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Live barriers and associated organic amendments mitigate land degradation and improve crop productivity in hillside agricultural systems of the Ecuadorian Andes

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Abstract

Land degradation caused by erosion and nutrient depletion in the Andes poses serious existential threats to small-scale farming. Although the potential of hedgerows to decrease water erosion is well recognised, their potential dual-use as a source of organic amendments to supplement farmer inputs is much less studied. The objective of this investigation was therefore to explore locally developed options for hedgerows that address these twin challenges. Experimental plots were installed to assess water erosion control by hedgerows and the effect of organic amendments harvested from the hedgerows on soil productivity, soil moisture, and soil fertility over the course of 2 years and three crop cycles (two of barley and one of rye). The experiment was conducted in two sites within the community at distinct elevations and associated biophysical contexts. At each site, four treatments were established, comparing a control treatment versus three types of hedgerows: (a) Andean alder, (b) canary grass strips, and (c) mixed canary grass and Andean alder. Results demonstrated that hedgerows and associated organic inputs comprised canary grass, and mixed canary grass and Andean alder reduced water erosion by 50–60% and increased biomass production by up to 1.1 $Mg\ ha^{-1}$ and grain yield by up to 0.5 $Mg\ ha^{-1}$. We conclude that although hedgerows are unlikely to produce sufficient quantities of organic resources to satisfy all nutrient input requirements, their potential to decrease erosion and supplement existing organic matter inputs indicates that they should be strongly considered as an option for improved agricultural management within this and similar resource constrained contexts.

KEYWORDS
Andean alder, Andes, canary grass, Ecuador, erosion, nutrient depletion

1 | INTRODUCTION

Small-scale farming in the Andean highlands often takes place in small indigenous communities with each family usually managing a number of fields dispersed across diverse topography and microclimates (Buytaert et al., 2007; Zehetner & Miller, 2006). Mixed crop-livestock farming systems tend to dominate regions below 3,800 m above sea level (masl). Potatoes (*Solanum* spp.) have long been the staple crop in the region, although other important crops include cereals, legumes, and native tubers. Most farming families own at least one or two heads of cattle (often used for draught power), whereas sheep, chickens, and guinea pigs are also important livestock. Critically, in addition to the constraints caused by the biophysical environment (climate and topography), many farmers have restricted access to basic agricultural inputs such as organic amendments, fertilizers, pesticides, and irrigation (Fonte et al., 2012).

Land degradation caused by erosion, soil organic matter (SOM) depletion, and negative nutrient balances represents a pervasive long-term threat to these small-scale farming systems (Vanek et al., 2016; Vanek & Drinkwater, 2013). The steep slopes of these mountainous agroecosystems mean that the landscapes are inherently susceptible to erosion. For example, a study in the southern Ecuadorian Andes found sediment loss in rural landscapes to range from 0.26 to 151 Mg ha^{-1} yr^{-1} with an overall average soil loss of 22 Mg ha^{-1} yr^{-1} (Molina et al., 2008). Another study in a watershed located close to the site considered here, found similar erosion losses, averaging 27 Mg ha^{-1} yr^{-1}, with estimates in some sites as high as 150 Mg ha^{-1} yr^{-1} (Henry et al., 2013).

Soil degradation, however, not only involves the loss of important soil nutrients, but also the loss of soil biological activity and associated structure, which play a critical role in soil water capture and retention, soil erosion, nutrient recycling, root penetration, and the overall productivity of agricultural lands (Bronick & Lal, 2005; Lal, 2001). Although the loss of soil fertility can be partly compensated for through the addition of fertilizers, the rehabilitation of overall soil health and productivity is a much slower process (Fonte et al., 2012).

