AGRONOMY, SOILS & ENVIRONMENTAL QUALITY

Yield and Nutrient Removal in Potato-Based Conservation Agriculture Cropping Systems in the High Altitude Andean Region of Ecuador

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ABSTRACT

The Illangama region of Ecuador's highlands is typical of much of the Andean region throughout South and Central America. Steep slopes, frequent soil disturbance and the short fallow periods threaten the sustainability of soil quality and crop production in this region. We evaluated several conservation agricultural practices, including deviation ditches, crop residue retention, and reduced tillage in the context of a potato (*Solanum tuberosum* L.)–oat/vetch (*Avena sativa* L./*Vicia sativa* L.)–barley (*Hordeum vulgare* L.)–faba bean (*Vicia faba* L.) rotation from 2011 to 2014 on crop productivity, crop and soil nutrient concentration, and nutrient removal from the system. Crop productivity tended to be higher in plots that had 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. Retaining crop and cover crop residues in the field had the greatest impact on recycling nutrients back to the soil, but was also the most costly conservation practice that we evaluated. Overall, conservation agricultural practices showed considerable agronomic promise for cropping systems in the Illangama region of Ecuador, but will require a longer evaluation period and a comprehensive outreach plan to help gain acceptance with regional farmers. Retaining crop and cover crops residues in the field rather than for animal fodder will make the greatest contribution to soil nutrient cycling, but likely to be the least accepted conservation agriculture (CA) practice evaluated in this study.

Core Ideas

- Conservation agriculture practices evaluated in this study were agronomically effective, but expensive.
- Reduced tillage resulted in similar yields in all crops of the potato–oat/vetch–barley–faba rotation to conventional tillage.
- Retaining crop and cover crops residues in the field rather than for animal fodder will make the greatest contribution to soil nutrient cycling, but likely to be the least accepted conservation agriculture practice evaluated in this study by regional farmers.

Published in Agron. J. 109:1–13 (2017)
doi:10.2134/agronj2016.11.0635

The Illangama region of the upper portion of the Chimbo River watershed in Ecuador's highlands (Fig. 1) is typical of much of the Andean region of South and Central America. High altitudes, steeply sloping soil surfaces and erratic climatic conditions make maintaining or increasing crop production while conserving the soil and water resource base an urgent challenge. The soils in this region are volcanically derived (i.e., Andisols); have not been highly weathered; and are characterized by deep A horizons with high organic matter contents (commonly 10%), and consequent low bulk densities (van Breemen and Buurman 2003; Buytaert et al., 2007). Although productivity of Andisols can be quite high, soil P is often limited due to P fixation by various mineral–and metal-based complexes (Brady and Weil 2008; Shoji et al., 1993; Wada and Gunjigake, 1979). Like many other parts of the Andean highlands, households in the Illangama rely primarily on small farm holdings for their livelihoods (see our first publication from this study for more details in Barrowclough et al. (2016). Cropping systems consisting of staple crops such as potato, barley, quinoa (Chenopodium quinoa Willd.), and faba bean are typically alternated with pasture-based fallow systems to support animal production activities. However, as outlined in our first publication on this study (Barrowclough et al., 2016), increased population pressure has resulted in more intensive cropping periods coupled with shorter fallow periods, resulting in serious degradation of soil productivity. Traditional farming practices in the Illangama region tend to rely on frequent soil cultivation to prepare soil for seeding and to control weeds, and removal of crop residues to be used for animal fodder. These practices, coupled with highly sloping terrain (commonly 30–50%) render agricultural fields in this region susceptible to erosion. For example, soil erosion for cultivated fields in these types of high altitude Andean

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Abbreviations: CA, conservation agriculture; SOM, soil organic matter.

ecosystems have been estimated to range from 3 (Otero et al., 2011) to 27 Mg ha^{-1} yr^{-1} (Henry et al., 2013) greater than non-cultivated soils. Such levels of erosion cause a rapid depletion of soil nutrients, degradation of overall soil quality, and eutrophication of waterways. In Otero et al. (2011), it was clearly demonstrated that pasture-based agricultural systems are far less susceptible to erosion than cultivated cropping systems. Although animal agriculture is an important component of the overall agricultural system in the Illangama region, small farmer holders also depend on staple crop production to meet their dietary and livelihood needs. It is imperative that crop cultivation regimes compatible with soil and water conservation are implemented to achieve and maintain food security in these regions.

Conservation agriculture production systems have evolved to improve the sustainability and profitability of agricultural production through application of three principles: minimal soil disturbance; permanent soil cover; and diversified crop rotations (FAO, 2014). Minimizing soil disturbance helps conserve the physical, chemical, and biological properties of soils; protect them from erosion by wind and water; and promote water and nutrient retention (Brady and Weil 2008). Permanent soil cover, either through retention of crop residues or inclusion of cover crops in the rotation, further protect soils from physical erosive processes and promote nutrient cycling. Diversifying crop rotations is a well-documented means of reducing the prevalence of soil-borne pests and enhancing crop productivity through several mechanisms (Bullock 1992). The benefits of CA, however, are not without their potential trade-offs or complications with respect to crop agronomy or management risk for the farmer (Knowler and Bradshaw, 2007). For example, reducing soil tillage typically leads to increased reliance on herbicides to manage crop vegetation and weeds. Herbicide-based weed management regimes may not be economically viable for low resource farmers and may pose health and environmental concerns (Crissman et al., 1994; Ecobichon, 2001). Maintaining greater ground cover requires leaving crop residues or cover crops in the field rather than feeding the residues to animals. In such cases, the immediate cost to farmer livelihood may outweigh the potential long-term benefit of more sustainable soil management. Residue retention may be more acceptable, however, if it can be demonstrated that it results in higher future crop yields due to direct nutrient contribution and enhanced nutrient cycling (Delgado and Follett, 2002). Finally, conservation-friendly rotation crops may not be as economically or culturally desirable as the primary staple crops farmers rely on to meet their nutritional needs for their families and to generate cash flow.

The objective of this study was to evaluate the effects and interactions of various common CA practices on crop productivity, nutrient uptake/removal and soil nutrient status in a potato-grain cropping system that typically follows pasture

