



Nitrogen Management Can Increase Potato Yields and Food Security for Climate Change Adaptation in the Andean Region

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Abstract

The Andean region of Ecuador is being impacted by climate change, and improved best management practices for agriculture are needed to increase yields and food security. We conducted a study comparing different nitrogen (N) rates to determine the optimum N application rate for potato (*Solanum tuberosum* L.) systems in this region. We examined five application rates of N: 0, 100, 200, 300, and 400 kg N ha⁻¹. The results suggest that an N application rate of 300 kg N ha⁻¹ increased productivity and net income by 87% and 146%, respectively, compared to no application of N. We transferred these improved practices to farmers, and all farms increased their yields and net economic returns. The average yields and net economic returns for these farmers increased by 50% and 64%, respectively. Additional N use efficiency (NUE) studies are needed to continue increasing yields and economic returns for farmers in the Andean region.

Keywords Best management practices; food security · Low-intensity agriculture · Nitrogen fertilizer · Nitrogen use efficiencies · Potato

Resumen

La región andina de Ecuador está siendo impactada por el cambio climático, y se necesitan mejores prácticas de manejo para la agricultura para aumentar los rendimientos y la seguridad alimentaria. Realizamos un estudio que comparó diferentes tasas de nitrógeno (N) para determinar la tasa óptima de aplicación de N para los sistemas de papa (*Solanum tuberosum* L.) en esta región. Se examinaron cinco dosis de aplicación de N: 0, 100, 200, 300 y 400 kg N ha⁻¹. Los resultados sugieren que una tasa de aplicación de N de 300 kg N ha⁻¹ aumentó la productividad y el ingreso neto en un 87% y 146%, respectivamente, en comparación con ninguna aplicación de N. Transferimos estas prácticas mejoradas a los agricultores, y todas las siembras aumentaron sus rendimientos y ganancias económicas netas. Los rendimientos medios y los rendimientos económicos netos para estos agricultores aumentaron en un 50% y 64%, respectivamente. Se necesitan estudios adicionales de eficiencia en el uso de N (NUE) para continuar aumentando los rendimientos y ganancias económicas para los agricultores de la región andina.

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Introduction

Climate change is impacting tropical regions and has the potential to affect food security. Assessments of the impacts of climate change in tropical areas with modeling tools suggest significant negative impacts in most regions; however, higher temperatures may provide some benefits in high-altitude tropical regions (Corlett 2014; Lobell et al. 2011; Trewin 2014; IPCC 2014). There is a need to conduct

assessments of best management practices (BMP) that could contribute to higher yields across these tropical regions and potentially increase food security.

In Brazil, Fontes et al. (2010) studied the effects of five nitrogen (N) application rates (0, 50, 100, 200, and 300 kg N ha⁻¹) on total, marketable, and dry-matter tuber yields for four potato cultivars (Ágata, Asterix, Atlantic, and Monalisa). For each cultivar studied, the total, marketable, and dry-matter tuber yields responded to increasing N application in a quadratic pattern. Similarly, Souza et al. (2018) examined the effects of N rates (0, 80, 120, and 160 kg N ha⁻¹) and sources on yields and agronomic efficiency of potato systems grown in irrigated sandy soils in Brazil. In a set of three experiments, they found that applications of N fertilizer between 136 and 160 kg N ha⁻¹ increased potato tuber yield compared to the control (no N fertilizer applied) in this tropical system, and this held true irrespective of the fertilizer source under study (ammonium sulfate; ammonium sulfate nitrate with a nitrification inhibitor [3,4-dimethylpyrazole phosphate]; and urea). Compared to urea, ammonium sulfate nitrate with the nitrification inhibitor produced higher potato tuber yield. However, amongst the three sources studied, the ammonium sulfate nitrate with the nitrification inhibitor resulted in the highest agronomic efficiency. In Argentina, García (2002) reported that potatoes require about 200 kg N ha⁻¹ to produce 25 t ha⁻¹ and that we should account for N in the soil plus N added from fertilizer.

In the USA, numerous studies have been conducted on intensive agriculture and N management. In the western USA (Colorado), Essah and Delgado (2009) reported that higher N rates of up to 296 kg N ha⁻¹ split between N applied at planting and during growing contributed to maximizing the yields of Canela Russet. They also found that a lower N rate of 229 kg N ha⁻¹ maximized the yields of the Sangre variety. Supporting similar findings by García (2002) in Argentina, Essah and Delgado (2009) reported that we need to account for soil N. As noted below, farmers' objectives are not purely yield maximization; we incorporate costs of N application and provide information on effects of management on gross and net incomes.

Essah and Delgado (2009) found that a large part of the N needed was accounted for as initial soil nitrate-nitrogen (NO₃-N) in the soil profile and N added as background N from irrigation water. Net N fertilizer applications for maximum yields were 157 kg N ha⁻¹ for Canela Russet and 90 kg N ha⁻¹ for Sangre since the soil and background N from irrigation were supplying a significant amount of N to the potato crop. The background N in the Colorado system was 139 kg N ha⁻¹.

Delgado et al. (2019) and Barrera et al. (2019) conducted a series of conservation agriculture studies in different sites

across the Chimbo sub-watershed, located in the high-altitude Ecuadorian provinces of Bolivar and Chimborazo. Conservation agriculture has been defined by the Food and Agriculture Organization (FAO) of the United Nations as an agricultural system that includes minimum disturbance of the soil (no till), permanent coverage of the soil, and improved rotations (diverse species) (FAO, 2016). Delgado et al. (2019) found that N fertilizer applied in small increments for corn (*Zea mays* L.) (80 vs. 0 kg N ha⁻¹), oat (*Avena sativa* L.)–vetch (*Vicia sativa* L.) (effects of residual N fertilizer vs. no fertilizer applied to the previous crop), and the common bean (*Phaseolus vulgaris* L.) (40 vs. 0 kg N ha⁻¹) increased yields from 3.9 to 4.1 Mg ha⁻¹, 19.7 to 20.8, and 1.6 to 2.2 Mg ha⁻¹, respectively. Although these increases in yields were relatively small at 5.1 and 5.6 Mg ha⁻¹, for the corn and oat–vetch, respectively, the increase was significant at 37.5% for the bean, and there was a significant increase (22%) in net economic returns for the cropping system. Adding N fertilizer in a zero or minimum tillage system, with or without crop residue harvested, increases net returns significantly for this crop rotation and has the potential to impact 200,000 farmers that could use these practices and increase their N input to corn to 80 kg N ha⁻¹ or their N input to bean to 40 kg N ha⁻¹ while implementing these conservation agriculture practices.

