Conservation Agriculture Increases Yields and Economic Returns of Potato, Forage, and Grain Systems of the Andes

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ABSTRACT

Physical and environmental vulnerability analysis conducted for the Illangama watershed located in Ecuador's Andean highlands, shows deteriorated soil quality and declining crop productivity. These problems are caused by soil erosion in steep slopes and inappropriate soil management practices. Research projects conducted from 2011 to 2014 adopted and examined the feasibility of conservation agriculture practices for potato (*Solanum tuberosum* L.), oat (*Avena sativa* L.) and vetch (*Vicia sativa* L.), barley (*Hordeum vulgare* L.), bean (*Vicia faba* L.), and a mixture of pastures (annual ryegrass [*Lolium multiflorum* Lam.], perennial ryegrass [L. *perenne* L.], orchardgrass [*Dactylis glomerata* L.], white clover[*Trifolium repens* L.], and red clover [*T. pratense* L.]). The practices included surface water deviation ditches, reduced tillage, residue retention, and application of N, all within an improved rotation. The study examined crop yields and economic returns in an effort to identify the best practices. Results indicate that crop productivity and net (of cost of production) benefits of the system were increased as much as 25 and 24%, respectively, using a feasible conservation agriculture system compared to conventional practices. This study shows that conservation agriculture increases yields and saves on production costs due to less tillage. We also found that N fertilization with these conservation agriculture practices increases yields and net returns. This study concludes that conservation agriculture practices are good alternatives for these high-altitude Andean soils. The practices should be promoted among Andean producers to increase the productivity and sustainability of their potato–grain–pasture systems.

Core Ideas

- The Andean region of Ecuador is critical for the country's food security.
- Cultivation of high-slope mountainous agriculture is accelerating erosion.
- Conservation agriculture is an attractive management alternative.
- Implementation of reduced tillage could contribute to higher net income for farmers.
- These practices could benefit nearly 200,000 Ecuadorean farms.

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In Ecuador's Andean highlands nearly 200,000 households use a potato–pasture production system. These farms have more than 47,000 ha of potato; 1,228,000 ha of pasture (many of which are improved); and approximately 731,000 head of cattle. Cows in the area produce, on average, 6.6 kg d^{-1} of milk per animal (INEC, 2013). The high-altitude Andean region is characterized by steep slopes, adverse weather conditions and annual erosion in cultivated fields between 10 and 50 t ha^{-1} (Henry et al., 2013; Chela 2008). The high level of erosion and consequent productivity losses through soil degradation are exacerbated by traditional agricultural production practices such as tillage, manual weed removal, and use of crop residues for animal feed (Fig. 1). Excessive use of agrochemicals and machinery has led to a steady rise in production costs and a significant reduction in yields (Barrera et al., 2012; Barrowclough et al., 2016; Escudero et al., 2014).

Physical and environmental vulnerability studies conducted in the Illangama watershed, a subbasin of the Chimbo River, show that due to inappropriate soil management and the use of fallow the soils have deteriorated and crop productivity has declined (Barrera et al., 2012; Escudero et al., 2014; Monar et al., 2013). Soils in this region are Andisols of volcanic type, characterized by a deep A horizon with high organic matter content (commonly exceeding 10%) and consequent low apparent density (Buytaert et al., 2007; van Breemen and Buurman, 2003). Although the productivity of Andisols can be quite high, soil P is often limited due to its fixation in several complexes based on minerals and metals (Brady and Weil, 2008; Shoji et al., 1993; Wada and Gunjigake, 1979).

Households in the watershed obtain their income from rotations that include annual crops (potato, barley, and bean), pasture (used for grazing by dairy cows), and fallow (Barrera et al., 2012). Chela (2008) showed that pasture-based farming systems are much less susceptible to erosion than those with permanent or annual crops. Although dairy cattle are an important component of the production system in the Illangama watershed, small-scale producers rely on staple crops to meet food needs; cycles of cultivation consistent with soil conservation are used to maintain food security.

