communities over the years of the field trial (Table 3). Both manure types used during the 2006-08 growing seasons had relatively high proportions of total

Table 2.Initial soil properties of the potato field trials in two growing seasons and in four communities of Umala. Samples were collected prior to planting and treatment application

Year/ community	Total org C	Total N	C:N ratio	pH_s (0.01 *M* $CaCl_2$)	Soil test Bray1 P	Soil test K	Exch. Ca	Exch. Mg	CEC	EC
	------------ % ------------				--------------------- mg kg^{-1} ---------------------				$cmol_c\ kg^{-1}$	dS cm^{-1}
2006-07										
Kellhuiri	0.9±0.0	0.08±0.01	12±3	5.2±0.1	35±9	232±10	690±33	84±9	7.5±0.1	0.4±0.2
Vinto Coopani	0.7±0.0	0.07±0.01	10±1	5.1±0.0	53±5	226±11	520±51	72±7	6.5±0.5	0.5±0.1
San Juan Circa	0.6±0.0	0.05±0.01	13±3	5.7±0.1	35±2	174±12	686±104	110±13	5.9±0.7	0.3±0.1
San José de Llanga	0.5±0.1	0.04±0.01	13±5	5.4±0.1	39±8	149±7	298±47	51±5	3.4±0.5	0.3±0.1
2007-08										
Kellhuiri	0.9±0.2	0.09±0.02	10±0	5.9±0.2	17±2	199±25	1965±125	171±22	12.6±1.2	0.2±0.1
Vinto Coopani	0.9±0.1	0.08±0.01	12±1	5.8±0.1	101±16	490±85	935±106	137±10	9.0±0.5	0.2±0.0
San Juan Circa	0.6±0.0	0.03±0.00	17±2	6.4±0.2	27±1	228±19	2312±337	330±47	15.5±2.0	0.3±0.1
San José de Llanga	0.8±0.1	0.08±0.01	10±1	7.6±0.2	15±1	152±18	2327±433	139±30	13.2±2.5	0.2±0.0

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

Table 3. Selected properties of the organic fertilizers used in the field trials during the 2006 to 2008 growing seasons in Umala

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

[†] D.M.= Dry matter

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

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

organic C, total N, total K and total P. However, higher concentrations of soil total C and total N were observed either in cow and sheep manure at higher elevations (Kellhuiri and Vinto Coopani) than those at lower elevations (San Juan Circa and San José de Llanga). Commercially-produced household/urban compost used for the field trials 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 (Table 3).

3.3 Plant Height

For the potato plots, plant height was not affected by growing season but it was significantly affected by the interaction between site and treatment factors (Tables 4 and 5). In all communities, organic and inorganic fertilizers treatments promoted taller potato plants than the control plots. In Kellhuiri, only treatments containing chemical fertilizers (T2, T7, T8 and T9) promoted taller plants than the control. In Vinto Coopani and San Juan Circa, all treatments, except for T6 (compost), produced taller plants than the control. In San José de Llanga, all treatments generated taller plants than the control. The fact that treatments containing inorganic fertilizers promoted taller plants across communities and growing seasons could possibly be attributed to the more rapidly available N and P contained in these fertilizer sources.

For the quinoa crop, there were no significant interactions among factors (i.e., growing season, community and treatment), but there were significant differences among treatments on plant height (Fig. 4). Except for T6, T10, T11 and T12, the residual effects of treatments containing organic or inorganic fertilizers applied alone or combined together (T2, T3, T4, T5, T7, T8, and T9) generated taller plants than the control. In general, the residual effects of T2, T7, T8 and T9 application generated significantly taller plants compared to that of the control, and these results are also supported by the higher soil total inorganic N (NO_3^- and NH_4^+) and soil test P found for the same four treatments in soil samples collected in quinoa plots before planting [13]. Sandy soils have relatively low water-holding capacity, high infiltration rates and a relatively high potential for nutrient leaching losses.