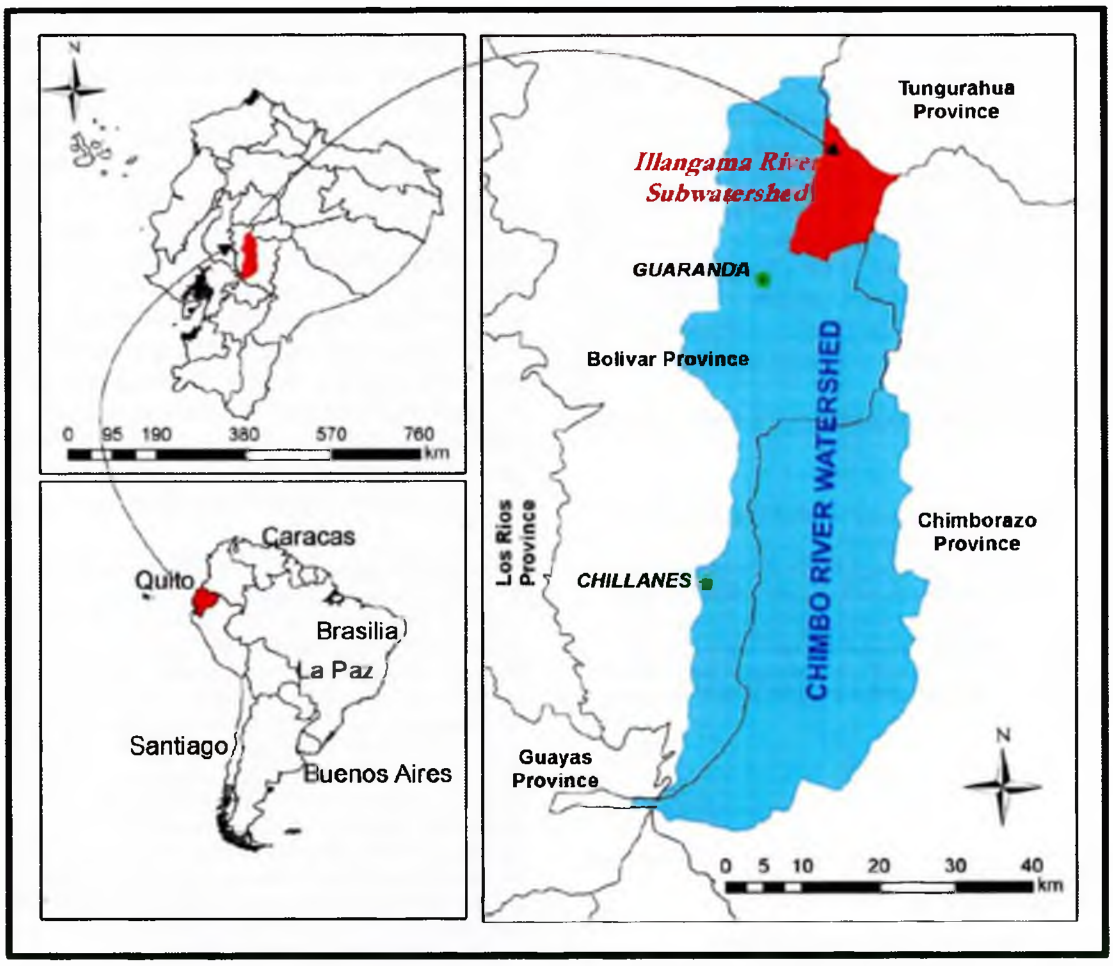

Fig. 1. The location of the Illangama sub-watershed of the Chimbo river in the Province of Bolivar, Ecuador.

in the high elevation and steeply sloping region of Illangama, Ecuador. The CA practices evaluated in this study included deviation ditched; retention of crop residues on the soil surface; and reduced tillage. These practices were incorporated into an improved crop rotation previously analyzed by the National Institute of Agrricultural Investigation (INIAP) in collaboration with International Potato Center (CIP). We hypothesized the CA practices that minimize soil run off, such as deviation ditches and crop residue retention on the soil surface, will promote soil nutrient conservation, making these nutrients more readily available to crops. Likewise, retaining crop residues in the field and inclusion of cover crops in the crop rotation would promote greater nutrient availability via direct nutrient contributions and enhanced cycling of the nutrients. Finally, we hypothesized that reducing soil water run-off and erosion, and improved nutrient availability greater would reduce the need to supplement soil fertility with inorganic fertilizers that are costly inputs for subsistence farmers. Our initial socioeconomic analysis of these CA practices indicated that they are economically viable for Illangama region farmers (Barrowclough et al., 2016). Information from this study will help establish the agronomic suitability of CA-based crop and soil management systems in smallholder farming systems in this and other high altitude Andean areas.

MATERIALS AND METHODS

Site Description

Two multi-year experiments investigating CA practices were conducted in the central Andean mountains of Ecuador, in the province of Bolívar located to the south of Quito in the Illangama sub-watershed of the Chimbo River from 2011 to 2014 (Fig. 1). The elevation of this region is quite variable, ranging from 2800 to 5000 m above sea level. In our experiments, replication (blocking hereafter) of treatments was done by location, with each block located in a different cooperating farmers' field, with an average elevation of 3700 m. The distance between blocks ranged from approximately 1 to 2 km. Temperatures remain cool year round, ranging from 7 to 13°C. Annual precipitation is highly variable, ranging from 500 to 1300 mm, and can vary substantially from field to field. The actual temperatures and precipitation levels at each experimental block were not monitored on a regular basis due to the geographical remoteness of the sites. The soils in the Illangama region are typical Andisols with organic matter contents between 8 and 10%, acidic pH near 6.0, and a typical bulk density of approximately 1.0 g cm^{-3} (Table 1). Cropping systems in this region are dominated by a 3 to 5 yr pasture phase which is typically rotated to potato, barley, and then faba bean planted as spring crops. The pasture plant community is generally comprised of a mixture of annual and perennial ryegrass (*Lolium multiflorum* Lam; *Lolium perenne* L.), Kentucky blue grass (*Poa pratensis* L.), red and white clover (*Trifolium pratensis* L.; *T. repens* L.), and narrow leaf plantain (*Plantago lanceolata* L.). It is common to cut the forage every 3 mo for animal fodder and maintain the N fertility of the pasture with annual addition of up to 40 kg N ha^{-1} applied as urea. Further information regarding the geographic and socioeconomic details of the Illangama region can be found in our first publication from this study (Barrowclough et al., 2016).

Treatment Structure and Experimental Design

We conducted two experiments evaluating a suite of CA practices in the context of a potato– barley–fava bean rotation following a 5-yr pasture phase as described above. In the first experiment, termed Exp. 1 hereafter, treatment components included: deviation ditches (with and without); residue management (crop residues retained or removed); tillage (conventional or reduced); and supplemental N fertilizers (added or not added--barley crop only) (Table 2). A split-plot experimental design was employed, with deviation ditch regime as the main plot factor, and residue management, tillage, and supplemental N (in barley) as the subplot factors. There were a total of three blocks. Blocks measured 25 m along the slope contour by 36 m down the slope. Blocks were divided in half (12 m each) down the slope to comprise the main plot factors of with and without drainage ditches, which were randomly assigned to one side of the block or the other. Within each main plot, there were a total of eight subplots (12 by 8 m), which were laid out in a two by four arrangement, with two plots along the contour by four plots down the slope. Drainage ditches (30 cm deep by 30 cm wide) were constructed along the contour of the slope on the upward slope side of each plot. A perennial grass strip was maintained between the upward side of the each contour–deviation ditch arrangement to prevent

Table 1. Mean baseline soil chemical properties by depth (up to 1 m) for Exp. 1 and 2 prior to the initiation of Exp. 1 and 2. Soil samples were taken in 2010 and the data represents the mean of the three experimental blocks for each experiment.

Depth	pH	SOM†	P	S	K	Ca	Mg	Zn	Cu	Fe	Mn	B
cm		%	kg ha^{-1}									
Exp. 1												
0–25	5.93	9.8	36	12	244	5,726	632	16	15	713	9	2
25–50	5.99	9.0	34	10	186	4,874	551	14	17	963	9	2
50–75	5.99	9.4	28	10	156	4,995	541	12	16	948	8	2
75–100	5.99	10.4	25	8	176	5,811	602	8	16	861	8	2
Profile total			124	39	762	21,407	2325	50	64	3485	34	8
Exp. 2												
0–25	6.33	8.5	15	24	147	5,010	541	11	12	491	8	1
25–50	6.48	8.9	31	15	147	6,763	842	12	17	704	6	2
50–75	6.43	9.9	25	12	156	6,262	963	11	17	732	5	2
75–100	6.41	10.6	25	11	225	6,463	963	9	18	759	6	1
Profile total			97	62	674	24,498	3309	43	64	2684	25	6

† SOM, soil organic matter.