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Fig. 1. Example of cropping systems in the Andean region of Ecuador. A high rate of erosion for these tilled systems can be observed in this photograph. In some areas the subsoil has become exposed to the surface because the surface soils have already been eroded (white areas). These exposed areas will have much lower productivity due to the exposure of the parent material. (Photo: Jorge A. Delgado, USDA-ARS).

Vulnerability analyses suggest the use of conservation agriculture practices to solve the problems of soil deterioration, increase productivity, and intensify production (Barrera et al., 2012; Escudero et al., 2014; Delgado et al., 2019). Conservation agriculture includes three basic principles: minimal disturbance of the soil, permanent cover, and improved rotations (FAO, 2016). Under conservation agriculture, the ground maintains a permanent or semi-permanent organic cover protecting it from the sun, rain and wind, and allowing microorganisms and soil fauna to prosper. Such practices promote nutrient balances and natural processes that may be harmed by mechanical plowing. The use of surface water deviation ditches, reduced tillage, crop coverage (e.g., oat–vetch), and improved rotations (e.g., potato–barley–bean–leguminous pasture), represents a conservation agriculture option that has been proven in other areas (Giller, 2009). Use of these practices can improve agricultural productivity, reduce soil degradation, improve the soil nutrient cycle, and increase income (Verhulst et al., 2010). Otherwise, farmers in the area would prefer to feed residues to their animals, particularly dairy cows (Barrowclough et al., 2016).

In the Illangama, Ecuador's National Institute of Agricultural Research (Instituto Nacional de Investigaciones Agropecuarias; INIAP) jointly with the National Secretariat for Higher Education, Science and Technology (Secretaría Nacional de Educación Superior, Ciencia, Tecnología e Innovación; SENESCYT), and the Sustainable Agriculture and Natural Resource Management- Collaborative Research Support Program (SANREM CRSP) funded by U.S. Agency for International Development (USAID), as well as USDA-ARS-Soil Management and Sugar Beet Research Unit (SMSBRU), Virginia Tech, and Penn State led a research program on conservation agriculture practices and conservation agriculture production systems. Preliminary results showed the potential for improvement of several production systems prevailing in the area (Alwang et al., 2013; Barrera et al., 2012; Barrowclough et al., 2016; Delgado et al., 2019; Escudero et al., 2014; Gallagher et al., 2017; Monar et al., 2013).

Erosion has reduced food security in the region (Monar et al., 2013). Reduced food security has negative social and environmental consequences worldwide (Brown and Young, 1990; Lal, 1987, 1995; Pimentel, 1993; Pimentel et al., 1987). Maintaining the soil cover can improve soil and water quality by reducing off-site transport of soils and agrochemicals and can subsequently increase nutrient cycling (Delgado and Follett, 2002; FAO, 2016).

On-farm research is needed to quantify and demonstrate the benefits of precision conservation in the Andean region. Precision conservation has been shown to be successful in regions of northwestern India and South Asia (Parihar et al., 2016). However, barriers to the adoption of reduced tillage systems by small farmers include the lack of equipment and that initially the crop yields may be smaller than those of conventional systems (Büchi et al., 2017; Martínez et al., 2016; Soane et al., 2012). Several studies suggest that precision conservation in the Andes can improve long-term stainability (Barrowclough et al., 2016; Delgado et al., 2019; Gallagher et al., 2017; Escudero et al., 2014). Escudero et al. (2014) reported that yields with the farmers' traditional farming practices and a N fertilizer application of about 40 kg N ha^{-1} were almost doubled with an additional application of 80 to 100 kg N ha^{-1} (total application of 120 or 140 kg N ha^{-1}). Barrowclough et al. (2016) reported that no till has the highest net profit when compared to the traditional tillage practice. Gallagher et al. (2017) concluded that "Crop productivity tended to be higher in plots that had surface water deviation ditches, and where crop and cover residues were retained in the field. Reduced tillage systems had yields similar to conventional tillage systems in all crops."

