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Conservation Agriculture Increases Profits in an Andean Region of South America

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Core Ideas

- Erosion is decreasing the potential for food security in the Andean region.
- Zero tillage would be a viable and economical practice for this region.
- Adding N fertilizer increased the net economic returns by 22%.
- These practices could potentially increase the income of 200,000 farmers.

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ABSTRACT

The Andean region of Ecuador is critical for the country's food security; however, cultivation of high-slope mountainous agricultural systems that experience significant precipitation is accelerating erosion of the soils and reducing the productivity and sustainability of these systems. For 5 yr we monitored tillage and crop residue management practices using a 2 × 2 factorial randomized block (Phase 1) and a 2 × 2 factorial randomized block with split plot (Phase 2) to assess the effects of tillage, crop residue management, and N fertilization on yields and economic returns. Our study found in the initial phase that for three out of the four crops zero tillage (ZT) had higher average yields than minimum tillage, and for one of these three crops, the increase was significant. Our study found in Phase 2 that when N fertilizer was added as a treatment, compared with crops that were not fertilized, yields were significantly higher in four out of five crops. Leaving the crop residue at the surface was a practice that increased the yields of one of the five crops. The higher net economic returns for Phase 1 were with ZT and with harvesting crop residue. When N was added as a treatment in Phase 2, higher net economic returns were found with ZT and residue removed and with N fertilization. Nitrogen fertilizer, crop residue removal, and zero tillage increased net economic returns by 22, 45.1, and 31.8%, respectively. There is potential to use ZT in this region of South America.

Abbreviations: CRH, crop residue harvest; H_0, null hypothesis; H_A, alternate hypothesis; INIAP, Instituto Nacional de Investigaciones Agropecuarias; LSD, Least Significant Difference; MT, minimum tillage; ZT, zero tillage.

A majority of the people living in the rural zones of Ecuador are living under extreme poverty driven by agricultural systems with low productivity, minimal access to agricultural extension services, and agricultural technologies that could help maximize agricultural production, and low access to banking systems and loans to invest in their farming operations (Barrera et al., 2010, 2012). Rural communities in these areas produce food, but the agricultural practices do not provide long-term food security and they diminish the sustainability of these fragile systems by increasing the potential for soil erosion and degrading soil health and quality (Monar et al., 2013). Figure 1 shows farm areas where the subsoil has already been exposed due to intensive soil erosion.

Plowing the soils where possible using animals and/or tractors is the traditional method of cultivating these soils on slopes of up to 50 degrees. The expectation is that this cultivation method increases agricultural production. However, soil disturbance in these high-altitude systems is contributing to loss of soil organic matter and soil particles at rates as high as 150 Mg ha^{-1}, leading to significant degradation of the soil system (FAO, 2014; Chela, 2008; Dourojeanni and Jouravlev, 2001).

It is necessary to develop and implement viable conservation agriculture systems with reduced soil disturbance to increase the sustainability of agricultural production and ensure future food security in Andean regions. Implementing some practices of sustainable agriculture (zero tillage [ZT] or minimum tillage [MT], covering the soil, and crop rotations)

Fig. 1. Example of the high erosion rate near our studies conducted at the Sicalpa River watershed in Chimborazo, Ecuador. Erosion is a problem throughout the Andean region of Ecuador. Note that some of the subsoils (white areas) with lower productivity potential are already exposed. In some areas, the parent material gets exposed due to this intensive cultivation and higher erosion potential without crop residue at the surface (Photo credit: Jorge A. Delgado, USDA-ARS).

in this region can help address this challenge (FAO, 2014). However, there are other potential agronomic problems that will need to be managed. Our study assessed the effects of ZT and MT on yields and economic returns. For these systems, MT is the use of a hoe to till the plots to plant the crop in a furrow and control weeds. Zero-till for these systems is the use of a pointed wood bar to make holes where the crop seeds were planted.

Minimum tillage has been reported to reduce yields for some systems and could increase the potential for weeds since weed control will not be conducted (Knowler and Bradshaw, 2007; Yanggen et al., 2003). For MT systems in Ecuador, weed control can be achieved using an application of glyphosate (*N*-(phosphonomethyl)glycine) to kill weeds 15 d before planting and a follow-up application of atrapac (atrazine, [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine]) to kill broadleaf weeds (Escudero et al., 2014). For small farmers, even though leaving crop residue on the soil surface may protect the soil, this could present a challenge if the residue is used to feed animals, and put the small farmer in a difficult situation where they have to choose between the immediate benefits of using crop residue for animal feed, or leaving the residue in the field to increase the long-term sustainability of cropping systems and food security for future generations (Delgado, 2010). There is a need to assess if these conservation practices that reduce the potential risk of erosion are viable for this Andean region, as they could contribute to sustainability and food security across the region.