Table 2. Treatment structure with respect to drainage ditches, tillage and residue management regimes, and supplemental fertilization in Exp. 1. See Table 4 for details regarding the specific agronomic practices.

Conservation agriculture component	Potato, 2011	Oat–vetch, 2012	Barley, 2012	Faba bean, 2013	Pasture, 2014
Drainage ditches	with or without				
Tillage	conventional or reduced				
Residue management	Removed or retained (prior pasture)	Removed or retained (prior potato)	Removed or retained (prior oat–vetch)	Removed or retained (prior barley)	Removed or retained (prior faba)
Supplemental N fertilizer	Without	Without	With or without	Without	Without

the downward movement of soil and water from one plot to the next. Water from the deviation ditches was channeled down a drainage ditch constructed between the main plots. The remaining residue management, tillage, and fertility management treatment regimens were randomly assigned to plots within the deviation ditch main plot. The same design approach was used in the main plot not containing deviation ditches. Perennial grass strips were also utilized between the contours in the main plots without deviation ditches. Crop or cover crop (i.e., oat/vetch) residues were either cut at the soil surface and removed, leaving the soil mostly bare for the "removed" treatments, or left intact in the plot for the "retained." Conventional tillage consisted of the complete inversion of the sod or previous crop, whereas reduced tillage was comprised of partial inversion of a small portion (20 by 20 cm) of the sod for potato and direct seeding of the grain crops in minimally tilled furrows.

The second experiment, termed Exp. 2 hereafter, was initiated primarily to focus on the effects of residue retention and reduced tillage on crop nutrient availability in the context of the pasture–potato–barley–faba bean rotation (Table 3). As such, our control treatment (Treatment 1) consisted of removal of all crop and cover crop residues, conventional inversion tillage and supplemented macronutrient fertilizer. Test treatments included reduced tillage as described for Exp. 1 and removal of crop and cover crop residues (Treatment 2) or reduced tillage and retention of crop and cover crop residues (Treatment 3). Treatments 2 and 3 had the same supplemented macronutrient fertilizer regime as Treatment 1. In contrast, Treatment 4 was included to evaluate the N contribution of the crop and cover crop residues, and was identical to Treatment 3 except did not include any supplemental N fertility. These four treatments were arranged in a randomized complete block, with each treatment extending from the top to the bottom of the slope. Each block measured 32 m across the contour and 15 m down the slope, with each treatment plot measuring 6 by 15 m. As in Exp. 1, there were a total of three blocks.

Table 3. Treatment structure regarding tillage, residue management and supplemental N fertilizers for Exp. 2. See Table 4 for details regarding the specific agronomic practices.

Crop and conservation agriculture components	Treatment			
	1	2	3	4
Potato, 2011				
Tillage	Conventional	Reduced	Reduced	Reduced
Residue management (prior pasture)	Removed	Removed	Retained	Retained
Supplemental N fertilizer	Yes	Yes	Yes	No
Oat–vetch, 2012				
Tillage	Conventional	Reduced	Reduced	Reduced
Residue management (prior potato)	Removed	Removed	Retained	Retained
Supplemental N fertilizer	No	No	No	No
Barley, 2012				
Tillage	Conventional	Reduced	Reduced	Reduced
Residue management (prior oat–vetch)	Removed	Removed	Retained	Retained
Supplemental N fertilizer	Yes	Yes	Yes	No
Faba bean, 2013				
Tillage	Conventional	Reduced	Reduced	Reduced
Residue management (prior barley)	Removed	Removed	Retained	Retained
Supplemental N fertilizer	No	No	No	No
Grass pasture, 2014				
Tillage	Conventional	Reduced	Reduced	Reduced
Residue management (prior faba bean)	Removed	Removed	Retained	Retained
Supplemental N fertilizer	No	No	No	No

Crop Agronomy

In the Illangama watershed, the conventional tillage practice includes use of hand hoes to break up and invert soil and crop residue from the pasture or the previous crop to create a full-width seed bed. The reduced tillage CA practice in our experiments opened a narrow planting furrow, leaving the inter-row soil and residues undisturbed. For the potato cycle, the reduced tillage regime was based on a farmer-tested technique where a small portion (approximately 400 cm^2) of the pasture sod was inverted, the seed potato into that gap and covered again with the sod. We estimate that this technique reduces soil disturbance by 70% to 80% compared to the conventional soil preparation for potato (data not shown). Conventional residue management is to remove aboveground plant biomass at harvest to provide fodder for animal consumption, thereby leaving the soil surface mostly bare. The CA practice was to leave crop or cover crop residues on the surface after harvest. Seeding rates and methods for all crops, as well as baseline and supplemental fertility regimes (when applied) and pest management are outlined in Table 4. Row crops (i.e., potato, barley, and faba bean) were all seeded along the contour of the slope. All crop and soil management was implemented by our research team. Crop and soil management among blocks was always conducted with in 1 to 2 d of each other.

Measurements

Soil samples (0–20 cm) were collected at baseline before the start of the experiment and following completion of the entire cropping cycle, and analyzed for macronutrient and micronutrient content. A 2.5 cm diam. soil probe was used to take five cores from each treatment plot. The cores were then combined to produce a composite sample for the plot. Soil samples were air dried and passed through a 2-mm sieve prior to extraction with a modified Olsen solution (1:10 v/v soil/solution ratio) and with calcium phosphate solution (1:2.5 v/v soil/solution ratio). Olsen extracts were analyzed for P by colorimetry and for K, Ca, Mg, Cu, Fe, Mn, and Zn atomic absorption spectrometry (Hunter, 1977). The calcium phosphate extracts were analyzed for B and S by colorimetry (Fox et al., 1964). Exchangeable inorganic N (NH_4^+ and NO_3^-) was extracted with a 2 M solution of KCl (Keeney and Nelson, 1982). Nitrite was seldom present in detectable amounts and therefore was not determined. Nitrate was determined colorimetrically using the salicylic acid in concentrated H_2SO_4 (Vendrell and Zupancic, 1990). Ammonium was determined colorimetrically utilizing the Berthelot reaction involving phenol (Keeney and Nelson, 1982). In barley, which followed the oat–vetch cover crop in some treatments of both experiments, exchangeable inorganic N was measured throughout the growing season. Fifteen 2.5 cm diam. cores were taken to a depth of 25 cm from each treatment plot and mixed well to form an initial composite sample. Approximately, 500 g was removed from each composite sample to be available for analysis. Unlike the pre- and post-season soil samples taken above, the soil samples taken within the barley season for inorganic N were kept under refrigerated conditions (i.e., coolers with ice or refrigerators) and processed within 1 wk of sampling. Sampling occurred on approximately 3-wk intervals from the time of planting to just following crop harvest. Extraction and analysis of the exchangeable inorganic N was conducted as describe above, except on wet soils, so therefore were also correct for soil water content.