There is a need to conduct N fertilizer studies for potato, oat and vetch, barley, bean, and/or a mixture of pastures at the farm-yield level, and to study the effects of N fertilizer application under surface water deviation ditches, reduced tillage, or retention of residue, on economic returns. Our study used plot yields collected in farmers' fields to quantify the effects of the conservation agriculture practices in the context of a production system at the farm level. The plots were harvested at the optimal time to represent farmers' yields and at the time that will allow farm products to be stored in farmers' storage sites and/or to be used to feed the animals. This will allow the conduction of a real economic assessment using the value of farmer harvest products at harvesting time. We provide evidence of the effects of adopting different combinations of practices on crop productivity and economic benefits of the production systems. Evaluated practices include surface water deviation ditches, reduced tillage, retention of residue on the soil surface, and the use of N in the cultivation of barley; these practices were incorporated into a rotation of crops.

Our study is innovative for this region because the farmers are not using zero-till practices, and the study is the first assessing the impacts of these practices on farm-level yield responses to conservation agriculture. Implementation of these conservation agriculture practices could potentially impact close to 200,000 farmers and improve their livelihoods if these studies find that conservation agriculture has a positive effect on yields at the farm level. Our hypothesis is that the conservation agriculture practices will lead to increased yields and to economic benefits in a relatively short time period.

MATERIALS AND METHODS

Physical, Social, and Economic Description of the Study Site

The Chimbo River Subbasin spans 3635 km^2 and includes part of the Bolivar and Chimborazo provinces in the high-altitude Andes region of Ecuador (Fig. 2). Within this subbasin, the Illangama River watershed covers 130.6 km^2 and extends from latitude 1°23'55.30" S to 1°34'4.80" S and longitude 78°50'39.38" W to 78°58'29.52" W. The elevation is between 2500 and 4500 m above sea level. During the study period, temperatures ranged between 10.3 and 13.8°C and rainfall ranged from 500 to 1300 mm. Experimental plots were established on fields of farmers whose soils were classified as Andisols with organic matter content, pH, and bulk density ranging from 8 to 12%; 5.8 to 6.0; and 0.8 to 1.0 g cm^{-3}, respectively (INIAP, 2010). The average altitude of the experimental plots was approximately 3700 m above sea level.

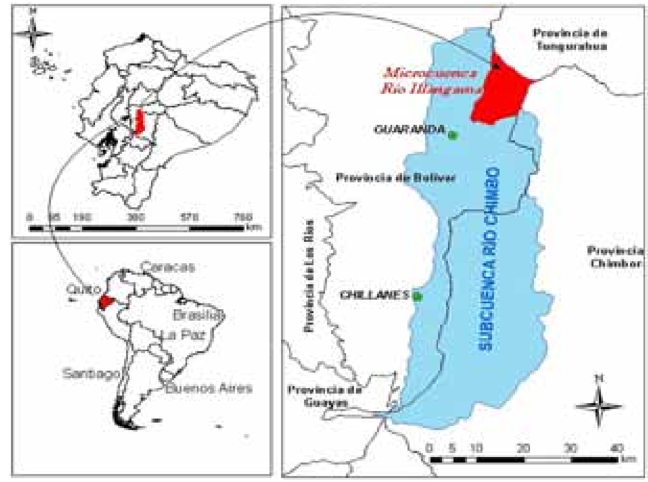

Fig. 2. Location of the watershed of the Illangama River in Ecuador (from Gallagher et al., 2017).

Settlements in the Illangama are relatively recent as the area was populated by indigenous groups resettled in the 1980s. The settlements are contributing to environmental degradation as there is obvious erosion on the steep hillsides and economic activities and populations are gradually moving into the pristine, high-altitude *paramo* (highlands). Erosion and runoff contribute to degradation of surface water and downstream pollution is a growing concern (Barrera et al., 2012; Monar et al., 2013).

Households in the Illangama have average holding sizes of 3.40 ha. More than 70% of the population claimed that agriculture is its main productive activity. As much as 95% of households have pastures, and 100% plant potato. Within this potato–pasture system, production consists of potato crops, oat and vetch, barley, bean, and a mixture of pastures. Households also cultivate traditional Andean tubers such as mashua (*Tropaeolum tuberosum* Ruiz & Pavon), oca (*Oxalis tuberosa* Mol.), melloco (*Ullucus tuberosus* Caldas), and native potato (*S. phureja* Juz. & Buk.), and these native varieties form an important part of regional diets (Barrera et al., 2012).