In the same watershed, Barrera et al. (2019) found that N fertilizer for barley (*Hordeum vulgare* L.) (with an initial application of 50 and 21 kg N ha⁻¹ at 50 d after sowing vs. 0 kg N ha⁻¹), bean (residual N fertilizer effects vs. no fertilizer applied to the previous crop), and pasture (18 kg urea-N ha⁻¹ vs. 0 kg N ha⁻¹) increased their yields from 1.7 to 2.22 Mg ha⁻¹, 2.48 to 2.53, and 10.47 to 13.51 Mg ha⁻¹, respectively. Barrera et al. (2019) found higher average responses in yields to N inputs of 30.6, 2.0, and 29.0% for the barley, bean, and pasture, respectively. They found that net revenues with this addition of N fertilizer were increased by 24% for the cropping system. Across all the practices employed (conventional or reduced tillage, harvesting crop residue or leaving it on the surface, and with or without surface water deviation ditches), increasing N application to 71 kg N ha⁻¹ for barley or 18 kg N ha⁻¹ for bean, contributed to higher yields and economic returns for this crop rotation. These studies by Delgado et al. (2019) and Barrera et al. (2019) provide evidence that by increasing N application rates with conservation agriculture, sustainable systems that increase yields and economic returns to farmers can be achieved in this region.

Escudero et al. (2014) compared higher fertilizer N rates of 120 and 140 kg N ha⁻¹ to the low N rates traditionally applied by farmers in the Andean region, ranging from 28 to 50 kg N ha⁻¹. The additional 80 to 100 kg N ha⁻¹ above what the farmers were applying nearly doubled corn yields,

increasing them from about 3.8 Mg ha⁻¹ to 7 Mg ha⁻¹. In recent potato studies in the Sicalpa watershed in Ecuador, Delgado et al. (2020) found that with conservation agriculture, leaving the crop residue in the field (vs. harvesting the residue) for a rotation of potato – oat/vetch- barley – faba bean (*Vicia faba* L.) - oat/vetch- potato – forage increased the potato yields from 24 to 26.2 Mg ha⁻¹. In the Paute watershed in Ecuador, Delgado et al. (2020) found that leaving crop residue in the field and applying conservation agriculture increased the potato yields from 20.1 to 24 Mg ha⁻¹ in the potato – oat/vetch- vetch – sweet corn - potato – forage rotation.

While potato-pasture systems predominate in the Chambo River sub-basin, other crops, such as corn, chocho (*Lupinus mutabilis* S.), barley, and quinoa (*Chenopodium quinoa* W.) are also cultivated in the area. In the past, the recommended N fertilizer application rate for potato in this region ranged from 0 to 160 to 220 kg N ha⁻¹, with the potential to increase yields from 15 to 30 Mg ha⁻¹ with the recommendation to apply 50% of the N at planting and the other 50% at tuberization (Oyarzún et al. 2002). Oyarzún et al. (2002) conducted studies in the Pichincha, Cotopaxi, Carchi and Cañar provinces, and found that the best economic returns are at 140 kg N ha⁻¹ (32.5 Mg ha⁻¹), while maximum yields are achieved at a rate of 160 kg N ha⁻¹ (32.8 Mg ha⁻¹). However, there is no information available about nitrogen use efficiency (NUE), the effects of N management on potential losses of N when achieving maximum yields and/or economic returns, or potential N management strategies to reduce these losses. There is a need to reevaluate the recommendations for N rates, the effect on economic returns, and how N management could impact NUE and the potential for N losses in this region. The objective of our research was to determine the best N management practices for achieving optimum yields and economic benefits in potato cultivation systems in the Chambo River sub-basin, as a climate change adaptation strategy. There is a need to conduct additional N fertilizer studies in these low-input small farms in the Andean region of Ecuador.

Materials and Methods

Description of the Study Site (*Natural, Social and Economic Characteristics*)

The experimental site is located in the Puculpala community in Riobamba Canton, located in the province of Chimborazo, in the high-altitude Andean region of Ecuador, 2,874 m above sea level [latitude 1° 23' 55.30" S [9,814,175 S] and longitude 78° 50' 39.38" W [768,788 W]; Fig. 1). Agroclimatic characteristics correspond to a semi-humid

Mesothermic climatic zone, with a temperature between 15 and 22 °C, annual precipitation between 500 and 2,000 mm, relative humidity between 50 and 70%, and an average slope of 50%. During the study period, average temperatures ranging between 10.3 and 13.8 °C and rainfall ranging between 500 and 1,300 mm were recorded. Relative humidity remained at 76% and wind speed at 12.5 km h⁻¹ (PDOT 2015).

The soils where the experimental plots were established are classified as Andisols with organic matter content, pH, and apparent bulk density typically ranging from 8 to 12%; 5.8 to 6.0; and 0.8 to 1.0 g cm⁻³, respectively (INIAP 2020). People in the Puculpala community fundamentally depend on the productivity of family plots, where crops that are grown for sale and family consumption predominate, such as potatoes, corn, quinoa, lupine (*Lupinus mutabilis* S.), beans, alfalfa (*Medicago sativa* L.), barley, mellico (*Ullucus tuberosus* C.), oat, coriander (*Coriandrum sativum* L.), and cabbage (*Brassica oleracea* L.), among others.

Farmers in this region confront social and economic risk with a high degree of vulnerability since the consequence of inappropriate management of natural resources and/or the effects of climatic changes could impact their livelihood (PDOT, 2015). 30% of the land in this sub-basin is dedicated to agricultural activity. Another 25% constitutes the *páramo* regions, an essential natural source of drinking water for cities—the vast majority of the *páramo* is involved in national conservation projects. The remaining 45% is natural vegetation, providing a home for native fauna species—though this habitat has been shrinking over the years due to the need for additional cropland, even in sloped areas (PDOT, 2015). The economically active population can be broken down by occupation as follows: 70% are involved in agricultural activities, 8.5% in construction activities, 4.4% in activities related to trade, 2.6% in craft/artisan activities, 3.6% in public sector work, and 10.4% in private sector work, among other occupational activities (PDOT, 2015).