Potato (tuber + aboveground biomass) and faba bean (vegetative biomass + grain) production was measured by harvesting all the plants with each treatment unit within each block (1 m border around each plot was not included in harvest sample). Oat–vetch biomass and barley (vegetative biomass + grain) production was measured by harvesting five 0.5 m^2 quadrants within each plot. Harvested material was weighed fresh and after oven drying. Dried material was ground prior to wet acid digestion using a combination of nitric and perchloric acid (Zasoski and Burau, 1976; Malavolta et al., 1989). Digestates were then analyzed for P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn by ICP. Total N was analyzed by the semi-micro Kjeldahl method (Bremmer, 1965). Since there were no discernable trends in nutrient uptake among the CA practices in both experiments, nutrient export estimates were based on experiment-wide averages for the individual elements multiplied by the per area biomass.

Table 4. Crop agronomy details for Exp. 1 and 2 from 2011 to 2014.†

Agronomic component	Rotation phase					
	Pasture	Potato	Oat/vetch	Barley	Fava bean	Pasture
Dates implemented	2006–2011	Spring 2011	Fall 2011	Spring 2012	Fall 2013	Spring 2014
Crop variety	mixed grass and legume	INIAP Fripapa	*Vicia sativa* INIAP-82 (oat)	INIAP Guarnga 2010	Huagrahaba	mixed grass and clover
Seeding rate and method	broadcast	990 kg ha^{-1} furrow or direct	90 kg ha^{-1} oat 45 kg ha^{-1} vetch broadcast	135 kg ha^{-1} Broadcast	60 kg ha^{-1} furrow or direct	48 kg ha^{-1} grass 4 kg ha^{-1} clover
Baseline fertilizer regime	40 kg N ha^{-1} yr^{-1}	120–131–50–30 kg ha^{-1} of NPKS	none	50–31–0 kg ha^{-1} NPK	none	none
Supplemental N fertility	none	none	none	45 kg N ha^{-1} applied as urea at tiller initiation	none	40 kg N ha^{-1} year
Pest management	Weed management typically included glyphosate applied at labeled rates prior to seeding and after harvest, with in-crop weed control achieved with hand cultivation and hand pulling. Depending on the insect pest or disease present, the typical insecticides used in this study included fipronil, cypermethrine, profenopos and clorpirifos, whereas the typical fungicides included cymoxanil, azufre, benomil and carbendazin. All products were used according to label specifications.					

† Farmer managed– no data obtained. Fertility adjustments are estimated.

Data Analysis and Interpretation

In Exp. 1, data were analyzed by using a General Linear Model split plot design with deviation ditches as the main plot factor, and residue management, tillage, and supplemental fertility (in barley) as the subplot factors (Steel and Torrie, 1960). The residuals from this analysis met the requirement of normal distribution and equal variance, so no transformation of the data was required. There was no evidence of interactions among the main and subplot factors; thus only the main effect means are presented. In Exp. 2, data was analyzed with a General Linear Model randomized complete block design. Again, the assumptions of normal distribution and equal variance among the residuals were met. Mean separation in both experiments were done using Fisher's Protected Least Significant Difference tests with an α level of 0.05. In cases where treatments had common factors, single degree of freedom contrasts were used to make more detailed comparisons beyond the initial mean separation tests. Yield and biomass production, and nutrient uptake and removal were analyzed for each crop in the cycle individually as well as the cumulative production and removal for the entire cropping cycle.

Table 5. Crop yield and biomass response to conservation agriculture practices in Exp. 1 from 2011 to 2014.

Year	Crop	Main effect comparison	Yield
			Mg ha^{-1}
2011	Potato	Residue effect	
		Removed	3.14
		Retained	3.98
		p value	0.001
2011	Oat/vetch	none	7.11 (SE = 0.43)
2012	Barley	Ditch effect	
		Without ditches	1.49
		With ditches	1.95
		p value	0.004
		Residue effect	
		Removed	1.53
		Retained	1.91
		p value	0.012
2013	Fava bean	Residue effect	
		Removed	2.39
		Retained	2.61
		p value	0.05
		Fertility effect	
		No N added in barley	2.62
		N added in barley	2.38
		p value	0.03
2014	Grass pasture	Ditch effect	
		Without ditches	2.30
		With ditches	2.50
		p value	0.04

RESULTS

Biomass and Crop Production

In Exp. 1 in 2011, residue retention was the only CA practice that affected potato tuber production, with potato tuber yields being 27% higher when residue from the previous year's pasture was retained in the experimental plots rather than harvested for animal fodder (Table 5). In 2011 following potato, there was no evidence that any of the CA practices impacted the oat/vetch biomass production, which averaged 7.11(SE = 0.43) Mg ha^{-1} for all the treatments. In 2012, barley yields were affected by the presence of deviation ditches and residue retention, but there was no evidence of interactions among these or other CA practices. Barley yields were 31% higher in the plots with the deviation ditches compared to those without the ditches. Barley yields were also 25% higher when forage from the oat/vetch was retained in the plots compared to when the oat/vetch forage was harvested for animal fodder. In 2013, faba bean grain yields were affected by the CA practice of residue retention and by the N management in the previous year's barley crop. Faba bean grain yields by were 10% higher in plots when the barley residue from 2012 was retained in the plots rather than being harvested for animal fodder. In contrast, faba bean yields were 10% lower in plots that received supplemental N fertilizer in the previous year's (2012) barley phase of the rotation. In the transition back to pasture in 2014, the grass/legume pasture yields were 10% higher in the plots that contained deviation ditches compared to those that did not. In all phases of the rotation in this experiment, there were no discernable relationships between crop yield response and soil nutrient status (data not shown).

In Exp. 2 in 2011, the pasture composition prior to the potato crop was estimated to be 74% blue grass, 16% white clover, and 10% weedy species, yielding an average of 3.9 Mg ha^{-1} across the experimental blocks (data not shown). Following this pasture in 2011, there was no evidence that any of the three CA systems affected potato tuber yields relative to the non-CA control, with tuber yields averaging 4.26 Mg ha^{-1} across treatments (Table 6). Following potato in 2011, single degree of freedom contrasts indicated that oat/vetch yields were significantly higher

Table 6. Crop yield and biomass response to conservation agriculture practices in Exp. 2 from 2011 to 2014. Means followed by a different letter are significantly different at an alpha level of 0.05 according to a Fischer's protected LSD test.

Treatment no.	Treatment description	2011 Potato tuber	2011 Oat/vetch biomass	2012 Barley grain	2013 Faba grain	2014 Pasture grass
				Mg ha^{-1}		
1	Conventional tillage, residue removed, full fertility	3.67	3.63a	1.14ab	1.85a	2.12a
2	Reduced tillage, residue removed, full fertility	4.31	4.69ab	1.45bc	2.64b	2.48b
3	Reduced tillage, residue retained, full fertility	4.51	6.34b	2.01c	2.77b	2.56b
4	Reduced tillage, residue retained, P, K, & S fertility only	4.55	6.90b	0.74a	2.88b	2.56b

(59%) when seeded into plots where the potato residue was retained compared to when it was harvested for animal fodder (Treatments 3 and 4 vs. Treatment 2). In 2012, single degree of freedom contrasts revealed that barley in the CA-intensive systems managed with supplemental N fertilizers yielded 52% higher than the non-CA treatment that included the same amount of supplemental N fertilizer (Treatments 2 and 3 vs. Treatment 1). Within the CA-intensive barley treatments, single degree of freedom contrasts revealed that the supplemental N fertilizer increased barley yields by 134% (Treatments 2 and 3 vs. Treatment 4). In 2013, faba bean yields were 49% higher in the CA-intensive treatments (Treatments 2–4) compared to the non-CA treatment (Treatment 1). Similarly in 2014, grass pasture yields were 20% higher in the CA-intensive treatments compared to the non-CA treatment. As in Exp. 1, there were no significant trends between soil nutrient status and crop yield or biomass trends (data not shown).