In response to the challenges posed by erosion, farmers in the Andes have long employed soil conservation structures such as terraces, both bench terraces, which are constructed by farmers, and slow-forming terraces, which develop overtime as soil accumulates behind vegetative barriers such as grasses, shrubs, and trees (Dercon et al., 2003). Although bench terraces are becoming less common nowadays due to their higher labour requirements for maintenance, slow-forming terraces are still frequently used by farmers in the Ecuadorian highlands (Dercon et al., 2003). Slow-forming terraces have been shown to be effective (e.g., Kagabo et al., 2013; Sánchez-Bernal et al., 2013; Tesfaye et al., 2018), but these techniques can also accentuate spatial variability in soil fertility, where the fertile topsoils from the upper part of the field accumulate at the lower part of the field leaving strong field-level fertility gradients (Dercon et al., 2006).

In addition to the inherent erosion processes of these mountainous landscapes, land degradation in the rural Andes is also being driven by negative SOM and nutrient balances, where small-scale farmers are unable to replace the degraded SOM and nutrients exported in the harvest of crops (Bahr et al., 2014; De Koning et al., 1997; Vanek & Drinkwater, 2013). Not only are the nutrient balances of the macronutrients nitrogen (N), phosphorus (P), and potassium (K) often observed to be negative in these farming systems, but SOM has also been observed to decrease as a result of agricultural management (due to accelerated degradation of SOM as a result of increased aeration of soils through ploughing). In a study from the southern Ecuadorian Andes, SOM levels under crop lands were observed to be 15% lower than those of nearby forest sites, which was attributed to land-use conversion and unsustainable soil management (Bahr et al., 2014). SOM plays a critical role in maintaining soil health, supporting biological activity and diversity (Moore et al., 2004), and regulating soil processes linked to agroecosystem functions such as nutrient cycling, plant growth, soil aggregation (structure), and water storage (Barrios, 2007; Bronick & Lal, 2005; Lavelle et al., 2006).

A major reason for the pervasive trend of negative nutrient balances within the rural Andes is that the smallholder farmers generally have limited access to agricultural inputs, due to both a low financial resource base to invest in agricultural inputs and their remoteness from population centres (Fonte et al., 2012). Although overall inputs are low, there appears to be great variability in the spatial allocation of the available nutrient and organic matter inputs. For example, farmers commonly allocate fewer agricultural inputs to fields that are further from their homestead or that are perceived to be less fertile (Caulfield et al., submitted; Vanek & Drinkwater, 2013). The fact that near fields can often receive high quantities of inputs relative to outer fields suggests that the negative nutrient balances (in the outer fields) are not simply a result of constrained resources but likely result from labour and logistical limitations as well. This could indicate that alternative, in situ mechanisms for addressing the negative nutrient balances of distant fields are required (Caulfield et al., submitted; Fonte et al., 2012).

One of the criticisms levelled at physical soil conservation structures, such as terraces, has been that they provide poor immediate economic returns given their focus on soil conservation and therefore often are not easily adopted by farmers (Erenstein, 2003; Posthumus & De Graaff, 2005). Organic amendments, green manures, and mulches on the other hand, given the right conditions, appear to show some important potential both in terms of improving soil conservation and agricultural productivity (Babalola et al., 2007; Félix et al., 2018). Moreover, such techniques may be applied in situ, providing important sources for nutrient and organic matter inputs in areas that may be less accessible to farmers such as distant fields.

Some promising findings in this regard have been observed with vetiver grass (*Vetiveria nigritana*). In two similar studies, one undertaken in the Central Highlands of Kenya, the other in Southern Nigeria, mulching with vetiver grass was shown to both increase yields and decrease run-off (Babalola et al., 2007; Okeyo et al., 2014). Another recent study in Burkina Faso investigated the harvesting of natural resources in situ (ramial wood from *Piliostigma reticulatum* shrubs) as soil amendments (Félix et al., 2018). They found that although the ramial wood chips did not contain sufficient nutrients to replace those lost from crop production, soil organic carbon (SOC) increased significantly, and biomass and grain yields were higher in the high ramial wood treatments compared with the control with no organic inputs. Finally, it is worth noting that leaf litter from N-fixing Alder trees (*Alnus rubra Bong.*),which are common in many parts of the high Andes, can provide significant amounts of N to the soil and to support crop growth (Swanston & Myrold, 1997; Visscher, 2018).