Experimental Design – Phase I

We studied the effects of BMPs on a potato-quinoa-barley-chocho-corn-grass production system. As part of these BMP studies, we included a Phase I N management study (*experimental study of N rate*) where we applied 0, 100, 200, 300 and 400 kg N ha⁻¹ with three replications in the same experimental area in the Puculpala community. The three Phase I replications were very close together and are identified by a single point in Fig. 1. A completely randomized block design was used, where each experimental plot had an area of 72 m² (12 m x 6 m). The total area covered by the five treatments in each block was 360 m². The total area covered

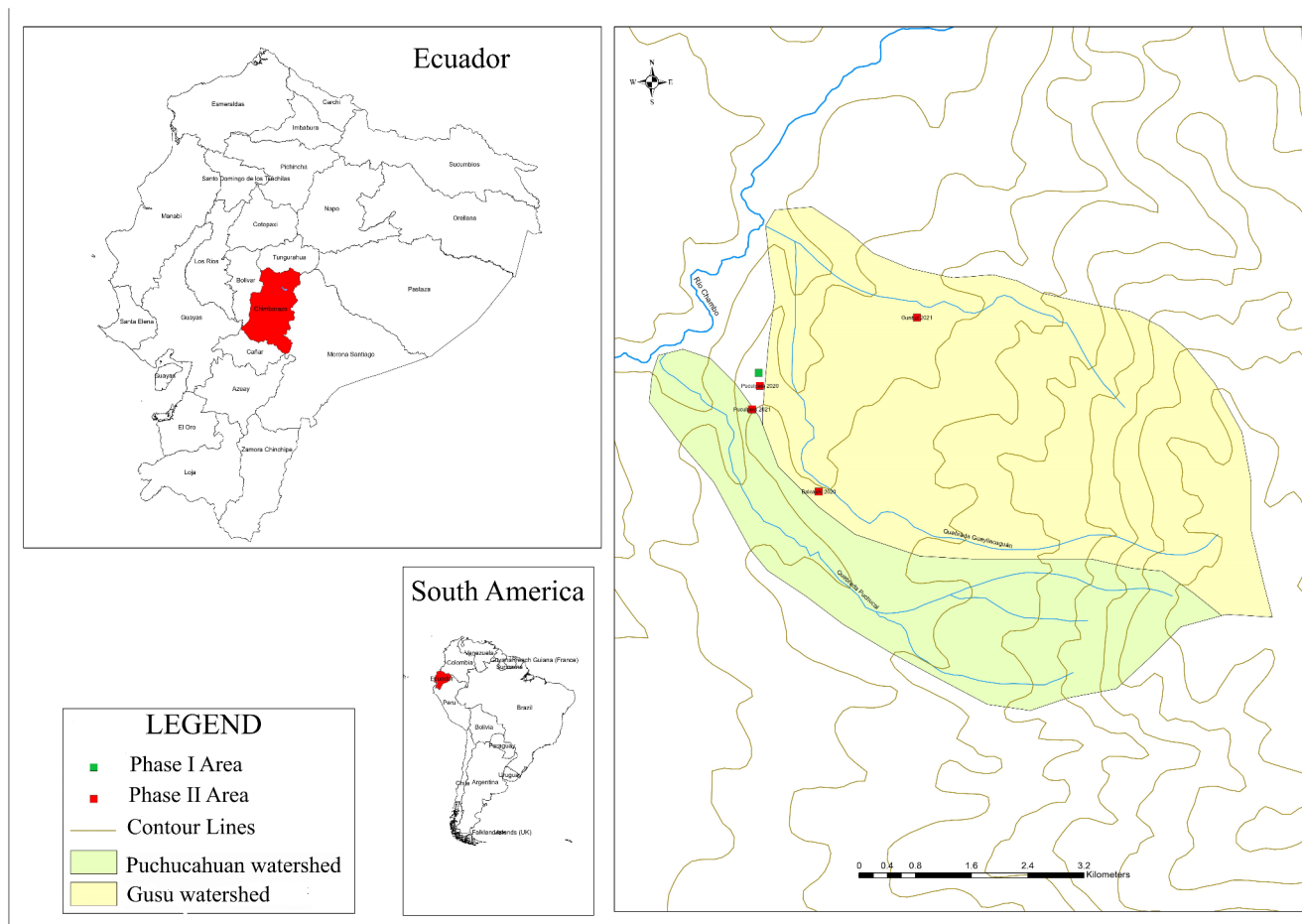


Fig. 1 Location of the research and validation sites in the Chambo river sub-basin, located in the province of Chimborazo in Ecuador. (Red dots indicate the four commercial potato farms where Phase II of these studies was conducted. Lines indicate the topographic contours.)

by the three blocks was 1,080 m². The total area including the buffer area between the three blocks was 1,295 m².

Management of the Experiment– Phase I

In the Puculpala community, for this study a 1,295 m² area was selected, which had been fallow for three years, to establish the three N rate experimental study. The Superchola variety was used, with a sowing density of 1,136 kg ha⁻¹, using the sowing method called ‘furrow and direct sowing.’ Tillage practices involved chopping and peeling work 15 days before sowing, and were carried out with a hoe until the soil was loose, and then the furrowing was conducted at a distance of 0.40 m between plants, 1 m between furrows, and a depth of 0.30 m. N was applied according to the treatments described above.

At sowing, 50% of N (0, 50, 100, 150 and 200 kg N ha⁻¹) and 300, 60, and 30 kg ha⁻¹ of phosphorus pentoxide (P₂O₅), potassium oxide (K₂O), and sulfur (S), respectively were applied to the bottom of the furrow in a continuous jet, and at weeding, the remainder was applied in a sideband

application. Integrated pest management was implemented for phytosanitary control. Additionally, depending on the plant pests or pathogens present, certain insecticides (lambda-cyhalothrin + thiamethoxam, cypermethrin, profenophos and chlorpyrifos) and fungicides (cymoxanil, sulfur, fosetyl aluminum and dimethomorph) were used. Crops were harvested at physiological maturity. In all treatments, the foliage was removed from one side of the plot; harvesting was done by hand. To reduce variability in the data, the plot was harvested by leaving one meter at the bottom and top, respectively, and 0.50 m on each side of the plot. For Phase I, potato production was measured through the harvest of all the plants in the 50 m² (10 m x 5 m) plots. The corresponding weight was recorded (kg ha⁻¹).

Plant density (number of plants per plot) was determined prior to harvesting the plants to assess potato production. While the potato production samples were collected, tubers and aboveground biomass of ten random plants per plot were collected as subsamples to assess dry weight production, N uptake and NUE. The subsamples were weighed and left in a 65 °C oven for at least 24 h and/or until weights

were no longer changing, and water content and dry biomass were calculated. For each plot, kg dry weight ha⁻¹ was calculated by multiplying the average dry weight of 10 plants by plant density.