Near subsistence conditions and lack of economic opportunity outside of agriculture contribute to poverty. Approximately 75% of the population is considered poor, with household incomes ranging from US$160 to $240 per month (INEC, 2013; Barrera et al., 2010). In the Illangama, 100% of households are indigenous, and average family size is six. Up to 14% of the adult population is illiterate and only 50% of adults have completed primary education. Average educational attainment is 3 yr. Data show the average male adult has 6 yr of education, while the average woman has less than 4 yr. Around 13% of the households are headed by women. The percentage of temporary emigration is high; more than 50% of households have at least one temporary emigrant, with the main destination being Quito (Barrera et al., 2010). More than 75% of farm sales go to intermediaries and, as a result, farmers are only able to capture very little of the total value added of their production (Barrera et al., 2010).

Experimental Design

These studies were conducted from 2011 to 2014 to assess the effects of surface water deviation ditches, tillage (conventional tillage vs. reduced tillage), crop residue (residue removal vs. coverage with residue) and N fertilizer (N fertilizer vs. no N fertilizer).

This long-term potato–pasture production system study was conducted in two phases. In Phase I (from January 2011 to January 2012) the experiment was set up as a fully randomized block design with split plots. The main plots were the surface water deviation ditches treatments (with and without surface water deviation ditches). The subplots were the factorial treatments of tillage and crop residue. Phase II (from January 2012 to December 2014) incorporated N fertilizer treatments that were randomly assigned to halves of the Phase I subplots. In Phase I, each plot was 96 m^2 (12 by 8 m) and in the second, each was 48 m^2 (6 by 8 m). The experiment was conducted at three farms with identical management practices, using each farm as a block where the plots were established. The farms (blocks) were close together, with similar Andisols. The distance between the first two blocks (reps) was 50 m, and the third block (rep) was 1000 m away.

Harvesting and Economic Analysis

The variables evaluated were yields (t ha^{-1}) of all crops throughout rotation; costs of production, including establishment and maintenance (US\$ ha^{-1}); and benefits (US\$ ha^{-1}) based on the value of yields. Yields of potato, barley, and bean were measured by harvesting the entire plot, excluding a 1-m buffer on each of its four sides. In the case of the oat–vetch cover and pasture production, biomass was measured in five areas of 0.25 m^2 within each plot.

Production costs included costs of construction of the surface water deviation ditches, soil preparation, seeds, fertilizers, pesticides, labor, and human and material costs of agronomic management and harvest. Prices for inputs were collected from suppliers in Guaranda, Ecuador (about 40 km from the watershed). Selling prices of harvested products were collected weekly in the Guaranda market; the actual prices used for the analysis depended on the expected timing of sales. Prices were US\$0.30 kg^{-1} for potato, US\$0.56 kg^{-1} for barley, and US\$0.89 kg^{-1} for bean. Forage values for oat–vetch and pasture were US\$0.03 kg^{-1} and US\$0.06 kg^{-1}, respectively. The economic benefits of oat–vetch used for groundcover are in the value of the fertility and moisture in the soil, reflected by productivity increments.

Crop Management Practices

In plots containing surface water deviation ditches, five ditches were constructed every 10 m down the slope with a length of 12 m and a depth of 0.5 m. These ditches were constructed on the contour with a slope of 1%. Including the surveying costs, and based on prevailing wages in the area, each ditch cost US\$0.46 m^{-1} with an annual maintenance cost of US\$0.27 m^{-1} yr^{-1}.