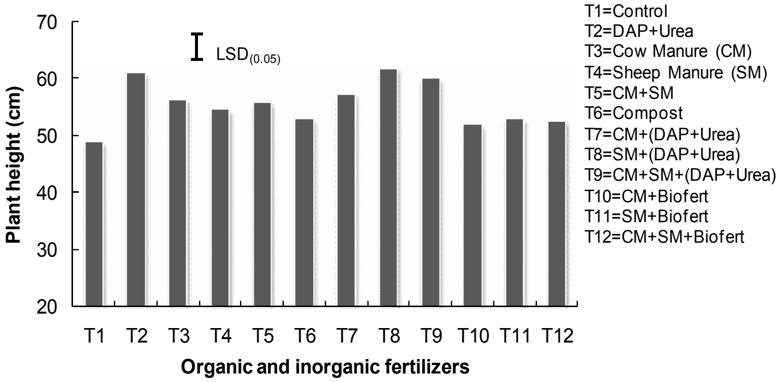

Fig. 4. Quinoa plant height at blooming time averaged across growing seasons and across communities of Umala. Vertical bar shows least significant difference at $P \leq 0.05$.

However, the relatively low amount of rainfall observed during both growing seasons at both elevations probably did not cause significant amounts of leaching of plant nutrients.

Table 4. Potato plant height in two communities of the relatively high elevation area of Umala with application of organic and inorganic fertilizers averaged across growing seasons

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

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

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

Table 5. Potato plant height in two communities of the relatively low elevation area of Umala with application of organic and inorganic fertilizers averaged across growing seasons

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

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

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

3.4 Plant Cover and Foliar Area

Plant cover measurements were performed for the potato crops trials in 2006-07 and 2007-08 growing seasons. There was no significant interaction between community and treatment factors but a significant interaction was found for growing seasons and treatments at all measuring times (Table 6). At the beginning of both growing seasons (at 44 and 58 Dap), higher plant cover was found in 2006-07 than in-2007-08 but the opposite happened as the growing season moved on (85 and 100 Dap) where higher plant cover was registered in 2007-08 compared to that observed in 2006-07. Apparently the lower amount of precipitation received from the beginning of January to the end of February in 2007 compared to same months in 2008, especially in the low area communities (Fig. 2) could have affected the average growth of the potato plants. In general, except for T6 (compost), all treatments generated greater potato plant cover than the control plots. Research has also found that the effect of inorganic fertilizer [23] applied alone or combined with organic fertilizer [24] resulted in higher potato plant growth compared to the control plots.

Foliar area was measured for the quinoa crop trials only for the 2007-08 growing season and results area presented in Table 7. At 60 Dap, no significant interactions were found between communities and treatments but there were significant differences among treatments on quinoa foliar area. Averaged across communities, except for T10 and T12, the residual effect of all treatments promoted higher leaf area than the control plots. At 90 and 120 Dap there was significant interaction among communities and treatments. Except for T6 at 90 and 120 Dap and T12 at 120 Dap, residual effects of all treatments promoted higher foliar area in low elevation communities (i.e., San Juan Circa and San José de Llanga) than the control plots; whereas in the high elevation communities (i.e., Kellhuiri and Vinto Coopani) only the residual effects of T4, T5, T7, T8, T9 and T10 generated higher leaf area than the control plots.

3.5 Crop Yields

3.5.1 Potato yields

Significant differences between growing seasons and among treatments were found for all the potato trials, but no significant interactions were detected for growing season, elevation and treatments (Fig 5A). There was higher average potato tuber yield in 2007-08 (12.4 Mg ha^{-1}) than in the 2006-07 (9.0 Mg ha^{-1}) growing season and higher yield in Vinto Coopani (11.7 Mg ha^{-1}) than in San Juan Circa and Kellhuiri (10.4 and 10.0 Mg ha^{-1} respectively) communities. The higher average tuber yield along with taller potato plants and higher potato plant cover found in 2007-08 than in 2006-07 growing season are most likely due to better initial soil properties, such as higher total organic C, total N and soil test K, exchangeable Ca and Mg and higher CEC (Table 2) and maybe the higher rainfall and uniform precipitation amount registered in 2007-08 than in 2006-07. In the trials planted to potato, all treatments generated higher total yields than the control (Figs. 5 A). Higher total yields occurred when inorganic fertilizers were added alone (T2) or combined with manures (T7, T8 and T9). The same treatments also generated higher marketable tuber size but T3 (cow manure), T4 (sheep manure) and T7 (cow manure+DAP+urea) generated the highest non-marketable tuber size (Fig. 5 A). The T2, T7, T8 and T9 treatments generated 67, 68, 79 and 74% increase in total potato tuber yield, respectively.