The N content was measured using the kjeldahl method with a Foss™ Kjeltac™ 8400 analytical instrument (Bremner 1996; Alvarado et al. 2000). Total N content in kg N ha⁻¹ for aboveground and tuber plant compartments was calculated by multiplying the %N in dry matter by the dry matter content. The total N content in the potato plant in kg N ha⁻¹ was estimated by summing the N content in the aboveground and tuber compartments. The NUE of the total crop (stalks, leaves, and tubers) N uptake (TNU) was calculated with Eq. 1 by subtracting the TNU (kg N ha⁻¹) in the control (non-fertilized) plots (TNU_{CP}) from the TNU (kg N ha⁻¹) in the N-fertilized plots (TNU_{FP}), and dividing the difference by the N fertilizer added to the fertilized plot (kg N ha⁻¹):

$$NUE(\%) = \frac{TNU_{FP} - TNU_{CP}}{N \text{ fertilizer applied}} \times 100 \quad (1)$$

The potential for N losses to the environment was calculated by subtracting the difference between TNU_{FP} and TNU_{CP} from total N fertilizer applied. With this method, we assumed that the potential for N losses to the environment from the control (non-fertilized) plots was zero (minimal losses or accumulation).

Experimental Design – Phase II

Due to the excellent results obtained in Phase I, and at the request of farmers in the area under study, we started Phase II (*technology transfer study*) at four small commercial potato farms to transfer best N management practices. These four technology transfer sites were located within or near the Puchucahuan and Gusu watersheds (Fig. 1). This phase, which took place at four commercial farm operations where we implemented our recommendations and compared them to the farmers' traditional practices, was a validation of the results from Phase I. At each of these four small farms we established an experimental plot with a surface area of 5,000 m² (50 m x 100 m) for the technology transfer treatment. The plots were in farmers' fields that have a larger area managed under the farmers' traditional practices. The treatments used to assess the effects of N management in the potato crop were the 300 kg N ha⁻¹ application and the farmers' traditional practices. These treatments were evaluated in a completely randomized block design, with four replications, located in different communities: Balcashi, Puculpala, and Guntuz.

Management of the Experiment– Phase II

Table 1 shows the agronomic management practices carried out in each plot used for validation of the practices corresponding to 300 kg N ha⁻¹, as well as the prevalent traditional management practices in each of the locations selected

Table 1 Description of the potato crops used in the validation of the N management practices in the Chambo River sub-basin, located in the province of Chimborazo in Ecuador (2020 to 2021)

	Balcashi (2020)	Puculpala (2020)	Puculpala (2021)	Guntuz (2021)
Variety	Superchola	Superchola	Superchola	Superchola
Technology Transfer of Improved N Management and Integrated Crop Management				
Planting density	900 kg ha ⁻¹	900 kg ha ⁻¹	900 kg ha ⁻¹	990 kg ha ⁻¹
Initial N fertilization	150 kg N ha ⁻¹	150 kg N ha ⁻¹	150 kg N ha ⁻¹	150 kg N ha ⁻¹
N fertilization 60 days after planting	150 kg N ha ⁻¹	150 kg N ha ⁻¹	150 kg N ha ⁻¹	150 kg N ha ⁻¹
Integrated management of pests and diseases	To control weeds, in the preparation of the soil, glyphosate was applied in doses of 12.5 cc l ⁻¹ of water 15 days before planting. Depending on the pest or disease present in the crop, products were used for pests (acephate and thiamethoxam; in the case of white worm, traps were used) and diseases (cymoxanil, metalaxyl, sulfur, fosetyl aluminum, dimethomorph).			
Farmers' Traditional Practices				
Planting density	1403 kg ha ⁻¹	1403 kg ha ⁻¹	1403 kg ha ⁻¹	1403 kg ha ⁻¹
Initial N fertilization	54 kg N ha ⁻¹	30 kg N ha ⁻¹	30 kg N ha ⁻¹	54 kg N ha ⁻¹
N fertilization 60 days after planting	37 kg N ha ⁻¹	31 kg N ha ⁻¹	58 kg N ha ⁻¹	62 kg N ha ⁻¹
Method of phytosanitary control	Weed management typically included manual control with a hoe. The control of pests and diseases was based on the knowledge of pesticide vendors who traditionally recommended products (for pests: cypermethrin, profenopos and chlorpyrifos; for diseases: cymoxanil, metalaxyl and dimethomorph) in higher doses and more frequently compared to conservation agriculture (CA) practices.			

for the study. Following is a summary of the practices for the technology transfer treatment (improved N management and integrated crop management) of applying 300 kg N ha⁻¹ as well as for the farmers' traditional practices. The Superchola variety was sowed at a density of 900 and 1,403 kg ha⁻¹ for the technology transfer treatment that included applying 300 kg N ha⁻¹ and the treatment representing the farmer's traditional management practices, respectively. The potato was planted using the same planting distances and tillage practices used for the N rate study in Phase I. The total N rate was 300 kg N ha⁻¹ for the technology transfer treatment, with 50% applied at sowing and 50% applied 60 days after planting. The total N rates for the farmers' traditional practices ranged from 61 to 116 kg N ha⁻¹. The farmers' split N application ranged from 30 to 54 kg N ha⁻¹ at planting and 31 to 62 kg N ha⁻¹ 60 days after planting. The technology transfer plots (total application of 300 kg N ha⁻¹) received 330, 90, and 30 kg ha⁻¹ of P₂O₅, K₂O and S, respectively, which were applied at planting with the same method used in Phase I. For the treatment representing the farmers' traditional practices, an average of 160, 80, and 15 kg ha⁻¹ of P₂O₅, K₂O and S, respectively were applied at planting using the same method used in Phase I. Weed and pest control for Phase II are described in detail in Table 1. Crops were harvested in a similar manner as in Phase I. For Phase II, potato production was measured through the harvest of all the plants in the plots (30 m x 60 m = 1800 m²) for the validation. A similar area of 1800 m² was harvested at the site with the farmers' traditional practices, adjacent to where our technology transfer plot was established.