Erosion is decreasing the potential for food security in this region of South America (Monar et al., 2013). In fact, erosion is impacting food security worldwide, reducing agricultural productivity, and affecting the sustainability of systems (Lal, 1987, 1995; Pimentel, 1993; Pimentel et al., 1987; Brown and Young, 1990). Keeping the soil covered will protect it against erosion forces and will increase nutrient cycling (Delgado and Follett, 2002; FAO 2014). Crop rotations will reduce the potential for plant diseases. Conservation agriculture and MT provide advantages for small farmers, especially if hand labor is not available (Martínez et al., 2001). There is a lack of research available about the potential to use conservation agriculture in this region. Conservation agriculture has been found to be a sustainable system in other regions. For example, Parihar et al. (2016) found that a zero-tillage corn (*Zea mays* L.)–bean (*Phaseolus vulgaris* L.) rotation can be a sustainable system for northwestern India and other areas of South Asia. Other researchers have reported that although initially there could be challenges maintaining yields when changing to a no-till system, after a few years the yields from no-till and MT systems are no different from the yields of conventional tillage systems (Büchi et al., 2017; Martínez et al., 2016; Soane et al., 2012).

Preliminary research conducted by Instituto Nacional de Investigaciones Agropecuarias (INIAP) found that there is potential to use conservation agriculture to develop more intensive and sustainable agriculture in this region of the Andes, specifically in the Chimbo sub-watershed (Barrera et al., 2012; Escudero et al., 2014). Our studies are innovative for this region because the farmers are not using the zero-till practice, and the implementation of this practice could potentially impact close to 200,000 farmers. The objective of these studies was to conduct long-term research to monitor the responses of agricultural systems to reduced tillage, decreased crop residue removal, and fertilizer application, for corn and bean crops grown, to assess the potential to increase yields and economic returns.

MATERIAL AND METHODS

Study Site

The approximate area of the Chimbo sub-watershed is 3600 km^2 in the high-altitude Ecuadorian provinces of Bolívar and Chimborazo. In this sub-watershed there is the micro-watershed region of Alumbre River, with an approximate area of 65.40 km^2. The Rio Alumbre micro-watershed extends from the latitude 1°54′29.14″ S to 2°1′36.90″ S and from the longitude

79°0′22.20″ W to 79°6′4.41″ W. The study was conducted at the Rio Alumbre micro-watershed, in the small farm communities of Bola de Oro and Guarumal. Small farmers' fields with the same Andisols and same management practices were selected.

The altitude of the Alumbre River micro-watershed varies greatly, ranging from 1800 to 2500 m. Our studies were conducted at three farms located in the micro-watershed. The three farm blocks were close together, with similar Andisols, and the farming management practices were identical. Since each farm had similar soil types and similar farming management practices, each farm served as a block for the experimental design, which was a 2 × 2 factorial randomized block during Phase 1 and a 2 × 2 factorial randomized block with split plot during Phase 2.

The average altitude for these three locations was 1950 m. From 2010 to 2014 average annual air temperatures and precipitation for the three locations ranged from 15 to 19°C and 812 to 1371 mm, respectively. The average annual relative humidity and wind speed at the three locations was 95% and 0.44 m s^{-1}, respectively. The weather data was collected with an automatic weather station established at each site.

The crops were grown in Andisol soils. The soils were sampled in March 2010 and had an initial soil organic matter, pH, and soil bulk density range of 7 to 10%, 5.8 to 6.0, and 0.8 to 1.0 g cm^{-3}, respectively for the surface 0 to 25 cm (INIAP, 2010). Soil samples were collected and transported to the plant and soil laboratory of INIAP in Quito. The major cropping systems planted at the sites were grain corn and the common bean. The typical crop rotation in the region is a corn–bean rotation.

Experimental Design

Phase 1 of the study utilized a 2 × 2 factorial randomized block design to evaluate the tillage and crop residue management factors. The two tillage treatments were MT and ZT. The two crop residue management treatments were leaving all aboveground residue in place and removing all the aboveground crop residue. Phase 1 was started in March 2010 and completed in March 2012.