Inorganic Soil Nitrogen Dynamics in Barley following Oat/Vetch

In Exp. 1 from April through September of 2011, soil inorganic N concentration (0–25 cm depth) ranged from as low as 33 kg N ha^{-1} to as high as 185 kg N ha^{-1}, and varied by time of the year, the presence or absence of deviation ditches, and the addition of supplemental N fertilizers (Fig. 2). Inorganic soil N levels were higher in May and June in plots that contained deviation ditches. This trend occurred in the plots with and without the addition of supplemental N fertilizers. In the plots with no supplemental N fertilizer, there was an increase in soil inorganic N from early April to late May, followed a gradual decrease in inorganic soil N throughout the remainder of the growing season. On the initial sampling date in April, plots that received supplemental N fertilizer had an average of approximately 175 kg ha^{-1} of inorganic N, compared to 75 kg ha^{-1} in the plots that did not received supplemental N fertilizer (Fig. 2A vs. 2B).

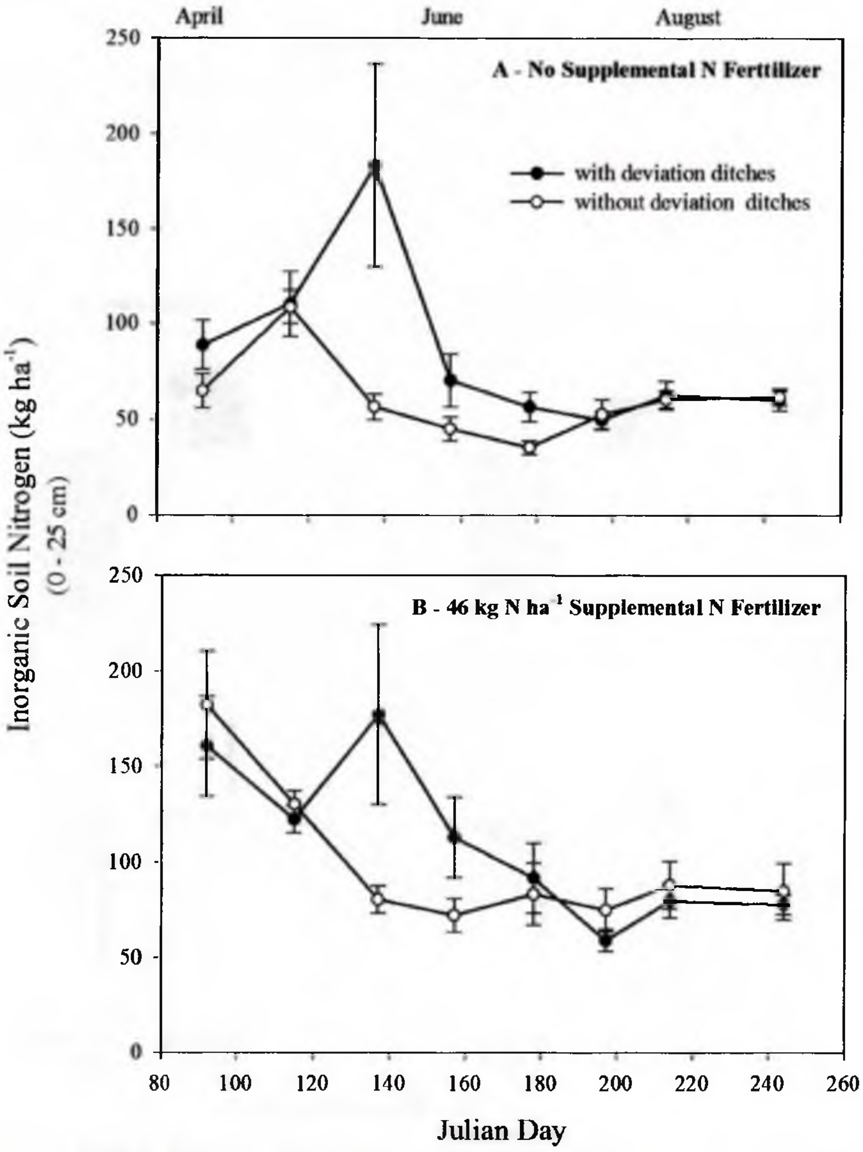

Fig. 2. Inorganic soil nitrogen dynamics (0–25 cm) as influenced by residue management and supplemental N fertility in Exp. 1 in the barley crop following oat/vetch. Error bars represent 1 SE of the mean. Tillage and residue management data pooled within the deviation ditch and fertility management means.

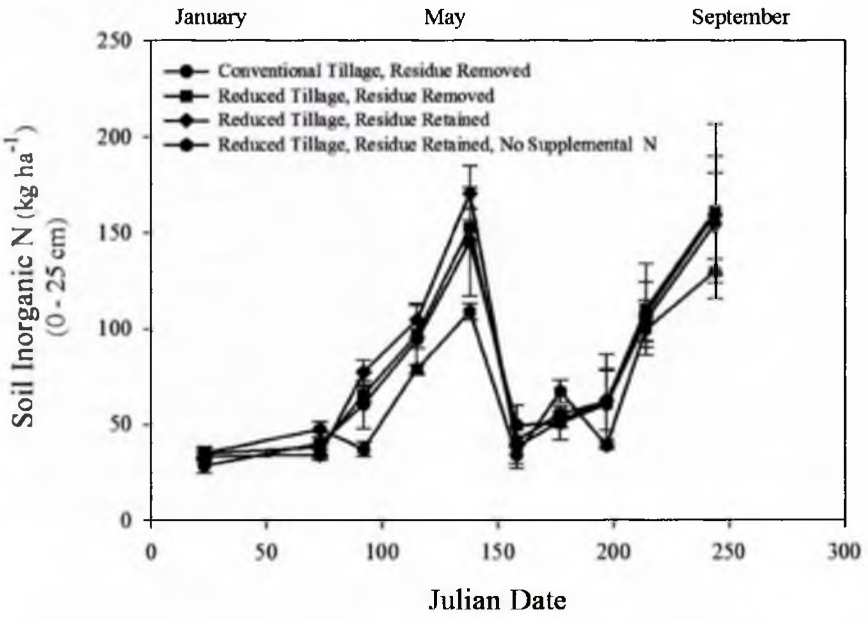

Fig. 3. Inorganic soil N dynamics (0–25 cm) as influenced by conservation agriculture (CA) management regime in Exp. 2 in the 2012 barley crop following oat/vetch. Error bars represent 1 SE of the mean.