Although some notable research has been conducted into the effects of slow-forming terraces (e.g., Dercon et al., 2003; Kagabo et al., 2013; Sánchez-Bernal et al., 2013), more research is required in different socioecological contexts to assess their efficacy in decreasing water erosion. More critically, however, the sparse research into the potential of hedgerows to act as supplemental sources of organic amendments appears to be an important gap in the scientific literature. This dual-use potential for hedgerows is particularly important to explore as farmers do not easily adopt improved land management techniques that do not provide immediate returns on investment(Erenstein, 2003; Posthumus & De Graaff, 2005). By exploring the potential of hedgerows to act as sources of organic amendments, such barriers to adoption may be overcome because this may offer a relatively short-term benefit for increased productivity.

The objective of this research was therefore to work with an indigenous community in the Ecuadorian Andes to explore locally developed options for dual-use hedgerows to address the twin challenges of erosion and nutrient depletion in rainfed small-scale farming systems. Based on consultation with community members, subsequent laboratory analyses of vegetative material present in the community, and according to the decision tree developed by Palm et al. (2001), the species identified for inclusion in the hedgerows were Andean alder and canary grass (*Phalaris tuberosa*; Figure 1).

Specifically, we studied the influence of hedgerow barriers and associated organic matter amendments on soil water erosion, topsoil moisture content, SOC and nutrient stocks, as well as on crop production in two different locations within the same landscape. As per Kagabo et al. (2013), we hypothesised that the hedgerows would significantly reduce water erosion in different biophysical contexts within the same community. Moreover, based on Babalola et al. (2007), Félix et al. (2018), Okeyo et al. (2014), and Visscher (2018), we postulated that incorporating organic amendments from these hedgerow species into the soil would have beneficial impacts on both soil quality and crop productivity, a prerequisite for farmers to adopt these soil conservation techniques more widely.

2 | MATERIALS AND METHODS

2.1 | Study site description

The research took place from July 2015 to July 2017 in the rural indigenous community of Naubug, Flores Parish, Chimborazo Province, Ecuador (1°51′24.0′S, 78°39′15.6′W), with around 640 inhabitants (120 families). Annual precipitation is approximately 400–500 mm, with most rain falling between November and May (wet season) and a drier, windier period from June to October (dry season). Average annual temperatures range between 12° and 16°C, with minimum temperatures rarely falling below zero and maximum temperatures rarely rising above 22°C. The community is characterised by steep topography (slopes are typically between 10° and 25°) with elevation ranging from 2,850 to 3,600 masl (Gobierno Autónomo Descentralizado Parroquial Rural de Flores, 2015). The long-term pedogenic processes of the region have been dominated by volcanic activity with pyroclastic deposits giving rise to the formation of volcanic (Andosol) soils rich in SOM, especially at the higher elevations (De Noni et al., 2001; Zehetner & Miller, 2006b). At lower elevations and in areas that have experienced high erosion the subsoils are exposed revealing thick layers of compacted volcanic ash known locally as 'cangahua.' The soils of these areas are roughly classified as entisols or inceptisols.

As a result of these soil patterns and the climate gradients associated with the elevation range, local farmers have delineated the landscape into three agricultural 'management zones,' broadly defined along elevation lines—the upper, middle, and lower zones. The lower zone has sandier soils with a low nutrient content, coupled with a climate that is characterised by a lower precipitation:evapotranspiration ratio. The upper and middle zones have soils higher in clay and nutrients and a cooler, more moist climate (Caulfield et al., submitted). Soil texture in the field considered here in the upper zone comprised 26% sand and 16% clay, whereas soil in the field of the lower zone had 34% sand and 12% clay.