After March 2012 we started Phase 2 and split all plots into zero-N fertilizer and N-fertilized plots. The experimental design for Phase 2 was a 2 × 2 factorial randomized block with split plot for N management. Phase 2 of the study started in April 2012 and continued until December 2014. We continued the two tillage treatments (MT and ZT) and the two crop residue management treatments (leaving all aboveground residue in place and removing all the aboveground crop residue).

The effects of tillage and crop residue management were monitored from March 2010 to December 2014. These long-term studies were conducted for 5 yr (from 2010 to 2014) to assess the effects of tillage, crop residue management, and N fertilization on yields and economic returns. To date, similar assessments have not been conducted for this region.

For the crop residue harvest (CRH) treatment, corn stalks and leaves were removed from the field, and all aboveground biomass for the oat (*Avena sativa* L.)–vetch (*Vicia sativa* L.) and bean crop was cut and removed from the field. For the not-harvested crop residue treatment (No-CRH), the corn stalks were cut by hand and left on the surface of the plots. The aboveground biomass for the oat–vetch and bean crops was cut and left on the surface of the plots. For the MT treatment a hoe was used to till the plots to plant the crop in a furrow and control weeds, and for the ZT treatment the crop seeds were planted with a pointed wood bar that was used to make holes where the corn or bean seeds were planted, keeping the other surface of the area undisturbed. The oat–vetch was planted by spreading the seed over the surface of the plots. During Phase 1 the plots were 10 m long × 8 m wide (80 m^2). In Phase 2, plots were split and each plot was 10 m long by 4 m wide (40 m^2).

Crop Management Practices

At each of the small farmers' fields, the experiment was established covering an area of 528 m^2. Fields that were producing forage were selected. For Phase 1, the rotation was corn (2010)–oat–vetch (2011)–bean (2011)–oat–vetch (2012). For Phase 2, the rotation was corn (2012)–oat–vetch (2013)–bean (2013)–oat–vetch (2014)–corn (2014). The planting dates for the rotation were 20 Mar. 2010 for corn; 12 Dec. 2010 for oat–vetch; 13 Apr. 2011 for bean; 5 Oct. 2011 for oat–vetch; 15 Mar. 2012 for corn; 10 Jan. 2013 for oat–vetch; 17 Apr. 2013 for bean; 18 Dec. 2013 for oat–vetch; and 27 Mar. 2014 for corn. The harvesting dates for the rotation were 8 Sept. 2010 for corn; 10 Mar. 2011 for oat–vetch; 19 Aug. 2011 for bean; 24 Jan. 2012 for oat–vetch; 8 Oct. 2012 for corn; 27 Mar. 2013 for oat–vetch; 26 Aug. 2013 for bean; 14 Mar. 2014 for oat–vetch; and 27 Oct. 2014 for corn.

The planting and harvesting dates for corn and bean are dates commonly used in this region. The planting dates for the oat–vetch cover crop are new dates since we are trying to introduce this cover crop mixture into the corn–bean rotation as a new cropping sequence for this region. For corn management, 15 d before planting, glyphosphate was applied at labeled rates to control weeds. The corn variety was INIAP-176, seeded at a rate of 120 kg ha^{-1}. Three corn seeds were planted per seed placement at 0.50 m between plants and 0.80 m between furrows. At 30 d after planting the plants were thinned to leave only two corn plants per spot. With MT, weeds were controlled with a hoe at 60 and 100 d after planting. With ZT, the field was not disturbed and weed control was conducted with atrazine (10 g L^{-1}) at growth stages V4 to V6.

For Phase 1, corn received 80–40–20–20 kg ha^{-1} of N–P_2O_5–K_2O–S, with 50% applied at planting and 50% applied 45 d after planting. For Phase 2, the N-fertilized treatments with corn received 80–40–20–20 kg ha^{-1} of N–P_2O_5–K_2O–S, with 50% applied at planting and 50% applied 45 d after planting. The non-N-fertilized corn treatments only received a fertilizer application of 40–20–20 kg ha^{-1} of P_2O_5–K_2O–S, with 50% applied at planting and 50% applied at 45 d after planting. For the MT corn, fertilizer was applied in a continuous line in the furrow and covered with a small amount of soil, and the seed was placed above the fertilizer band. In the ZT treatment, the fertilizer was applied in the hole where the seed was planted, covered with a small layer of soil, and the seed was placed on the soil and covered to fill in the hole.