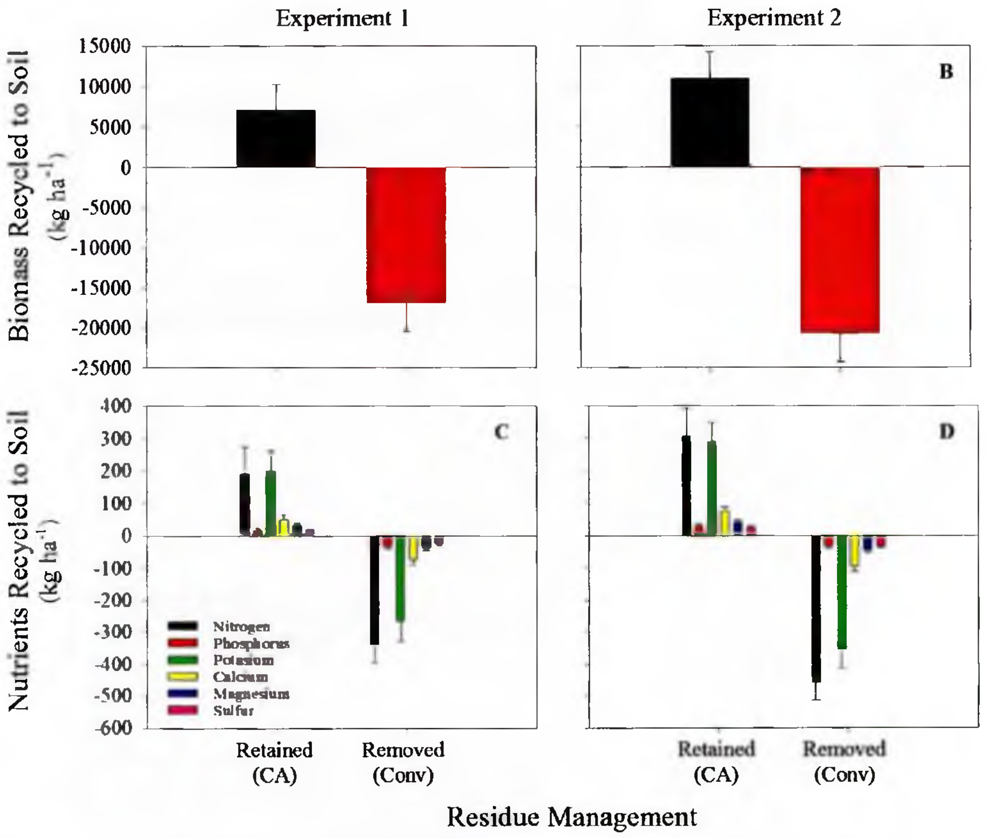

Fig. 4. The net biomass and nutrients recycled or removed from the potato–oat/vetch–barley phase of the cropping system in Exp. 1 and the pasture–potato–oat/vetch–barley phase of the cropping system in Exp. 2. Positive values indicate biomass or nutrients recycled to the soil, whereas negative values indicate biomass or nutrients exported from the system. Error bars represent 1 SE of the mean. Data adapted from Tables 7 and 8.

In Exp. 2 during a similar time frame, the lower and upper levels of inorganic N were similar to that seen in Exp. 1 (Fig. 3). There were no discernable differences among the treatments over the course of the 2011 growing season. There was a general seasonal trend in increased soil inorganic N from January to mid-May, followed by a relatively sharp decrease from mid-May to late June. In contrast to Exp. 1 where soil inorganic N concentrations remained near or below 100 kg ha^{-1} in the late summer and early fall, soil inorganic N in Exp. 2 rose sharply in June through September of 2011, exceeding 150 kg N ha^{-1} on the last sampling date.

Soil Nutrient Conservation

Plant biomass and their associated nutrients returned to the soil vs. removed from the field were only compared between the residue management treatments (i.e., retained or removed), since these management regimes would, by far, have the greatest effect on nutrients leaving or remaining in the cropping systems. We recognize that other CA practices, such as deviation ditches or reduced tillage, could impact nutrient uptake into the crops, but assumed that these trends would be reflected in crop yield since crop nutrient content was calculated as an average of all treatments and replicates. Grain and tuber yields were harvested and removed from the field in both the CA and conventional (Conv) residue management regimes, always constituting a net export of biomass and nutrient.

In potato in Exp. 1, harvesting the tubers, which comprised 68% of the total crop biomass, resulted in a net export of biomass, N and P in both the CA and conventional systems (Table 7). There was a modest net recycling of the other macronutrients in the CA systems, with a modest export of these macronutrients in the conventional system. The oat/vetch cover crop produced approximately 7000 kg ha^{-1} biomass, 140 kg ha^{-1} or more each of N and K, and 16 kg ha^{-1} or less of the other macronutrients, which were all either recycled in the CA system, or exported in the conventional system. Unlike in the potato tubers, the barley grain only accounted for 27% of the total barley crop biomass. As such, retaining the barley straw in the CA system helped to offset biomass and nutrient export in this system, resulting in a modest net recycling of biomass, potassium, and calcium compared to the biomass and nutrient export in the conventional system. Over the course of this rotation, retaining crop and cover crop residues resulted in a net recycling of over 5000 kg ha^{-1} biomass to the soil in the CA system, compared to a net export of more than 15,000 kg ha^{-1} in the conventional system (Fig. 4A). The net total N and K recycled to the soil from this biomass were each near 200 kg ha^{-1} in the CA system, compared to an excess of this amount exported for the conventional system (Fig. 4C). The other macronutrients ranged from 50 kg or less, which were either recycled to the soil in the CA system, or exported in the conventional system.

In Exp. 2, biomass and nutrient content data were available for the pasture component that preceded the potato phase of the rotation, and therefore were added to the nutrient conservation analysis for this experiment. The trends in the biomass and

Table 7. Biomass and macronutrients recycled or removed from the cropping system in Exp. 1. Positive values indicate biomass or nutrients returned to the soil, whereas negative values indicate biomass or nutrients removed from the system. Values in parenthesis represent one standard error of the mean. Data for the deviation ditches, tillage, and fertility factors pooled within residue management regimes.

	Aboveground plant biomass		Tuber or grain biomass		Net recycled to soil	
Element	CA†	Conv.	CA	Conv.	CA	Conv.
	kg ha^{-1}					
Potato						
Biomass	1645 (35)	−1650 (24)	−3938 (162)	−3142 (112)	−2293	−4771
N	32 (<1)	−31 (<1)	−54 (2)	−43 (2)	−22	−75
P	3 (<1)	−2 (<1)	−7 (0.1)	−6 (1)	−5	−8
K	51 (<1)	−51 (<1)	−43 (2)	−34 (1)	8	−85
Ca	23 (<1)	−23 (<1)	−2 (0.1)	−1 (0.1)	22	−24
Mg	12 (<1)	−11 (<1)	−6 (0.1)	−4 (0.1)	6	−16
S	4 (<1)	−4 (<1)	−4 (0.1)	−3 (0.1)	0	−17
Oat–vetch						
Biomass	7460 (309)	−6754 (776)	na		7460	−6754
N	160 (7)	−145 (7)			160	−145
P	14 (1)	−13 (1)			14	−13
K	145 (6)	−131 (15)			145	−131
Ca	16 (1)	−14 (2)			16	−14
Mg	9 (0.4)	−8 (1)			9	−8
S	9 (0.3)	−7 (1)			9	−7
Barley						
Biomass	2236 (76)	−2318 (96)	−1582 (99)	−1878 (119)	669	−4196
N	10 (<1)	−10 (<1)	−24 (15)	−29 (2)	−14	−40
P	1 (<1)	−1 (<1)	−4 (0.2)	−4 (0.3)	−3	−5
K	14 (<1)	−15 (<1)	−7 (0.4)	−8 (0.5)	7	−23
Ca	7 (<1)	−7 (<1)	−1 (0.1)	−2 (0.1)	6	−9
Mg	3 (<1)	−2 (<1)	−3 (0.2)	−3 (0.2)	0	−5
S	1 (<1)	−1 (<1)	−2 (0.1)	−2 (0.1)	0	−4

† CA, conservation agriculture; Conv., conventional.