Variables and Methods of Evaluation

The variables evaluated in Phases I and II were: yield (t ha⁻¹); costs of the studied practices and of potato cultivation (USD ha⁻¹); and the benefits (in USD ha⁻¹) based on the production of the crop (in kg ha⁻¹). For Phase I, potato production was measured through the harvest of all the plants in the 50 m² (10 m x 5 m) plots; and for Phase II, through the harvest of 1800 m² (30 m x 60 m) plots for the validation. Production costs taken into consideration were the preparation of the soil, seeds, fertilizers, pesticides, labor, phytosanitary controls, and harvest. The prices of the inputs used were monitored in the vending warehouses of the city of Riobamba. The sale price of the potatoes was monitored every week in the local Riobamba market; the price was 330 USD t⁻¹.

To assess NUE, we evaluated N recoveries in plant compartments in Phase I for the different five N rates by harvesting 10 plants (the whole aboveground biomass and the tubers of these 10 plants). We measured the total nitrogen content (TNC) in the plant compartments.

Data Analysis

For Phase I (*experimental study of N rate*), the effect of treatment and replicate (block) on each response was determined by two-way analysis of variance (ANOVA); for those variables for which the block effect was not significant ($\alpha=0.05$), the effect of treatment was determined by one-way ANOVA. For variables that exhibited heteroscedasticity, the effect of treatment was determined by Welch's ANOVA. For Phase II (*technology transfer study*), the effect of treatment and replicate on each response was determined by two-way ANOVA. Because replicate was not significant for any variable ($\alpha=0.05$), the effect of treatment on each response was determined by paired t-test, in which observations were paired by replicate because of a site change in the second year. Statistical analysis was performed using R (R Core Team, 2021). Normality of residuals was tested using shapiro.test, and homogeneity of variances was tested using bartlett.test. ANOVA was performed using aov, Welch ANOVA was performed using oneway.test, and paired t-tests were performed using t.test. Least significant differences of response means were determined using LSD.test from the R package agricolae, and pairwise.t.test from the R package stats.

Results and Discussion

Phase I (*Experimental Study of N Rate*)

Potato Crop Yield (t ha⁻¹)

In the research study, the N fertilizer rate significantly increased yields as the N rates continued to increase up to the point that maximum yields were achieved; beyond this, additional N fertilizer reduced the yields (Table 2; $P<0.01$). The average yields of 19.3 Mg ha⁻¹ with the control (zero N fertilizer) were significantly increased (by 40%) with an additional 100 kg N ha⁻¹ ($P<0.05$). The 200 kg N ha⁻¹ rate significantly increased yields (by 77%) over the control treatment ($P<0.05$) and by 26% over the 100 kg N ha⁻¹ rate ($P<0.05$). The 300 kg N ha⁻¹ rate significantly increased yields (by 87%) compared to the control ($P<0.05$) and by 33% compared to the 100 kg N ha⁻¹ rate ($P<0.05$). The 400 kg N ha⁻¹ rate significantly increased yields (by 71%) compared to the control ($P<0.05$), and it increased the yields by 22% compared to the 100 kg N ha⁻¹ rate ($P<0.10$). The quadratic response of potato yield (t ha⁻¹) versus different rates of N (kg ha⁻¹) ($y = 3246.20 + 34.856x - 0.061x^2$; $r^2=0.99$) estimated that the maximum yield response of 35.5 t ha⁻¹ was obtained at an N rate of 294.7 kg

Table 2 Average tuber yields[†] during Phase I N management study (*experimental study of N rate*) where we applied 0, 100, 200, 300, and 400 kg N ha⁻¹ with three replications in the same experimental area in the Puculpala community, located in the province of Chimborazo in Ecuador (2020)

N Treatments (kg N ha ⁻¹)	Potato – 2020 (t ha ⁻¹)
0	19.3 c
100	26.9 b
200	34.1 a
300	36.1 a
400	33.0 ab

[†] Means with different letters are significantly different at $P \leq 0.05$

Table 3 The average gross income, total cost, and net income (USD ha⁻¹) for potato crops grown in Phase I study (*experimental study of N rate*) where 0, 100, 200, 300 and 400 kg N ha⁻¹ were applied. Phase I was conducted in the Puculpala community located in the province of Chimborazo in Ecuador (2020)

N Rate kg N ha ⁻¹	Costs and Benefits (USD ha ⁻¹)		
	Gross Income	Total Cost	Net Income
0	6,767 c [†]	3,361 d	3,406 c
100	9,489 b	3,728 c	5,760 b
200	11,949 a	4,073 b	7,876 a
300	12,645 a	4,269 a	8,376 a
400	11,549 a	4,311 a	7,238 ab

[†] Within a column, means with different letters are significantly different at $P \leq 0.05$

N ha⁻¹, and any increase above 294.7 kg N ha⁻¹ contributed to a reduction in tuber yields.

Costs and Benefits of Potato Cultivation (in USD ha⁻¹)

The total cost, gross income, and net income increased significantly with N fertilizer application (Table 3; $P < 0.05$). Net income, which was 3,406 USD ha⁻¹ with the control (zero N fertilizer), significantly increased (by 69%) with an additional 100 kg N ha⁻¹ ($P < 0.05$). The 200 kg N ha⁻¹ rate significantly increased the net income (by 131%) compared to the control ($P < 0.05$) and increased it by 37% compared to the 100 kg N ha⁻¹ rate ($P < 0.05$). The 300 kg N ha⁻¹ rate significantly increased net income (by 146%) compared to the control ($P < 0.05$) and by 45% compared to the 100 kg N ha⁻¹ rate ($P < 0.05$). Although the 400 kg N ha⁻¹ rate significantly increased yields (by 113%) compared to the control ($P < 0.05$), the increase was lower than those obtained with the 200 and 300 kg N ha⁻¹ rates. Additionally, although the 400 kg N ha⁻¹ rate increased yields by 26% compared to the 100 kg N ha⁻¹, this difference was not significant at $\alpha = 0.05$. The quadratic response of net income (USD ha⁻¹) versus different rates of N (kg ha⁻¹) ($y = 3246.2 + 34.856x - 0.0614x^2$; $r^2 = 0.99$) estimated a maximum net income at 8,193 USD per ha with an N rate of 285 kg N ha⁻¹; any increase above 285 kg N ha⁻¹ contributed to a reduction in net incomes.