For the bean crop, similarly to the corn, the soil was not disturbed prior to planting for the MT and ZT treatments, and 15 d before planting glyphosphate was applied at labeled rates to control weeds. A hoe was used to make a furrow where the bean was planted with MT, and for the ZT, a pointed wood bar was used to make holes where the bean seeds were planted, keeping the other surfaces of the area undisturbed. The variety used was INIAP Portilla 430, seeded at a rate of 100 kg ha^{-1}, and had three seeds planted per seed placement at a distance of 0.40 m between plants and 0.60 m between lines. Two weeding operations were done with a hoe at 30 and 60 d after planting. For ZT, weeds were controlled with Flex (fomesafen,

5-[2-chloro-4-(trifluoromethyl)phenoxy]-*N*-(methylsulfonyl)-2-nitrobenzamide) herbicide 30 d after planting at labeled rates. During Phase 1, the bean crop was not fertilized. During Phase 2, the bean crop was fertilized with 40 and 92 kg ha^{-1} of N and P_2O_5, respectively, for the N fertilized treatement. The bean plots that were not fertilized with N received 92 kg ha^{-1} of P_2O_5. For MT, the fertilizer was applied similarly to how the fertilizer was applied to corn.

For the oat–vetch MT plots, the soils were prepared with a hoe to control the weeds, whereas for the ZT treatment the weeds were controlled with glyphosphate applied at labeled rates. Oat–vetch was planted by hand, spreading the seeds over the surface of the whole plot at a rate of 120 kg ha^{-1} (80 kg ha^{-1} for oat and 40 kg ha^{-1} for vetch). The oat variety planted was INIAP 82 and the vetch variety planted was the common variety. The seed was covered with a small amount of soil in all the MT and ZT plots. At 45 d after planting, weeding was done by hand. In Phase 1, the 2011 oat–vetch fertilizer application was 73 and 69 kg ha^{-1} of N and P_2O_5, respectively. In Phase 2 the oat–vetch was not fertilized.

Harvesting and Economic Analysis

For Phase 1, corn and bean yields were measured by harvesting the whole plot area, except for 1 m around the plot that was left as an outside border; the harvested area was 48 m^2 (8 m long × 6 m wide). For Phase 2, the corn and bean harvested area was 16 m^2 (8 m long × 2 m wide). For CRH, all of the aboveground biomass that was produced was removed from the plots. For No-CRH, all of the residue was left in the plots; only the grain was removed from the plots. For the No-CRH corn, all of the grain and cobs were removed.

Aboveground production for oat–vetch was measured by harvesting five 0.25-m^2 square samples. For the oat–vetch plots with crop residue, all the aboveground biomass produced was removed from the plots. These studies were conducted at small farmers' fields at high-altitude sites in the Andes; therefore, all yields were collected at the field sites with calibrated field balances. The yields were determined at the best time of harvesting for the farmers. For corn, the grain was harvested at black layer when the corn was dry and could be stored in farmers' storage sites. The forage was harvested at the time when the farmers would cut oat–vetch to feed their animals. The commercial value of the yields was used to evaluate the net income for farmers at these locations. The cost of production was assessed by assessing the cost for each operation. Smaller subsamples were collected to assess dry weights and nutrient content, but since no fresh weights were collected in the field at the time of subsampling for these smaller subsamples, we made the decision to only present the fresh weights that were collected in the fields with calibrated field balances for the large areas described above. This procedure is a strong assessment of the effects of the management practices on commercial farmers' yields (essentially the entire plot, except for the border area, was weighed at the field).

For total cost, the costs of soil preparation, seed, fertilizer, weed killer, and hand labor to do all of the field operations such as fertilizer application, control of weeds, and harvesting, were accounted for. The actual cost of the inputs was monitored and taken into account when the farmers were buying their inputs. The value of the crop when the farmer sells the product was monitored in local markets in the small farm communities of Bola de Oro and Guarumal as well as the large cities of Guaranda and Chillanes. During the study the value for the harvested corn fluctuated between US$0.36 to US$0.60 kg^{-1}, and for the bean crop it fluctuated from $0.90 and $2.00 kg^{-1}. The forage cut of oat–vetch had a standard price of $0.03 kg^{-1}. For the crop residue management treatments where the forage was left in the field no income was generated since the crop residue remained in the field. The harvested yield in Mg ha^{-1} for the corn, bean, and oat–vetch crops was accounted for in the income.

Data Analysis

For Phase 1 our null hypotheses are H_0: MT = ZT and H_0: CRH = no residue harvest; in other words, yields and economic returns are the same. The statistical analyses were conducted with SAS (SAS Institute, 2008). We used a Least Significant Difference (LSD) α level of $P < 0.05$ to detect significant differences in treatments for yields and economic returns for both phases of the study. Our alternative hypotheses are then H_A: MT ≠ ZT; and H_A: crop residue harvest ≠ no residue harvest; in other words, that there are differences in the measured values for yields and economic returns for tillage and crop residue management. Phase 1 was analyzed with a General Linear Model for a factorial randomized block design, where the factors are tillage and crop residue management (Steel and Torrie, 1960).