nutrient balance were similar to those reported for Exp. 1, but with even more pronounced differences between the CA and conventional systems with the added pasture phase (Table 8). This initial pasture phase resulted in nearly 4000 kg ha^{-1} of biomass, near 100 kg ha^{-1} each of N and K, and 25 kg ha^{-1} or less of the other macronutrients, which were either recycled to the soil in the CA systems or exported in the conventional system. Potato tuber comprised 87% of the total potato crop biomass, resulting in a large export of biomass and nutrients in both systems. The oat/vetch cover biomass was more than 6000 kg ha^{-1} in the CA system, resulting in the recycling of 140 kg ha^{-1} each of N and K, and 31 kg ha^{-1} or less of the other macronutrients. The barley grain comprised 43% or the total barley crop biomass. As in Exp. 1, retaining the straw in the CA systems more than offset the biomass and nutrient export associated with the barley grain and resulted in modest recycling of biomass K and Ca in this system. Over the course of the crop rotation, in excess 10,000 kg ha^{-1} biomass and 200 kg ha^{-1} each of N and K were recycled to the soil in the CA system (Fig. 4B and 4D). In contrast, nearly 20,000 kg ha^{-1} biomass and in excess of 300 kg ha^{-1} were exported from the conventional system.

Soil Nutrient Status

In both experiments, there were no discernable trends of any of the CA practices affecting soil nutrient status (i.e., pH, macronutrients, micronutrients, soil organic matter [SOM]) with the exception of soil inorganic N previously discussed (Fig. 2 and 3).

DISCUSSION

Based on our collective experience and the review by Jat et al. (2012) on the prospects and problems associated with CA, we did not necessarily predict that the CA practices evaluated in this study would impact soil and crop parameters in the relatively short duration of a single four year rotation cycle. There were, however, numerous clear indications in our data that CA-based crop and soil management can have positive agronomic benefits

Table 8. Biomass and macronutrients recycled or removed from the cropping system in Exp. 2. Positive values indicate biomass or nutrients returned to the soil, whereas negative values indicate biomass or nutrients removed or exported from the system. Values in parenthesis represent one standard error of the mean.

	Aboveground plant biomass		Tuber or grain biomass		Net recycled to soil	
Element	CA†	Conv.	CA	Conv.	CA	Conv.
	kg ha^{-1}					
Pasture			na			
Biomass	± 3879 (302)				± 3879	
N	± 118 (22)				± 118	
P	± 10 (1)				± 10	
K	± 87 (10)				± 87	
Ca	± 25 (1)				± 25	
Mg	± 9 (1)				± 9	
S	± 7 (1)				± 7	
Potato						
Biomass	787 (154)	–535 (56)	–4507 (545)	–4309 (812)	–3720	–4844
N	16 (5)	–11 (0.4)	–64 (8)	–61 (12)	–48	–72
P	1 (0.4)	–1 (0.1)	–7 (1)	–6 (1)	–6	–7
K	9 (1)	–7 (1)	–51 (6)	–49 (9)	–42	–56
Ca	18 (3)	–13 (4)	–2 (0.2)	–2 (0.3)	–17	–15
Mg	9 (3)	–6 (1)	–5 (1)	–5 (1)	4	–11
S	2 (1)	–1 (0.3)	–5 (1)	–5 (1)	–3	–7
Oat–vetch						
Biomass	6343 (1828)	–4690 (1901)	na		6343	–4690
N	140 (40)	–104 (42			140	–104
P	16 (5)	–12 (5)			16	–12
K	141 (41	–104 (42)			141	–104
Ca	31 (9)	–23 (9)			31	–23
Mg	16 (5)	–12 (5)			16	–12
S	11 (3)	–8 (3)			11	–8
Barley						
Biomass	2596 (6)	–1968 (395	–2013 (406)	–1447 (348)	583	–341
N	21 (4)	–15 (2	–41 (8)	–30 (7)	–21	–44
P	1 (0.1)	–1 (0.1)	–6 (1)	–4 (1	–5	–5
K	21 (2)	–13 (3)	–7 (1)	–5 (1	14	–18
Ca	11 (2)	–8 (3)	–2 (0.4)	–1 (0.4	10	–10
Mg	4 (0.3)	–3 (1)	–3 (1)	–2 (1)	1	–5
S	3 (1	–2 (1)	–3 (1)	–2 (1)	0.3	–4

† CA, conservation agriculture; Conv., conventional.

in the short term. Deviation ditches improved crop productivity in barley in 2012 and pasture in 2014 (Table 5) and helped to conserve soil inorganic N in 2012 following the oat/vetch cover crop that preceded the barley crop (Fig. 2). This conservation of inorganic N may have contributed to the higher yields in barley grown with deviation ditches. This trend, however, is not consistent with the trend of the barley not responding to the supplemental N fertilizer additions in Exp. 1 (Table 5), suggesting that N may have not been limited in this barley crop. It is well established, however, that synchrony between soil N availability and N uptake in the crop is an important factor in determining crop response to N, and may be more efficient in cover crop systems compared to conventional fertilizer regimes (reviewed in Crews and Peoples, 2005; Cook et al., 2010). The 45 kg N ha^{-1} of supplemental N fertilizers applied to barley in this study was applied 50 d after planting, which may not have corresponded with optimal period of uptake in the barley crop for that year. Although there were no significant trends among soil nutrients and the presence or absence of deviation ditches, the reduction in soil rilling in plots with deviation ditches after intense precipitation events was visually very obvious during the course of the study, which is consistent with the results reported by Freebairn and Wockner (1986) in Australia. Longer-term evaluation of the deviation ditch systems at Illangama may reveal that deviation ditches can play an important role in measurable soil and soil nutrient conservation. Although the agronomic and ecological benefits of deviation ditches are relatively obvious, deviation ditches are labor intensive to install and maintain, and thereby a potential economic liability for farmers. We determined, however, that with the cost of US\$0.46 m^{-1} to install a ditch and \$0.27 m^{-1} year^{-1} to maintain a ditch, there still is a positive economic incentive for farmers to employ this CA practice, although only 31% of the Illangama region farmers actually do (Barrowclough et al., 2016).

In addition to deviation ditches, retaining crop or cover crop residues in the field was also a CA practice that yielded positive agronomic benefits. Residue retention improved the productivity of nearly all the crops in Experiment 1 (Table 5), but the effect of residue retention on crop yields in Exp. 2 were less clear (Table 6). Of all the CA practices evaluated in this study, retaining residues had the greatest effect on nutrient recycling (Tables 7 and 8, Fig. 4). From these data, we can see that retaining cover crop residues in the field rather than harvesting them for animal fodder resulted in positive nutrient recycling values. Economically, encouraging farmers to leave crop and cover crop residues in the field will be challenging, costing farmers in the Illangama region over \$2000 ha^{-1} over the course of the 4-yr rotation and resulting in an overall negative economic outcome (Barrowclough et al., 2016). Contrary to our initial hypotheses, we did not detect discernible trends between soil inorganic N and residue management, although soil inorganic N levels were at or well above 30 kg N ha^{-1} at any time during the cropping season (0–25 cm; Fig. 2 and 3). We can only speculate that a more frequently sampling regime may have been needed to detect differences in soil inorganic N resulting from cover crop mineralization compared to the base-line soil N mineralization from the high SOM Andisol soils of our study sites (Table 1). Likewise, supplemental active organic matter analysis, such as particulate organic matter (Cambardella and Elliott, 1993), may have revealed higher levels of organic (but readily mineralizable) N expected when an oat/vetch cover crop is retained in the field.