The total cost of 3,728 USD ha⁻¹ with the control (zero N fertilizer) significantly increased (by 11%) with an additional 100 kg N ha⁻¹ ($P < 0.05$). The 200 kg N ha⁻¹ rate significantly increased the total cost with a 21% increase compared to the control ($P < 0.05$) and 9% increase compared to the 100 kg N ha⁻¹ ($P < 0.05$). The 300 kg N ha⁻¹ rate significantly increased the the total cost (by 27%) compared

to the control ($P < 0.05$), by 15% compared to the 100 kg N ha⁻¹ ($P < 0.05$), and by 5% compared to the 200 kg N ha⁻¹ ($P < 0.05$). The 400 kg N ha⁻¹ rate significantly increased the total cost, with a 28% increase in total cost compared to the control ($P < 0.05$), a 16% increase compared to the 100 kg N ha⁻¹ rate ($P < 0.05$), and a 6% increase compared to the 200 kg N ha⁻¹ rate ($P < 0.05$). While the 400 kg N ha⁻¹ rate also saw a 1% increase in total cost relative to the 300 kg N ha⁻¹ treatment, this was not significantly different.

The gross income (6,767 USD ha⁻¹ with no N fertilizer) significantly increased (by 40%) with an additional 100 kg N ha⁻¹ ($P < 0.05$). The 200 kg N ha⁻¹ rate significantly increased gross income, with a 77% increase over the control ($P < 0.05$), and a 26% increase relative to the 100 kg N ha⁻¹ rate ($P < 0.05$). The 300 kg N ha⁻¹ rate significantly increased the gross income, with an 87% increase over the control ($P < 0.05$), and a 33% increase compared to the 100 kg N ha⁻¹ ($P < 0.05$). We also found that the 300 kg N ha⁻¹ rate resulted in a 6% higher gross income compared to the 200 kg N ha⁻¹ rate; however, this was not significantly different. Additionally, although not significant, the 400 kg N ha⁻¹ rate reduced the gross income compared to the 200 and 300 kg N ha⁻¹, by 3% and 9%, respectively.

Dry Weight Production

The dry aboveground biomass of potato leaves and stalks increased with N rate ($P < 0.05$; Table 4). The 200, 300 and 400 kg N ha⁻¹ rates resulted in significantly higher dry aboveground biomass than the 0 and 100 kg N ha⁻¹ rates ($P < 0.05$; Table 4). The 200, 300 and 400 kg N ha⁻¹ rates increased dry aboveground biomass compared to the control (non-fertilized plots) by 145, 193, and 184%, respectively ($P < 0.05$). Although the difference was not significant

Table 4 Average dry matter yields[†] during Phase I N management study (*experimental study of N rate*) where we applied 0, 100, 200, 300, and 400 kg N ha⁻¹ with three replications in the same experimental area in the Puculpala community, located in the province of Chimborazo in Ecuador (2020)

N Treatments (kg N ha ⁻¹)	[§] Stalks + Leaves (t ha ⁻¹)	[§] Tubers (t ha ⁻¹)
0	0.9 b	5.0 b
100	1.3 b	6.8 ab
200	2.3 a	8.6 a
300	2.7 a	8.9 a
400	2.6 a	8.0 a

[†] Means with different letters are significantly different at $P \leq 0.05$

Table 5 Average N uptake (kg N ha⁻¹) by potato stalks plus leaves and by tubers, total N uptake in the plant[¶] and NUE during Phase I N management study (*experimental study of N rate*) where we applied 0, 100, 200, 300, and 400 kg N ha⁻¹ with three replications in the same experimental area in the Puculpala community, located in the province of Chimborazo in Ecuador (2020)

N Treatments (kg N ha ⁻¹)	[§] Stalks + Leaves (kg N ha ⁻¹)	[§] Tubers (kg N ha ⁻¹)	[§] Total (kg N ha ⁻¹)	[¶] NUE (%)
0	11 b	55 b	66 b	
100	17 b	79 b	96 b	30 ab
200	42 a	113 a	155 a	44 a
300	49 a	139 a	188 a	41 ab
400	36 a	112 a	148 a	21 b

[¶] Total N uptake in the plant compartments is the sum of the total N content in stalks, leaves and tubers

[§] Means with different letters are significantly different at $P \leq 0.05$

[¶] Means with different letters are significantly different at $P \leq 0.10$

($P < 0.05$), the 100 kg N ha⁻¹ had an average dry aboveground biomass production 36% higher than that of the control plots. The N rate of 400 kg N ha⁻¹ had an average dry aboveground biomass production 3% lower than that of the 300 kg N ha⁻¹, but this difference was not significant. The 400 kg N ha⁻¹ rate had an average dry aboveground biomass production 16% higher than that of the 200 kg N ha⁻¹ rate, which was also not significant.

The total dry potato tuber biomass increased with N rate ($P < 0.05$; Table 4). The N rates of 200, 300 and 400 kg N ha⁻¹ resulted in significantly higher dry tuber biomass than the 0 kg N ha⁻¹ ($P < 0.05$; Table 4). The 200, 300 and 400 kg N ha⁻¹ rates increased tuber dry biomass compared to the control plots by 72, 79, and 60%, respectively ($P < 0.05$). The 100 kg N ha⁻¹ rate had an average tuber dry biomass production 36% higher than that of the control plots, although this difference was not significant. The 400 kg N ha⁻¹ rate had an average tuber dry biomass production 10% and 7% lower than that of the 300 and 200 kg N ha⁻¹ rates, respectively, although these differences were not significant.

N Content in Plant Compartments and Total N Uptake

The total N uptake in the aboveground potato leaves and stalks increased with N rates ($P < 0.05$; Table 5). The 200, 300 and 400 kg N ha⁻¹ rates had significantly higher N content in the aboveground biomass than the 0 and 100 kg N ha⁻¹ rates ($P < 0.05$). The 200, 300 and 400 kg N ha⁻¹ rates increased N uptake in the aboveground biomass by 287, 357, and 237%, respectively, compared to the control plots

($P < 0.05$). The N rate of 100 kg N ha⁻¹ had aboveground biomass with 54% higher N content than that of the control, although this difference was not significant. The 400 kg N ha⁻¹ rate resulted in aboveground biomass production with 13 and 26% lower N content than that of the 200 and 300 kg N ha⁻¹, applications, respectively, but these differences were not significant.

The N uptake of the potato tuber biomass increased with N rate ($P < 0.05$; Table 5). The N rates of 200, 300, and 400 kg N ha⁻¹ resulted in significantly higher N content in the tuber biomass than the 0 and 100 kg N ha⁻¹ rates ($P < 0.05$). Additionally, these rates increased N uptake in the tuber biomass by 105, 152, and 103% respectively, compared to the control plots ($P < 0.05$). The N application of 100 kg N ha⁻¹ resulted in 43% higher N content on average in the tuber biomass than the non-fertilized plots, although this was not a significant difference. The 400 kg N ha⁻¹ rate had an average N content in the tuber biomass production that was 1% lower than that of the 200 kg N ha⁻¹ rate and 20% lower than that of 300 kg N ha⁻¹ rate, but these differences were not significant.