For Phase 2, our null hypotheses are H_0: MT = ZT; H_0: crop residue harvest = no residue harvest; and H_0: added N = without added N; in other words, that yields and economic returns are the same. Our alternative hypotheses are then H_A: MT ≠ ZT; H_A: CRH ≠ no residue harvest; and H_A: added N ≠ without added N; suggesting that there are differences in the measured values for yields and economic analysis for tillage, crop residue management, and N fertilizer use. For Phase 2, the data were analyzed using a General Linear Model Split Plot, where Factor A, tillage (MT and ZT) and B, crop residue management (with and without crop residue harvesting), correspond to the main factor, and Factor C, fertilization with N and without N, is the split plot over Factor A and B (Steel and Torrie, 1960).

Mean separation was done using the LSD means test procedure. Additionally, to assess what the long-term economic effects of tillage and residue management will be, we used the same model described for Phase 1 to analyze the same plots from 2010 to 2014. This was done only to assess the long-term economic impacts of tillage and crop residue (only the N-fertilized plots from 2010 to 2014). In this long-term analysis we did not include the non-fertilized plots and analyzed the plots using the 2 × 2 factorial randomized block design, using the same plots from 2010 to 2014. We acknowledge that the size of the plots was changed when we split the plots into fertilized and non-fertilized plots, but we assumed that for the economic analysis, since we used the same plots, that this was still a valid long-term approach, especially since no machinery or animals were used to plow the cropping systems and the crops were harvested by hand.

RESULTS AND DISCUSSION

Crop Yields and Economic Responses to Tillage and Crop Residue Management during Phase 1

The results for analysis of variance, yields (Mg ha^{-1}), and economic responses ($ ha^{-1}) due to tillage and crop residue management for corn (2010), oat–vetch (2011), bean (2012), and oat–vetch (2012) are in Tables 1 and 2. We found no significant interactions between tillage and crop residue management for yields and economic responses ($P < 0.05$). Bean yield was greater with ZT than with MT (Table 1). Leaving the crop residue in place vs.

Table 1. Average yields (Mg ha^{-1}) for corn, oat–vetch, and bean crops grown from March 2010 to March 2012 under different tillage and crop management systems at the Alumbre River watershed in the province of Bolívar in Ecuador (Phase 1).†

Treatments	Corn 2010	Oat–vetch 2011	Bean 2011	Oat–vetch 2012
Minimum tillage (MT)	2.9	42.4	1.5 b	20.1
Zero tillage (ZT)	3.2	50.5	1.8 a	19.5
Crop residue harvested (CRH)‡	2.6 b	45.6	1.6	18.5
No crop residue harvested (No-CRH)§	3.5 a	47.3	1.7	21.1

† Within a column (crop residue harvesting vs. no crop residue harvesting; MT vs. ZT), numbers with different letters are significantly different (LSD) at $P \leq 0.05$.

‡ CRH, crop residue was harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and removed from the field.

§ No-CRH, no residue harvested for corn and all aboveground biomass for the oat–vetch and bean crops were cut and left on the soil surface.

Table 2. Average gross and net income and average cost for the corn, oat–vetch, and bean crops grown from March 2010 to March 2012 under different tillage and crop management systems at the Alumbre River micro-watershed in the province of Bolívar in Ecuador (Phase 1).†

Treatments	Gross income	Total cost	Net income
		US$ ha^{-1}	
Minimum tillage (MT)	4800	2900 a	1800 b
Zero tillage (ZT)	5500	2500 b	2900 a
Crop residue harvested (CRH)‡	5800 a	2900 a	2900 a
No crop residue harvested (No-CRH)§	4400 b	2600 b	1900 b

† Within a column (crop residue harvesting vs. no crop residue harvesting; MT vs. ZT), numbers with different letters are significantly different (LSD) at $P \leq 0.05$.

‡ CRH, crop residue was harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and removed from the field.