The main sources of income in Naubug include the sale of very modest amounts of agricultural products to local markets, monthly government subsidies, and remittances from temporary and permanent migrant family members. Limited financial resources mean access to agricultural

FIGURE 1 Photos of existing hedgerows in the community used to control erosion. Andean alder (*Alnus acuminata*) trees interspersed with canary grass (*Phalaris tuberosa*) hedgerow (left); canary grass strip (right)

inputs and markets are also heavily restricted. Land is privately owned, and most farmers own between 12 and 18 fields dispersed throughout the landscape amounting to between 2 and 3 ha of land managed by each farming family. There is no access to irrigation water.

2.2 | Experimental design

A workshop was held with community members to identify existing and alternative improved agricultural techniques that have the potential to decrease land degradation and also 'aggrade' (improve) soils (Figure 1). Dual-use hedgerows were identified as having potential to reduce water erosion and provide sources of soil organic amendments to supplement the small amounts of organic resources currently available to community members. Three types of hedgerows were selected to meet these objectives: (a) grass strips of canary grass (*P. tuberosa*), (b) 'native' tree hedgerows of Andean alder (*A. acuminata*), and (c) mixed hedgerows of both Andean alder and canary grass. A control with no live barrier or organic inputs was also included in the experimental design. Subsamples of these organic resources were assessed for nutrient content and quality (Table 1) at the laboratory of the Ecuadorian National Institute for Agricultural Research.

Twelve closed experimental plots (8×3 m^2) were installed in each upper and lower zones of the landscape (24 plots total), representing the greatest contrasting biophysical contexts found within the landscape. These plots were oriented vertically and placed side-by-side along the contour. Plots in the upper zone were located at approximately 3,600 masl and had a slope of around 20°, whereas plots in the lower zone were at around 3,100 masl and with a slope of around 13° (with minimal variation in slope between plots ±1°). Given the objective of this research was to compare the different hedgerow treatments in controlling erosion processes, as well as improving soil fertility and productivity through associated organic amendments, a relatively small, closed experimental plot design was selected, as such plot designs enable easy comparison among different responses at the same spatial scale, with exactly the same size of drainage area (Boix-Fayos et al., 2006). Furthermore, plot size was chosen to allow for significant overland flow, although also ensuring a similar slope across plots and an acceptable amount of area by participating farmers. In each of the zones, the four treatments (three hedgerow treatments and the control) were assigned randomly to replicate blocks. The tops and the sides of each experimental plot were fenced off using corrugated zinc-metal sheets inserted vertically into the soil to a depth of 45 cm and supported by wooden stakes. At the bottom of each plot, an erosion trench was dug and lined with thick plastic sheet into which the run-off and sediment would collect. The hedgerows were established at the bottom of the plots, located within the experimental plot area, just uphill from the erosion trenches with six *A. acuminata* saplings (1-cm diameter) planted in the pure alder hedgerows and three saplings in the mixed hedgerows. Canary grass tussocks (30 cm in height and 20–30 cm in width) were planted adjacent to one another 8 months before beginning the first crop cycle and data measurements (Figure 2). Canary grass was cut every 3 months to a height of 20–30 cm. To measure erosion, the run-off and sediment were emptied from the sediment capture trenches after each significant precipitation event using a plastic jug. The run-off was filtered twice through cotton cloth. The remaining sediment was then dried in an oven at 60°C until no weight change was observed and the weight recorded. Measurements were taken from July 2015 until July 2017.

To understand the effects of the organic amendments harvested from hedgerows, 40 kg of fresh grass and/or alder leave residues (equivalent of around 16.5 Mg ha^{-1} fresh weight, harvested from nearby the plots) were applied to the soils in each plot and incorporated 2 weeks before the planting of each crop with equal weight of seed. The organic amendments incorporated into the soils reflected the hedgerow composition of the experimental plots such that the experimental plots with Andean alder received 40 kg of Andean alder leaves, the grass strips received 40 kg of canary grass amendments, and the mixed hedgerows treatment received 20 kg each of canary grass and Andean alder leaves. The control treatment received no inputs.