The total N uptake in the potato stalks, leaves, and tubers increased with N rate ($P < 0.05$; Table 5). Application rates of 200, 300 and 400 kg N ha⁻¹ led to significantly higher N content in the stalks, leaves and tubers than that observed with the 0 and 100 kg N ha⁻¹ ($P < 0.05$). The 200, 300 and 400 kg N ha⁻¹ rates increased N uptake in the stalks, leaves, and tubers, by 134, 185, and 125%, respectively, compared to the control plots ($P < 0.05$). Although not significant, the 100 kg N ha⁻¹ rate had a 45% higher average N content in

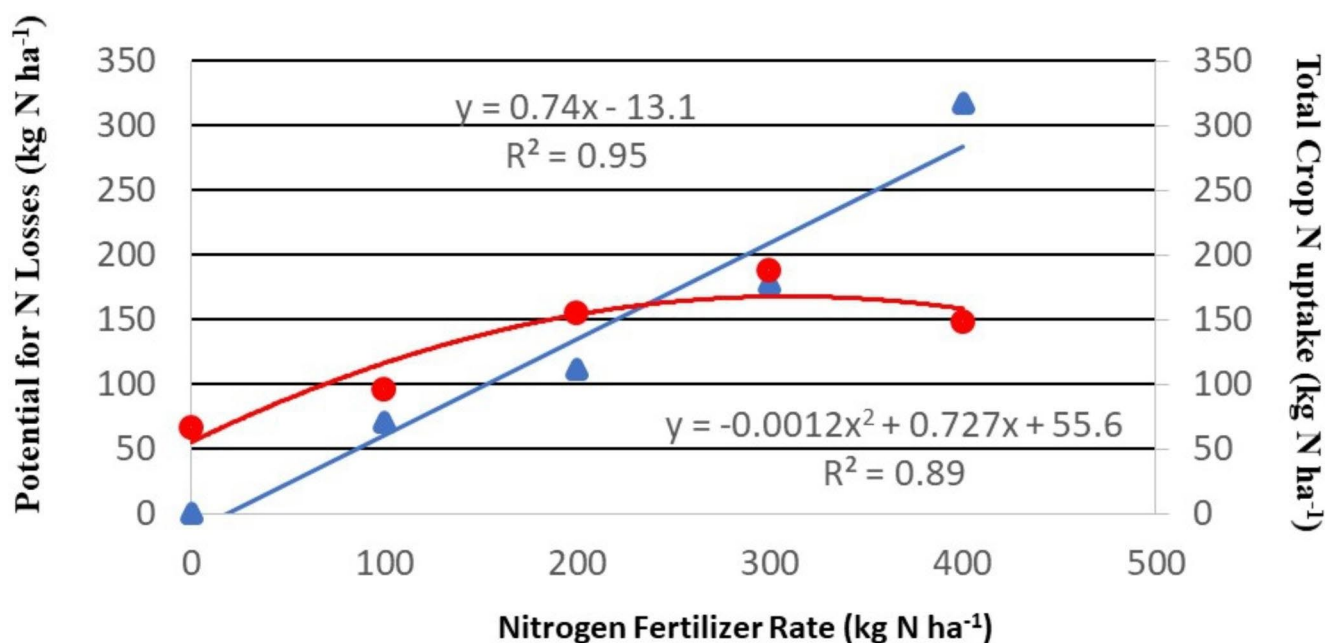


Fig. 2 Potential amount of nitrogen (N) fertilizer that could be available for escape to the environment as rate of N fertilizer application is increased (blue triangles show potential N losses). Total crop N uptake

(stalks, leaves, and tubers) per hectare (red circles) as rate of N fertilizer application is increased

the stalks, leaves, and tubers than observed with the control (zero N fertilizer) plots. The N rate of 400 kg N ha⁻¹ had 4% lower average N content in the stalks, leaves, and tubers than that of the 200 kg N ha⁻¹ rate, and 21% lower than that of the 300 kg N ha⁻¹ rate, although these differences were not significant.

N Use Efficiencies (NUE) and Potential for N Losses

The potential for N losses to the environment increased significantly with N rate (Fig. 2; $r^2 = 0.95$; $P < 0.01$; Table 5). The NUE of the 100, 200, 300 and 400 kg N ha⁻¹ applications were 29.6, 44.3, 40.7 and 20.6%, respectively (Table 5). The highest NUE of 44.3% observed with the 200 kg N ha⁻¹ rate was significantly higher than the NUE of 20.6% found with the 400 kg N ha⁻¹ rate ($P < 0.10$). The NUE of the 100, 200, and 300 kg N ha⁻¹ rates were not significantly different among themselves. Additionally, the NUE of the 400, 300 and 100 kg N ha⁻¹ were not significantly different among themselves.

Phase II (Technology Transfer of N Management for Potato Production in the Andes)

Potato Crop Yield (t ha⁻¹) and Economic Returns (USD ha⁻¹)

For the technology transfer study of N management with small farmers in the Andean region during 2020 and 2021, we found that the improved N management practice of

adding 300 kg N ha⁻¹ significantly increased the farmers' yields compared to traditional practices in this region (Table 6; $P < 0.01$). The improved practices increased the average potato tuber yields by 50%, from 18.3 Mg ha⁻¹ to 27.5 Mg ha⁻¹. Increasing the historically typical application of 89 kg N ha⁻¹ to 300 kg N ha⁻¹ increased yields by 9.2 Mg ha⁻¹.

Although the total cost significantly increased with improved N management practices, gross income and net economic returns also increased with the improved N management practices (Table 7; $P < 0.01$). The total cost of \$2,807 USD ha⁻¹ of the traditionally employed practices increased to \$3,741 USD ha⁻¹. However, the gross income increased from \$6,389 USD ha⁻¹ to \$9,626 USD ha⁻¹. The net economic income for the farmers increased from \$3,582 USD ha⁻¹ to \$5,885 USD ha⁻¹ for a 64% higher net income, a substantial improvement.