§ No-CRH, no residue harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and left at the surface.

harvesting and removing the residue did not affect yields of bean and oat–vetch ($P < 0.05$). Although the corn yield of the with-residue plots was greater than yields of the residue-removed plots, this cannot be a residue effect since we started leaving crop residue at corn harvesting (Table 1). These results are very important because ZT did not reduce the yields of corn, bean, and oat–vetch forage when compared with MT, and leaving crop residue in the field did not suppress yield; our results suggest a beneficial trend to leaving crop residue in the field and to utilizing ZT. Our results finding yields with ZT to be similar or higher than MT agree with reports from Büchi et al. (2017), Martínez et al. (2016), and Soane et al. (2012).

These results are also important because when we compare the cost and returns of the available products, the ZT provides a significant economic advantage for the small farmers, providing a higher net income (Table 2). The cost of MT of \$2900 ha^{-1} was higher than the cost of ZT of \$2500 ha^{-1} (at $P < 0.001$). The cost of harvesting crop residue of \$2900 ha^{-1} was higher than the cost of leaving all the crop residue in the field of \$2600 ha^{-1} (at $P < 0.001$). These long-term ecosystem services have a value, but this value was not included in the study. Thus, the benefits for ZT understate the social value of the practice. We found that using ZT with similar yields, or if anything, higher average yields, resulted in a net income of \$2900 ha^{-1}, which was higher than the net income of \$1800 ha^{-1} for MT (at $P < 0.05$). This net income relationship, which is very important for the small farmers in this area, shows that ZT provides over 33% greater income in 2 yr (at $P < 0.05$) (Table 2). Using ZT with similar yields, or if anything higher average yields, which are significant for oat–vetch, provides over 33% greater income in 2 yr (at $P < 0.05$) (Table 2). This is a significant increase in net income for a small farmer in this region.

Harvesting crop residue provides approximately 33% higher income for the farmer than leaving residue in the field (Table 2). One advantage in comparing these costs and net returns was that we did not assign a nutrient value to the cycling for the crop residue, nor did we assign a value to the reduction of erosion and transport of nutrients off site that resulted from keeping the crop residue in the field. This is significant for the implementation of conservation agriculture since ZT, which provides more cover and soil and water conservation than MT, is also the conservation practice with higher net returns in Phase 1.

Although harvesting crop residue has a higher cost than not harvesting crop residue, the net income was much higher with crop residue harvesting than with leaving all of the crop residue covering the surface of the plot. This is expected since crop residue is a source of income. This highlights the importance of ZT implementation because removing the crop residue to provide a source of income will increase the potential for soil erosion. However, the higher net income was with ZT and crop residue harvesting for this diverse crop rotation and/or use of cover crops, which implements two of the pillars of conservation agriculture, minimal soil disturbance, and having a diverse crop rotation. Although leaving the crop residue on the soil surface does not provide a significant yield advantage, especially during the oat–vetch forage crop, using ZT will contribute to sustainable systems and higher incomes in this area. Because sustainable systems contribute to food security, these ZT systems that increased net economic returns also have the potential to increase food security in this region. We recommend that future studies assess the potential effect of harvesting 50% of the residue on yields and economic returns, and conduct a more in-depth evaluation of the fertilizer value of the crop residue with respect to cycling of nutrients such as N.

Crop Yields and Economic Responses to Tillage, Crop Residue Management, and Nitrogen Fertilizer during Phase Two

The results for analysis of variance, yields (Mg ha^{-1}), and economic responses ($ ha^{-1}) due to tillage and crop residue management for the corn (2012), oat–vetch (2013), bean (2013), oat–vetch (2014), and corn (2014) crops are in Table 3. We found nonsignificant interactions between N and tillage, N and crop residue management, and between N, crop residue management, and tillage, as far as yields and economic responses ($P < 0.05$). The only significant interaction between tillage and crop residue management was for oat–vetch in 2014.

Some farmers do not apply N fertilizer. Phase 2 of our study shows that there is a benefit to applying N fertilizer, with higher yields for corn (2012) and bean (2013) (Table 3). The 2013 and 2014 yields of oat–vetch were greater following N-fertilized corn or bean than non-N-fertilized corn or bean, suggesting a residual effect of the N fertilizer applied to corn and bean since the oat and vetch were not fertilized (Table 3).

There was an interaction between tillage and crop residue management for oat–vetch in 2014 when yield for ZT with no crop residue harvested was greater than yield for the ZT with crop residue harvested ($P < 0.05$, Table 3). Tillage did not significantly affect yields of corn in 2012, oat–vetch in 2013, bean in 2013, oat–vetch in 2014, or corn in 2014. The yield of corn with no crop residue removal was higher than the yield with crop residue harvested in 2012. These results agree with research conducted at other regions where researchers had found that yields from ZT systems are similar to yields from MT systems (Büchi et al., 2017; Martínez et al., 2016; Soane et al., 2012).