Table 6. Potato plant cover with application of organic and inorganic fertilizers in two growing seasons averaged across communities of Umala

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

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

[‡] *Significant interaction between year and treatments*

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

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

Table 7. Foliar area of quinoa plants established on harvested potato fields with application of organic and inorganic fertilizers during the 2007-08 growing season in four communities of Umala

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

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

[§] *Significant interaction for the community and treatment factor*

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

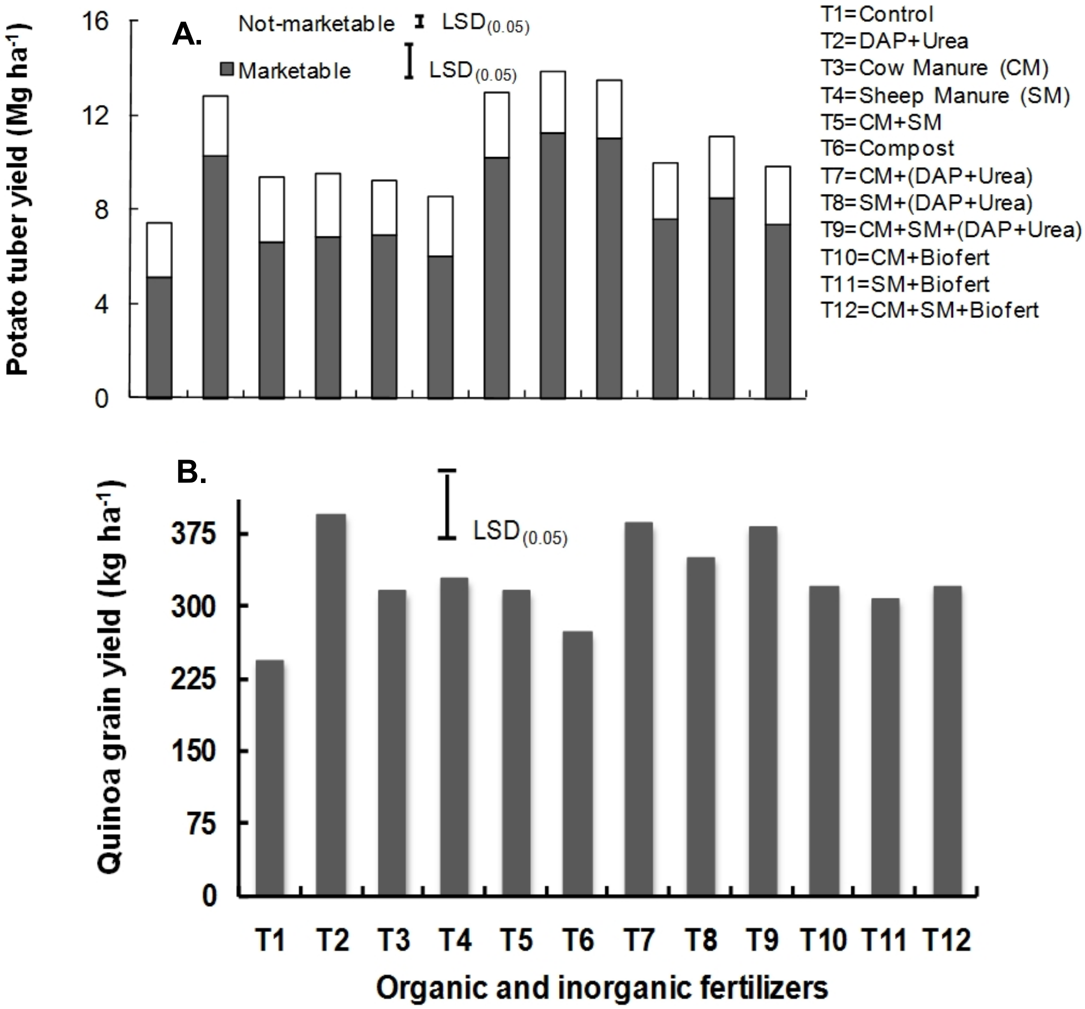

Fig. 5. A) Potato tuber and B) quinoa grain yields by effect of organic and inorganic fertilizers applied in potato trials averaged across growing seasons and communities of Umala. Vertical bar shows least significant difference at $p\leq0.05$.