Overall, pin-pointing the exact contribution residue retention and cover crops make to crop productivity can be difficult, but certainly improved nutrient availability (Derpsch et al., 1986; Sisti et al., 2004; Thierfelder and Wall 2010a), soil water status (Roth et al., 1988; Lal, 1974; Farooq et al., 2011; Thierfelder and Wall 2010b) and suppression of weeds and other pests (Gallagher et al., 1999; Stone et al., 2004) are among the contributing factors (reviewed in Crews and Peoples, 2005).

The general increases in soil inorganic soil N seen in the late winter to early spring in both experiments can likely be attributed to N mineralization from the SOM, whereas subsequent decreases in soil inorganic N are likely attributed to crop N uptake (Fig. 2 and 3). Evaluation of plant N status throughout the growing season would have helped confirm this speculation. In Exp. 1, plots that received an addition 45 kg N ha^{-1} at the time of tillering of the barley showed considerably elevated soil inorganic N levels in the early spring of 2012 (Fig. 2B). Soil sampling for inorganic N in this experiment did not begin until after the barley crop was established, so the elevated inorganic N in supplemental N fertility treatments is likely a result of the additional urea fertilizer applied to these plots. In Exp. 2, there was a large post barley harvest increase in inorganic soil N (Fig. 3) which did not occur in Exp. 1. The baseline soil organic matter levels (Table 1), oat/vetch biomass production prior to the barley crop, and barley yields (Tables 5 and 6) were subjectively similar, suggesting that the N mineralization potential of the soils and N uptake in barley crop were similar between the two experiments. The soil pH in Exp. 1 (5.93) was somewhat more acidic than in Exp. 2 (6.33), possibly resulting in lower soil N mineralization potential in Exp. 1 compared to Exp. 2 (Curtin et al., 1998). However, a more detailed analysis of N mineralization potential of these two soils would be necessary to determine if this magnitude of difference in soil pH could account the observed differences in N mineralization dynamics between the two experiments in 2012. Overall, it is clear that inorganic soil N was often quite high in these soils even in the cooler months of the year when crops are not typically cultivated. Retaining high levels of crop carbon-rich residues (Starovoytov et al., 2010) and more frequent inclusion of cover crops (Crews and Peoples, 2005) during the non-crop periods may be ways to help sequester inorganic soil N in these systems.

Of the CA practices evaluated in this study, reduced tillage is the most widely adopted in the Illangama region, with 76% of farmers practicing some sort of minimal tillage crop production (Barrowclough et al., 2016). In both experiments, reduced tillage had a neutral effect on crop yields, neither increasing nor decreasing crop productivity. The most tangible benefit of reduced tillage for farmers would be reduced labor costs, which exceed \$1000 ha^{-1} of the course of the 4 yr rotation (Barrowclough et al., 2016). Although reduced tillage is common with cereal and legume crops, it is less commonly practiced with potato. Of the studies that have evaluated reduced tillage in potato, negative (Lanfranconi et al., 1993), neutral (Wallace and Bellinder 1990; Carter and Sanderson 2001), and positive (Pierce and Burpee 1995) yield responses have all been reported.

Our hypothesis that CA-intensive systems would require less supplemental N fertilizer than conventional systems was partially supported, with barley following oat/vetch in Exp. 1 (Table 5) and potato in Exp. 2 not responding to supplemental N fertilizer, suggesting that N mineralization from the oat/vetch cover crop or pasture residue that preceded these crops and from the soil organic matter was sufficient to meet the N needs of the crops. In contrast, however, barley following oat/vetch in Exp. 2 was quite responsive to supplemental N fertilizer, with barley yields being almost three times higher when the 45 kg N ha^{-1} was applied compared to being withheld (Table 6, Treatment 3 vs. 4). There was evidence in Exp. 2 that soil inorganic N in the early spring of 2012 was lower in plots where the supplemental N fertilizer was withheld (Fig. 3). This may be an indication that N was limited in this treatment. However, in all treatments in both experiments, soil inorganic N levels throughout the barley growing season were well above (i.e., >25 mg L^{-1}) the level where one would expect a yield response to supplemental N fertilizer in cereal crops (Ketterings et al., 2012; Camberato and Nielsen, 2015). Although grass/legume cover crop mixtures can often meet most if not all of the N needs of the subsequent crop, predicting when N is deficient in cover crop-based systems is a continued challenge (Crews and Peoples, 2005). Risk adverse farmers may choose to apply supplement N even when is likely not needed, seeing it as sort of an "insurance policy". Such approach, however, will be costly, both economically and environmentally, and not suitable for low resource farmers. Although there are number of soil and tissue tests that can help determine the N status of soils and crops, farmers in remote regions such as Illangama need relatively low-tech decision support tools to help guide their crop fertility decisions.

Given the design of our experiments, we had the opportunity to evaluate the effect N fertilizer application in barley phase had on the subsequent faba been phase, although no formal hypothesis were initially formulated in this regard. We were perplexed by the lower faba bean yields in plots that received supplemental N fertilizer in the previous barley crop in Exp. 1. Soil inorganic N levels (0–25 cm) at the end of the 2012 growing season were approximately 25 kg N ha^{-1} higher in the plots that received the 45 kg N ha^{-1} supplemental N fertilizer earlier that spring (Fig. 2A vs. 2B). Although it is well established high levels of inorganic soil N reduces symbiotic N fixation in legumes (Becana and Sprent 1987), this was not evaluated in our study. There is no evidence to our knowledge that excess N has a negative impact on legume productivity.

CONCLUSIONS

The CA practices of deviation ditches, residue retention, reduced tillage, and cover crops evaluated in this study all had a positive or neutral impact on crop productivity and nutrient recycling in the potato-based cropping system of the Illangama region of Ecuador. In the short term, there is a modest positive economic incentive for farmers to adopt deviation ditches and reduced tillage, but a strong negative economic incentive to retain crop residues in the field rather than using or selling them for animal fodder (Barrowclough et al., 2016). Retaining residues in the field, however, greatly enhances nutrient recycling, which contributes to crop productivity, and provides the valuable ecosystem service of protecting soils from erosion. Although Illangama region farmers are typically mindful of environmental benefits of CA, economic considerations are the primary drivers to adopt CA practices or not. However, it has been well demonstrated in high altitude Andean cropping systems that soil nutrients are rapidly depleted by cropping, but slowly replenished by traditional fallow systems (Aguilera et al., 2013). Shorter fallow or pasture periods coupled with cultivation of more marginal land will certainly strain the sustainability of these types of cropping systems. It is imperative that collaborative farmer-research studies such as ours continue to provide grass-root level demonstrations for low-resource farmers to improve the sustainability of their cropping systems. Our study was conducted over the relatively short period of 4 yr, which is not sufficient to fully realize the benefits of CA-intensive soil and crop management on soil quality and crop productivity (Jat et al., 2012). As such, it is also imperative that studies such as ours are conducted over the long term so that the potential of CA in climatically extreme cropping regions such as Illangama can be properly vetted.

ACKNOWLEDGMENTS

Funding for this research was provided by the SANREM CRSP and was made possible by the United States Agency for International Development and the generous support of the American people through USAID Cooperative Agreement no. EPP-A-00-04-00013-00. We would like to thank Professor Neal Eash for his thoughtful review of this manuscript prior to its submission to this journal.

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