Conventional and reduced tillage were evaluated as part of the experiment. Under conventional tillage of potato, cultivation occurred 15 d before planting. Potato seeds were planted 0.40 m apart in furrows that were spaced 1 m apart. Under reduced tillage, the sod was cut open and folded back, the potato seed was placed under the cut and the sod was replaced (the system is known locally as "chamba"). Potato seeds were planted with the same spacing as in the conventional tillage. For barley and oat–vetch cultivation, under conventional tillage, the soil was broken open with hoes, and furrows were prepared manually; seeds were manually broadcasted. With reduced tillage, for oat–vetch, seeds were broadcasted on undisturbed soil, while barley seeds were broadcast in furrows spaced 0.40 m apart. In each case, a small layer of soil was distributed over the seeds. Conventional tillage for bean meant the seeds were planted in furrows at a distance of 0.40 m between plants and 0.80 m between rows. For reduced tillage, a handspike was used to open small pits every 0.4 m with 0.8 m between rows. One or two seeds were deposited in each pit. For pasture, seeds were broadcast manually with no soil preparation for either conventional or reduced tillage.

In the case of reduced tillage, glyphosate [N-(phosphonomethyl) glycine] was applied in doses of 12.5 cc L^{-1} of water 15 d before planting to control weeds. In the conventional tillage plots weeds were removed manually with a hoe. Integrated pest management was employed for phytosanitary control. In addition, and depending on the appearance of insects and diseases, fipronil {(*RS*)-5-Amino-1-[2,6-dichloro-4-(trifluoromethyl)phenyl]-4-(trifluoromethylsulfinyl)pyrazole-3-carbonitrile}, cypermethrin {[cyano-(3-phenoxyphenyl)methyl]3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-1-carboxylate}, profenophos {4-bromo-2-chloro-1-[ethoxy(propylsulfanyl)phosphoryl]oxybenzene}, and chlorpyrifos (*O,O*-Diethyl *O*-3,5,6-trichloropyridin-2-yl phosphorothioate) were applied as insecticides and cymoxanil [1-(2-cyano-2-methoxyiminoacetyl)-3-ethylurea], sulfur, benomyl {methyl [1-[(butylamino)carbonyl]-1H-benzimidazol-2-yl]carbamate methyl 1-(butylcarbamoyl)-2-benzimidazolecarbamate}, and carbendazim (methyl *1H*-benzimidazol-2-ylcarbamate) were used, as appropriate, for fungicides.

The varieties used were INIAP-Fripapa for potato; Oats INIAP-82 and *Vicia sativa* for oat and vetch, respectively; INIAP- Gauranga 2010 for barley, Huagrahaba for bean and grasses and legumes for pasture. Seed densities were 990 kg ha^{-1} for potato; 45 and 90 kg ha^{-1} for oat and vetch, respectively; 135 kg ha^{-1} for barley; 60 kg ha^{-1} for bean and 48 and 4 kg ha^{-1} for grasses and legumes, respectively. The potato and bean were placed with direct seeding, the oat–vetch and pasture were broadcast seeded, and the barley was seeded with volley and steady stream. For Phase I, potato received 120 kg N ha^{-1}, 300 kg P_2O_5 ha^{-1}, 60 kg K_2O ha^{-1}, and 30 kg S ha^{-1}. The oat–vetch was not fertilized. For Phase II the non-N-fertilized plots received zero N fertilizer. The N-fertilized barley received an initial application of 50 and 21 kg N ha^{-1} at 50 d after sowing. All barley plots received 71 kg P_2O_5 ha^{-1}. The bean was not fertilized. The N-fertilized plots for pasture received 18 kg urea-N ha^{-1}.

Results were evaluated for the with- and without-residue treatments. For the treatments with residue, the product was harvested, and plant waste was allowed to remain on the ground. For the treatments where forage was left in the field no income was generated since the crop residue was also left in the field (oat–vetch and forage crops with residue). In treatments without residue, the product was harvested and remaining residue was removed from the plots. For the cultivation of oat–vetch, forage was cut and removed from the plot for animal feeding. For barley, the whole plant was cut and removed for threshing. The bean crop was harvested and residue remained in the field. Finally, in the case of pasture, forage was cut on all parcels and withdrawn for animal feeding. The market value of the harvested residue was accounted for in the economic analysis.

RESULTS

For the first evaluation phase, potato and oat–vetch yields were higher with no crop residue removal (Table 1). Oat–vetch

Table 1. Least-squares means of crop yields (t ha^{-1}) for Phases I and II.