Research has also shown greater potato tuber yield when inorganic fertilizer was applied alone or combined with organic fertilizer [25,26,27,28,29] or when half rates of inorganic fertilizers along with organic fertilizers were applied [24]. Since soil N and P are limiting production factors in this region, addition of rapid plant available N and P through inorganic fertilizers, either alone or complemented by organic fertilizers had an important impact on potato and subsequent quinoa crop performance. Potato needs adequate amounts of N in its early growing stages to keep optimum shoot and tuber growth [3], and adequate amounts of P to promote good root development and overall plant health [8].

3.5.2 Residual quinoa yields

Similar to responses observed in the potato trials, the quinoa trials had significant differences between growing seasons and among treatments, but no significant interactions were detected for growing season, elevation and treatments (Fig. 5B). There was higher quinoa grain yields in 2007-08 (0.37 Mg ha^{-1}) than in 2008-09 (0.29 Mg ha^{-1}) and higher grain yield in San Juan Circa (0.34 Mg ha^{-1}) than in higher Kellhuiri and Vinto Coopani (0.23 Mg ha^{-1}) communities. Higher rainfall and uniform precipitation observed in 2007-08 compared to that of 2006-07 were not reflected in better residual quinoa crop yields in 2008-09 than in the 2007-08 growing season. The residual effects of the T2, T7, T8 and T9 treatments on quinoa caused 61, 58, 44 and 58% increase in total grain yield over the control, respectively.

Johnson and Ward [30] observed in their review that research under the rain-fed conditions of South America has found significant quinoa production response to applied N. Tapia [31] has reported a significant quinoa plant response to addition of N and P in agricultural Andean soils.

These results provide evidence of the existence of a residual effect of fertilizers, especially inorganic fertilizers, applied in potato on subsequent crops in this environment. Even though the soils examined in this study had a high proportion of sand and would be vulnerable to nutrient leaching, significant amounts of residual soil total inorganic N was detected in quinoa plots before planting, which implies little inorganic N was lost [13]. This effect could possibly be attributed to the low rainfall observed during and after each growing season. The same trend happened with soil test P [13], where higher residual content in plots was observed where inorganic fertilizers had been applied (T2, T7, T8, and T9).

Compost did not significantly increase potato tuber or quinoa grain yield compared to the control plot because this organic fertilizer normally only gradually releases available N over time [32]. Organic fertilizers combined with Biofert (T10, T11 and T12) also did not significantly affect potato plant height, plant cover and tuber yield compared to when the same organic fertilizers were applied alone (T3, T4 and T5).

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

4. CONCLUSION

Addition of the inorganic fertilizers, diammonium phosphate (DAP) and urea, either applied alone or combined with either cow or sheep manure produced higher total and marketable tuber yield for the farmers in the Central Bolivian Altiplano communities studied during this research. The residual effects of these soil amendments also significantly increased quinoa plant growth, foliar area and grain yield in higher and lower elevation communities of the Central Bolivian Altiplano. These results suggest that further efforts may be needed to help farmers to overcome obstacles for use of inorganic fertilizers since this form of fertilizer can be effective in this environment despite the challenges associated with adverse climatic events, such as drought and early frost.

Use of a commercially-available household/urban compost did not improve initial or residual potato and subsequent quinoa plant growth in the field trials of this research. The solid commercial biofertilizer product tested in this study did produce higher yields when combined with either the cow or sheep manures as compared to when the manures were applied alone but further testing of this product may be necessary to assess its effects on other soil properties, such as soil P availability.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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