In Phase 2 the N management studies showed a significant increase in the net economic returns for farmers (Table 4). Plots receiving N fertilizer resulted in a net income of $2700 ha^{-1}, whereas the plots not receiving N fertilizer resulted in a lower net income of $2200 ha^{-1} (at $P < 0.001$). Even though the N fertilizer had a higher cost ($3500 ha^{-1}) than the plots without fertilizer ($3300 ha^{-1}) (at $P < 0.001$), applications of this essential element for these Andean soils increased yields and net economic returns (at $P < 0.001$). For Phase 2 there was a similar response to that observed in Phase 1 for crop residue management. The cost of harvesting crop residue ($3600 ha^{-1}) was higher than the cost of leaving all the crop residue in the field ($3200 ha^{-1}) (at $P < 0.001$).

Harvesting the residue also provides about 30% more income for the farmer (at $P < 0.001$) (Table 4). Harvesting the crop residue resulted in a gross income of $6500 ha^{-1}, which was higher than the $5100 in gross income from not harvesting crop residue or leaving all of the oat–vetch crop to cover the surface soil ($P < 0.001$). Thus, harvesting the crop residue provided a net income of $2900 ha^{-1},

Table 3. Average yields (Mg ha^{-1}) for the corn, oat–vetch, and bean crops grown from April 2012 to December 2014 under different tillage, crop management, and N management systems at the Alumbre River micro-watershed in the province of Bolívar in Ecuador (Phase 2).†

Treatments	Corn 2012	Oat–vetch 2013	Bean 2013	Oat–vetch 2014	Corn 2014
Minimum tillage (MT)	4.0	19.7	1.9	39.7	4.2
Zero tillage (ZT)	4.0	20.8	1.9	42.6	4.3
Crop residue harvested (CRH)‡	3.8 b	18.5	1.8	37.7 b	4.2
No crop residue harvested (No-CRH)§	4.2 a	22.1	2.0	44.6 a	4.3
Nitrogen fertilizer (NF)	4.1 a	20.8 a	2.2 a	42.9 a	4.3
Zero nitrogen (ZN)	3.9 b	19.7 b	1.6 b	39.4 b	4.2
Minimum tillage (MT) Crop residue harvested (CRH)‡¶				38.9 ba	
Minimum tillage (MT) No crop residue harvested (No-CRH)§¶				40.5 ba	
Zero tillage (ZT) Crop residue harvested (CRH)‡¶				36.5 b	
Zero tillage (ZT) No crop residue harvested (No-CRH)§¶				48.7 a	

† Within a column (crop residue harvesting vs. no crop residue harvesting; MT vs. ZT; N fertilizer vs. no N fertilizer) numbers with different letters are significantly different (LSD) at $P \le 0.05$.

‡ CRH, crop residue was harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and removed from field.

§ No-CRH, no residue harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and left on the surface.

¶ Tillage × Crop residue significant at $P \le 0.05$, numbers with different letters are significantly different (LSD) at $P \le 0.05$.

Table 4. Average gross and net income and average cost for the corn, oat–vetch, and bean crops grown from April 2012 to December 2014 under different tillage, crop management, and N management systems at the Alumbre River micro-watershed in the province of Bolívar in Ecuador (Phase 2).†

Treatments	Gross income	Total cost	Net income
	US$ ha^{-1}		
Minimum tillage (MT)	5900	3600 a	2300
Zero tillage (ZT)	5800	3200 b	2600
Crop residue harvested (CRH)‡	6500 a	3600 a	2900 a
No crop residue harvested (No-CRH)§	5100 b	3200 b	2000 b
Nitrogen fertilizer (NF)	6200 a	3500 a	2700 a
Zero nitrogen (ZN)	5500 b	3300 b	2200 b

† Within a column (crop residue harvesting vs. no crop residue harvesting; MT vs. ZT; N fertilizer vs. no N fertilizer) numbers with different letters are significantly different (LSD) at $P \le 0.05$.

‡ CRH, crop residue was harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and removed from the field.

§ No-CRH, no residue harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and left on the surface.

which was higher than the $2000 in net income resulting from not harvesting crop residue or leaving all of the oat–vetch crop to cover the surface soil ($P < 0.001$).