Treatment	Phase I		Phase II		
	Potato	Oat/Vetch	Barley	Bean	Pasture
With ditches	14.44	43.25	2.07	2.56	12.00
Without ditches	13.66	41.29	1.84	2.45	11.98
Conventional tillage	13.56	40.86b†	1.74b	2.40b	11.82b
Reduced tillage	14.55	43.67a	2.17a	2.61a	12.17a
Residue harvested	12.88b	41.18b	1.94	2.38b	11.97
No residue harvested	15.23a	43.35a	1.98	2.62a	12.01
Nitrogen applied	–	–	2.22a	2.53	13.51a
No N applied	–	–	1.70b	2.48	10.47b

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

yields were higher with minimum tillage. For Phase II, yields of barley, bean, and pasture were significantly higher with no-till than conventional tillage. For Phase II, bean yields were significantly higher with no residue harvested than with residue harvested. Additionally, for Phase II, yields of barley and pasture were significantly increased with addition of N fertilizer.

The analysis of variance for the variables gross profit, total cost, and net profit throughout the two experimental phases showed statistically significant differences (Table 2). For Phases I and II, respectively, minimum tillage had a 17 and 24% higher net benefit compared to conventional tillage. For Phase I, no residue harvest led to a 6% higher net benefit over conventional tillage. For Phase II, N fertilizer increased by 24% the net benefit compared to non-fertilized treatments. Although N fertilizer application results in about 9% higher costs, the positive impact is so high that the net economic impact is 24% higher than the no-N outcome. Conventional tillage and implementation of surface water deviation ditches had a higher cost during both phases of the study. The net income with surface water deviation ditches was not significant. Total cost for residue harvest was significantly higher in Phase I of the study. Reduced tillage is associated with a lower cost compared to conventional, which should create incentives for its use; its high gross benefit combined with its low cost means that net profits are about 20% higher with reduced tillage.

DISCUSSION

Evaluation of Drainage, Tillage, Residue Harvest, and Nitrogen Fertilizer Practices

For potato yield, no crop residue removal was the only practice affecting production and was 18% higher than the yield obtained with crop residue removal. Although the potato yield of the with-residue plots was greater than yields of the residue-removed plots, we cannot attribute this difference to a residue effect since this was the start of the study and the start of not removing crop residue at potato harvesting. Additionally, during Phase I the yields of oat–vetch were significantly higher (by 5%) with no residue removed than with residue removed. Leaving the residue of the potato crop in the field had a significant impact on the yields of oat–vetch.

As far as tillage, the results obtained for Phase I are very important because no-till potato yields were not reduced when compared to the conventional-tillage potato, suggesting that farmers could incorporate no-till practices for these potato systems without expecting a reduction in yields. These responses where yields were maintained with no-till potato and yields increased by 7% with no-till oat–vetch compared to conventional oat–vetch are in agreement with results from other scientists (Büchi et al., 2017; Martínez et al., 2016; Soane et al., 2012). The yields with surface water deviation ditches were not significantly higher.

During Phase II, barley yields with reduced tillage and with N use were higher by 25 and 31% compared to yields obtained with conventional tillage and no supplemental N application, respectively. Bean grain yields with reduced tillage and residue cover practices were 9 and 10% higher compared to yields with conventional tillage and no cover, respectively. It is important to note that bean yields were not affected by N fertilizer applied to the prior barley crop. Finally, in the case of the pasture, yields with the reduced tillage and N treatment plots were 3 and 29% higher than yields with conventional tillage and no supplementary N, respectively.

These results agree with reports from Büchi et al. (2017), Delgado and Follett (2002), Martínez et al. (2016), and Soane et al. (2012) that reported that the addition of organic C and nutrients to the soil through leaving crop residue in the field, as well as the reduction of C oxidation by implementing no-till practices, improve soil quality and/or crop yields. This is in agreement with Delgado (2010) who reported that crop residue is key for conservation of our biosphere. This also agrees with studies showing the detrimental impacts of traditional cultivation methods on such soils in highly sloped areas of the tropics (Calegari and Alexander 1998). Use of cover crops is a conservation agriculture practice that improves crop productivity and soil health (Dabney et al., 2001; Farooq et al., 2011). These results show that when plant residue is left in the field rather than removed for animal feed, it can be productive.