At harvest, the total fresh crop biomass of each plot was weighed and recorded. A subsample of 100 tillers was then collected, weighed, and dried in an oven at 60°C until no change in weight was recorded. The subsample was then separated into component parts (grain and stalk) and reweighed. The first experimental crop cycle was planted with barley (*Hordeum vulgare*) in October 2015 and harvested in March 2016 (subsequently referred to as Barley 2016); the second crop cycle was planted with rye (*Secale cereale*) in September 2016 and harvested in January 2017 (subsequently referred to as Rye 2016); and the last crop cycle was planted with barley in February 2017 and harvested in July 2017 (subsequently referred to as Barley 2017). In the lower zone, this last crop failed, and therefore, no data were collected for Barley 2017 in this zone.

To measure the effect of the organic amendments on soil moisture, we used a soil moisture probe with a SM300 sensor (https://en.eijkelkamp.com/products/field-measurement-equipment/soil-moisture-measuring-system-with-sm300-sensor.html). Measurements were taken every 2 weeks from July 2015 to July 2017 at three different points in each plot, 1.5 m in from the side and 2, 4, and 6 m down from the top of the experimental plot, at a depth of 10 cm. An average of each of these measurements per plot was used for data analysis.

TABLE 1 Moisture content and chemical composition of the organic amendments applied to the experimental plots (phenols, lignin C, N, P, K, Ca, and Mg presented as % of dry matter)

	Property (%)								
Organic amendment	**Water**	**Phenols**	**Lignin**	**C**	**N**	**P**	**K**	**Ca**	**Mg**
Canary grass	74.95	1.04	6.58	51.10	4.23	0.25	3.18	0.34	0.32
Andean alder leaves	59.17	3.65	11.67	48.98	3.17	0.2	1.18	0.86	0.36

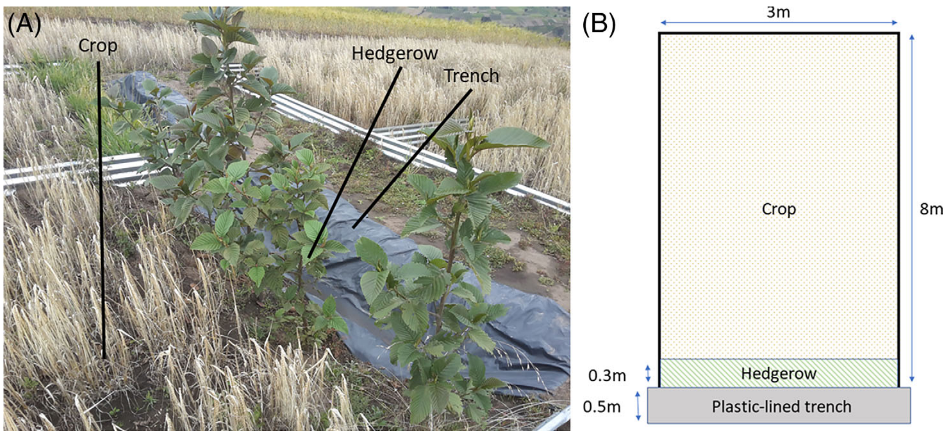

FIGURE 2 (a) Photo showing experimental plots and sediment capture trenches located in the lower agricultural management zone. Near: Andean alder hedgerow treatment; Left: canary grass strip treatment. (b) Schematic representation of the experimental plot dimensions and components

To assess overall impacts of the organic amendments on the chemical composition of the soils, composite soil samples were taken from each experimental plot at the beginning of the study, in July 2015, and following the harvest of the last crop cycle, in July 2017. Twenty subsamples (0–20 cm) were combined to create a composite sample of around 2 kg. All soil samples were air-dried and transported to the laboratory of the Ecuadorian National Institute for Agricultural Research for analysis of SOC (Walkley & Black, 1934), total N (Kjeldahl, 1883), as well as available P (Olsen method; Olsen et al., 1954), and exchangeable K, Ca, and Mg (modified Olsen method, pH 8.5). Plant and other organic debris were removed, and soil was ground and sieved (2 mm) before chemical analysis. Net changes in soil chemical properties were then calculated for each plot by subtracting the pre-experiment soil values from the postexperiment soil chemical composition results.