Discussion

For both the Phase I and Phase II studies, we found highly significant responses ($Pr \leq 0.05$) for gross income, total cost, and net income [in USD ha⁻¹], showing that the costs and income were influenced by the level of N fertilization applied. We found that increasing N fertilization rates from 0 to 300 kg N ha⁻¹ can result in higher gross income and net income in potato systems. However, this is not the case when N fertilization rates are increased from 300 to 400 kg

Table 6 Average tuber yields[†] during Phase II (*technology transfer study*), at four commercial farm operations where we implemented our recommendations for N management practices and compared them to the farmers' traditional management practices in the Puculpala community, located in the province of Chimborazo in Ecuador (2020 to 2021). Areas under farmers' traditional practices received an average application of 89 kg N ha⁻¹, whereas areas testing our recommended N management received 300 kg N ha⁻¹

Locality, Year	Average (t ha ⁻¹)	
	Our Recommended N Management	Farmers' Traditional Practices
Balcashí, 2020	26.1	17.6
Puculpala, 2020	27.3	18.5
Guntuz, 2021	31.3	19.7
Puculpala, 2021	25.4	17.2
Average	27.5a[†]	18.3b

[†] Means with different letters are significant at $P \leq 0.05$

Table 7 The average gross income, total cost, and net income (USD ha⁻¹) for potato crops grown in Phase II (*technology transfer study*), at four commercial farm operations where we implemented our recommendations for N management practices and compared them to the farmers' traditional management practices in the Puculpala community, located in the province of Chimborazo in Ecuador (2020 to 2021). Areas under farmers' traditional practices received an average application of 89 kg N ha⁻¹, whereas areas testing our recommended N management received 300 kg N ha⁻¹

Indicators	Our Recommended N Management (USD ha ⁻¹)	Farmers' Traditional Practices (USD ha ⁻¹)
	Average	Average
Gross Income	9,626 a [†]	6,389 b
Total Cost	3,741 a	2,807 b
Net Income	5,885 a	3,582 b

[†] Means with different letters are significantly different at $P \leq 0.05$

N ha⁻¹, where total and net income decrease. Fitted curves also showed the the highest yield is obtained at a higher N rate of about 295 kg N ha⁻¹, while the maximum economic benefit is achieved at a somewhat lower N rate of about 285 kg N ha⁻¹.

Since there is always the possibility that climate variability could result in year-to-year yield variability and more N may be needed to achieve higher yields, our recommendation is to use the 300 kg N ha⁻¹ rate in these regions of similar soils and where historically, low N application rates have predominated. All commercial sites, which were tested in different years (Phase II), significantly responded to the 300 kg N ha⁻¹ rate, with higher yields, gross income, and net income. We found the same response in four small commercial farms across the Andean region.

These practices have the potential to help farmers in Balcashí, Puculpala, and Guntuz. They have the potential to imminently contribute to higher potato yields in the Chambo river sub-basin. This is encouraging, as it means that farmers already have a management option that they can gradually incorporate into their potato-pasture systems. These preliminary results motivated local farmers to use 300 kg N ha⁻¹, as it demonstrated increased economic returns that would improve their families' standard of living. The 50% increase in yields and 64% increase in net economic returns for these small commercial farms is an incentive to change current N management practices and increase potato tuber

yields for food security in the region and adaptation to a changing climate.

Our results in this Andean region of Ecuador align with findings from N management studies conducted by Essah and Delgado (2009) in high-altitude potato systems in Colorado. Essah and Delgado (2009) found that overapplication of N fertilizer not only reduced NUE and increased the potential for N losses to the environment, but it could also contribute to lower total potato tuber yield and lower economic returns to farmers. In contrast to research conducted by Essah and Delgado (2009) that included assessment of the levels of inorganic NO₃-N in the soil profile, this study in Ecuador does not present data on residual NO₃-N in the soil. However, the crop N uptake data for the aboveground and tuber compartments serve as an indicator of the N balance for this system, suggesting there is potential for high residual NO₃-N content in the soil and/or large N losses from the system, especially since all NUEs were lower than 50%, and at the highest N rate they were about 20% (Fig. 2; Table 5). There is a need to continue studies to increase NUE in this region. The maximum NUE of just 44% was achieved with 200 kg N ha⁻¹, and the 300 kg N ha⁻¹ rate had an NUE of 40%. These preliminary data suggest that close to 80% of the N is potentially vulnerable to losses at an N rate of 400 kg N ha⁻¹. Additional studies in this region are needed to capture the potential N that could be available for losses at the recommended 300 kg N ha⁻¹ rate or even at

the 200 kg N ha⁻¹ rate, which has the higher NUE and still significantly increased yields and economic returns. This is a research gap in the Andean region, and we propose that a third phase of research should include assessments of residual soil NO₃-N after potato systems and how to recover this important resource with cover crops suitable for the Andean region and deep-rooted crops such as corn to increase system NUE before it is lost to the environment via NO₃-N leaching and/or denitrification.

Since we did not collect deep soil cores and/or measure changes in soil NH₄ and NO₃-N with these different nitrogen rates, we cannot assess how much residual N there was in the soil profile after harvesting the tubers. With that said, the amount of N that is available to escape to the environment increased significantly and linearly with higher N input (Fig. 2; Table 5). While it has been reported that the potential for N losses in potato cropping systems is significant, we know that if we follow the potato crop with a crop that has a deeper root system, such as corn, we could increase the NUE of the potato crop (Delgado et al. 2000, 2001; Meisinger and Delgado 2002) since the deep-rooted crop acts as a scavenger crop that recovers N that may be left in the soil as inorganic N, reducing the losses of N to the environment. Additionally, as shown by Delgado et al. (1999, 2000, 2001) in potato systems, there is potential to use cover crops that can mine NO₃ from deeper in the soil profile to recover some of this N, and these cover crops could also be used for grazing or even forage (Delgado et al. 1999). Delgado et al. (2021) discussed the potential to use cover crops across the tropics, and there is potential to incorporate cover crops in these potato systems of the Andean region to increase farmers' economic returns and yields.

This three-year study showed that for those areas that are not currently using adequate levels of N to maximize yields and economic returns there is potential to improve N management practices to increase yields, net income, and food security; and adapt to a changing climate. There is potential to use improved N management with additional practices such as conservation agriculture, use of cover crops, and following the potato with a deep-rooted crop, to increase the system N use efficiencies and NUE, as well as the agronomic efficiency of the applied N (Delgado et al. 2020, Delgado et al. 2019). We were able to transfer this N management practice to improve potato tuber production at all farms by increasing yields by 50% and net economic returns by 64%, and help farmers adapt to a changing climate and potentially increase food security across the region.

Declarations

Conflict of Interest The authors declare that they do not have any conflicts of interest.

Disclaimer Mention of trade names or commercial products are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable.

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