Evaluation of Costs and Benefits of Conservation Agriculture Practices

The surface water deviation ditches factor was associated with significantly higher costs, but insignificant differences in gross or net benefits (profits). This means that farmers are unlikely to adopt this factor because short-term benefits are negligible while the costs of their installation are substantial. Incentives will be needed for such structures to be built, because farmers themselves will not make the investments as they are unable to capture the full benefits (reduced siltation downstream) from their adoption. An incentive system will have to be justified on the basis of long-term improvements in productivity (not seen here) or avoid costs off-the-farm from erosion (external costs).

The highest net profit over the entire cycle is obtained with reduced tillage, soil cover maintained with residue, and supplementary N application. Net profit is the most appropriate measure of economic benefits, especially to the farmer. Although the

Table 2. Least-squares means of gross profit, net profit and total cost (US$ ha^{-1}) for Phases I and II.

Treatment	Phase I			Phase II		
	Gross profit	Net profit	Total cost	Gross profit	Net profit	Total cost
With ditches	5629.75	2999.92	2629.83a†	5595.83	3106.63	2489.21a
Without ditches	5337.00	2768.58	2568.42 b	5366.83	2997.13	2369.71b
Conventional tillage	5293.08	2661.08b	2632.00a	5234.46b	2723.13b	2511.33a
Reduced tillage	5673.67	3107.42a	2566.25b	5728.21a	3380.63a	2347.58b
Residue harvested	5098.25b	2475.75a	2622.50a	5359.21	2955.04	2404.17
No residue harvested	5868.50a	2622.50b	2575.75b	5603.46	3148.71	2454.75
Nitrogen applied	–	–	–	5921.00a	3381.58a	2539.42a
No N applied	–	–	–	5041.67b	2722.17b	2319.50b
With ditches, residue harvested, N applied						2604.17a
With ditches, residue harvested, no N applied						2340.33cd
With ditches, no residue harvested, N applied						2612.67a
With ditches, no residue harvested, no N applied						2399.67bcd
Without ditches, residue harvested, N applied						2409.67bc
Without ditches, residue harvested, no N applied						2262.50d
Without ditches, no residue harvested, N applied						2531.17ba
Without ditches, no residue harvested, no N applied						2275.50cd

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

total cost is higher with supplementary N application, this cost is rewarded by increased production and subsequently higher profits. Use of surface water deviation ditches does not lead to a statistically higher profit outcome, so if the government of Ecuador wants to encourage their use, some system of incentives would need to be developed. We suggest that profitability will also increase with higher costs of labor, since these costs have almost doubled from $7 to $8 per day at the beginning of our study to $15 per day according to recent estimates from Barrera (personal communication, 2019).

CONCLUSIONS

The study was conducted over 4 yr, and the theory of conservation agriculture is that improvements in soil health will foster greater productivity gains over time. Reduced tillage, retention of crop residues, and use of cover crops and N fertilizer applications are positively associated with yields (potato, oat, barley, bean, and pasture) and profits, demonstrating the economic viability of conservation agriculture in the Andean region of Ecuador. Although Illangama farmers are aware of the environmental benefits of conservation agriculture practices, economic considerations are the main drivers of adoption. The increase in net benefits from using reduced tillage, enhanced groundcover, and application of N compared to conventional practices can motivate adoption. These conservation agriculture innovations can improve the sustainability of the potato–pasture system and also generate off-farm benefits in the form of reduced erosion (and reduced impacts from erosion on water quality downstream). Also, our study demonstrates the short-term economic viability of conservation agriculture and we recommend that follow-up studies be conducted to study the effects of these practices over an extended time on soil organic matter, macro- and micronutrients, and soil health. Cost savings, increased net returns, and better agronomic practices make the system attractive to small-scale farmers in these ecologically vulnerable areas. With limited adaptations, these practices could benefit nearly 200,000 Ecuadorean farms located in similar environments, by helping farmers adapt to a changing climate and helping ensure future food security in the region with implementation of more sustainable and economically viable management practices.

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