2.3 | Statistical analysis

A repeated measures analysis of variance was applied with fixed effects for location (zone) and for each year measured (2015/2016 and 2016/2017) with random block effects to test for differences in erosion among the four experimental treatments. A Fisher's least significant difference test was applied to test which treatments were different at 5% significance level. The same structure of statistical model was also applied to test for differences among treatments for biomass production, grain yield, soil moisture, and net changes in soil chemical properties (SOC, total N, available P, exchangeable K, Ma, and Ca) from the start of the trial to after the last harvest. All analyses were carried out within the RSTUDIO environment version 1.2.1335 for R (version 3.6.1) using ade4, agricolae, lmerTest, and emmeans packages.

3 | RESULTS

3.1 | Erosion

Erosion was significantly lower in the canary grass and mixed canary grass and Andean alder treatments compared with the control treatment. Although the Andean alder treatment exhibited greater erosion than the canary grass and mixed treatments, it also displayed significantly less erosion than the control treatment (Figure 3, Table S1).

3.2 | Biomass production and yield

The statistical analyses revealed significant differences among treatments for biomass production and grain yield (Table S2). The canary grass and the mixed canary grass and Andean alder treatments displayed significantly greater crop biomass production and grain yield compared with the control treatment for all crop cycles (Figure 4). The Andean alder treatment did not display improved biomass production or grain yield compared with the control (Figure 4).

3.3 | Soil moisture

Soil moisture measurements displayed significant differences among treatments. A significant interaction between treatments and date of measurements (time) was also observed (Table S3). Soil moisture under the control treatment was significantly lower than for the treatments receiving amendments (hedgerows). The canary grass treatment exhibited the greatest soil moisture content among treatments (Figure 5). In general, soil moisture tended to remain higher under the treatments receiving organic amendments compared with the control condition throughout the research period (Figure 6). It is noteworthy, that although during the first extensive period of low soil moisture levels (around January 2016), differences between treatments did not appear to be large; in the second period of lower soil moisture levels (around August–September 2016), differences between treatments were more pronounced (Figure 6).

3.4 | Net changes in soil chemical fertility

Soil chemical analyses of the experimental plots taken before the first crop cycle (Barley 2016) and after the last crop cycle

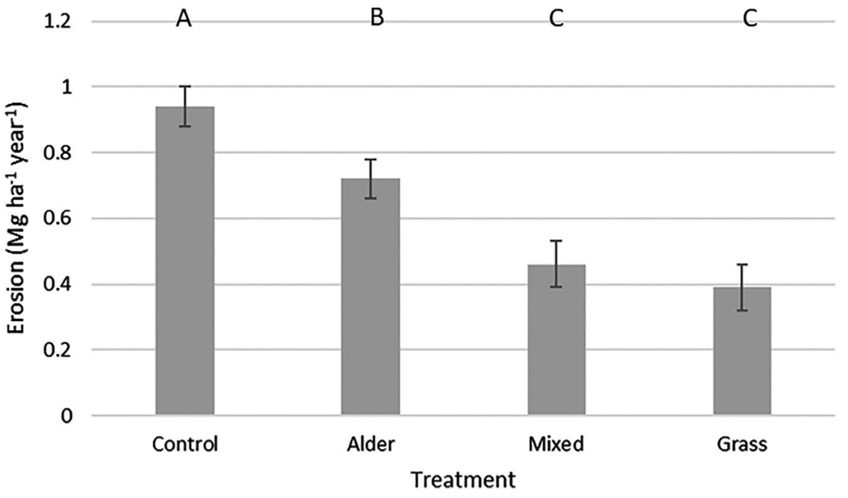

FIGURE 3 Annual soil erosion by treatment (control, Andean alder, mixed canary grass, and Andean alder and canary grass hedgerows). Error bars indicate standard error of the mean; letters above bars indicate results from Fisher's least significant difference test, such that treatments with different letters have significantly different means