Although there were no significant differences in yields due to ZT and MT, the data suggest an advantage for the ZT over the MT. The cost of $3200 ha^{-1} for ZT was significantly lower than the cost for MT of $3600 ha^{-1} ($P < 0.001$). The net income between ZT and MT was very similar, with a difference of about $300 ha^{-1} in favor of ZT, but not a significant difference. Since there was a lower cost for the ZT when compared with the MT ($P < 0.001$) on average the net income for ZT of $2600 ha^{-1} was higher than the net income of MT of $2300 ha^{-1}, but not significantly higher ($P < 0.11$). Phase 2 also suggests that the best conservation practice is the use of ZT with N fertilizer and harvesting the crop residue. These practices will protect the soil and water of this region. One alternative that was not studied was harvesting only 50% of the crop residue, which would generate some additional income, but would also contribute to environmental conservation and reduce erosion. Additional follow-up studies on crop residue management should be conducted for this Andean region.

Long-Term Economic Responses to Tillage and Crop Residue Management from 2010 to 2014

The long-term (2010–2014) ZT provides a significant economic advantage for the small farmers, providing a net income of $2900, which is higher than the $2200 obtained with MT ($P < 0.001$). The cost of $3300 for MT was higher at $P < 0.08$ than the cost of 2900 for ZT. The total income was not different between ZT and MT. Removing residue provided a higher total income ($6307) than when the residue was left at the surface ($5000) ($P < 0.01$). Although the cost of removing the crop residue of $3300 was higher than the cost of leaving the crop residue at the surface, which cost $2900 ($P < 0.05$), the net income of $3000 when the residue was removed was higher than the net income of $2000 when the residue was left in the field ($P < 0.01$). These long-term economic analyses from 2010 to 2014 show a significant advantage in net income from ZT and also a significant advantage in net income when the crop residue is removed. Additional long-term studies are needed to assess the economic effect of removing just half of the crop residue and leaving the remaining half at the surface.

CONCLUSION

All across this Andean region soils are being cultivated intensively and crop residue is being harvested to feed animals, and for these soils on steep slopes that receive significant amounts of precipitation, erosion is contributing to degradation of these soils (Fig. 1). These innovative studies assessing the effects of tillage, crop residue management, and N fertilizer management, together with an economic analysis for this grain forage rotation (corn–cover crop mixture of oat–vetch) in the high-altitude soils of this Andean region, are unique and have not been done before. Our studies show that the implementation of ZT for rotations of corn and bean and a forage mixture of grain and leguminous forage (oat–vetch) would be a viable and economical practice for this region that could contribute to higher net incomes for farmers. Our results agree with research studies from other regions that have reported that a ZT maize–leguminous rotation can be a sustainable intensification system for regions of northwestern India and other areas of South Asia (Parihar et al., 2016). Since farmers in this region are not currently using ZT practices, this unique economic analysis of these practices shows that there is potential to impact close to 200,000 farmers if these new technologies/best management practices can be transferred to farmers across the region. Nitrogen fertilization and adding a leguminous crop into the rotation is also another practice that contributed to higher yields and higher net economic returns.

Zero tillage with N fertilizer and crop residue removal was the most viable conservation practice that contributed to the higher net income. We found that although leaving crop residue in the field does not reduce the yields, the immediate economic value of harvested crop residue makes ZT with N fertilization and harvested crop residue a more viable practice. We found that although leaving crop residue in the field does not reduce the yields and in some cases it increases the yields, the immediate economic value of harvested crop residue makes ZT with N fertilization and harvested crop residue a more viable practice.

Our study found in the initial phase that the bean crop with ZT had higher average yields than with MT at $P < 0.05$. For Phase 2, with N fertilization, yields were significantly higher in four out of five crops ($P < 0.05$). Leaving the crop residue at the surface was a practice that increased the yields of one of the five crops at $P < 0.05$.

Nitrogen fertilizer increased corn and bean yields by an average of 2.5 and 41%, respectively. Additionally, residual N fertilizer increased by 7.3% the yield of the non-fertilized oat–vetch mixture that was sowed following the fertilized corn and beans plots. Adding N fertilizer increased the net economic returns by 22%. Removing crop residue from 2010 to 2014 to provide a source of income increased the net economic returns by 45.1% when compared with plots where the residue was not harvested. Implementing ZT from 2010 to 2014 increased the net economic returns by 31.8%.

These studies show that conservation agriculture is an attractive management alternative even in systems where, due to small farm sizes and highly sloped fields, mechanization is not viable. Simple techniques such as jab-planting, combined with chemical weed control, can be easily adapted. Implementation of ZT could contribute to higher net income for farmers and these practices could benefit nearly 200,000 Ecuadorean farms.

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