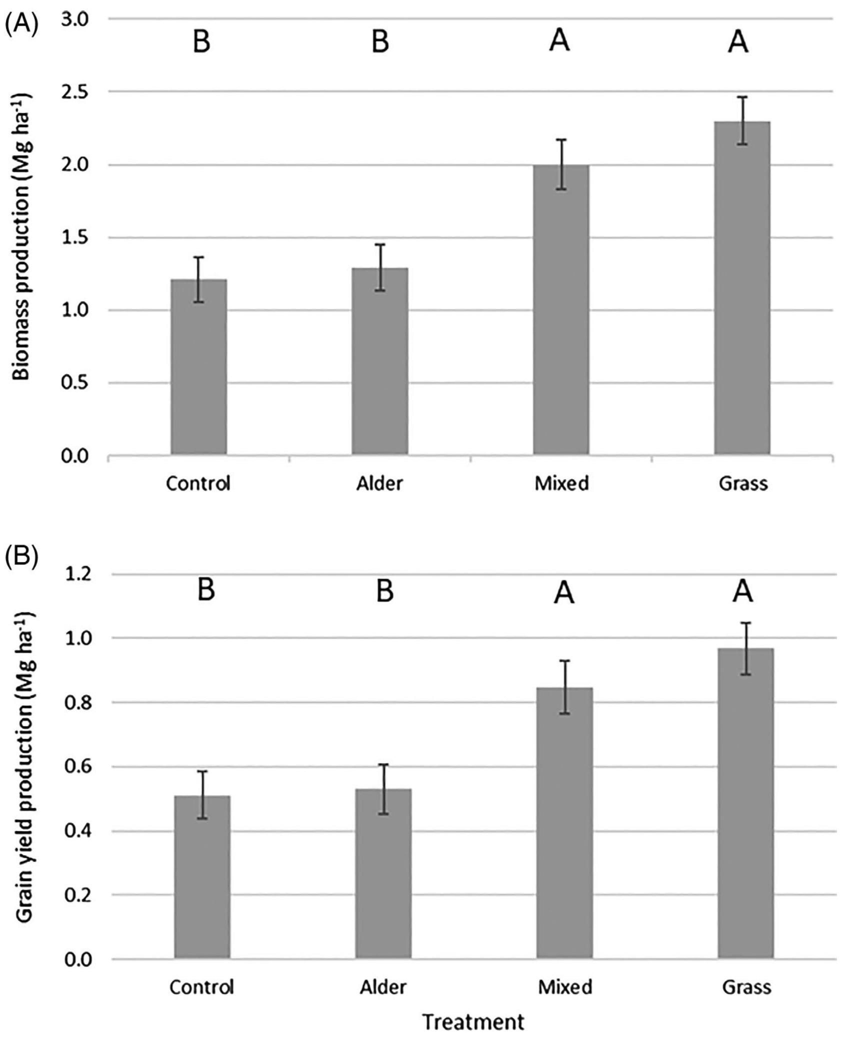

FIGURE 4 Production of total dry crop biomass (a) and grain yield (b) by treatment (control, Andean alder, mixed canary grass, and Andean alder and canary grass amendments). Error bars indicate standard error; letters above bars indicate results from Fisher's least significant difference test, such that treatments with different letters have significantly different means

(Barley 2017; Table S4) revealed significant increases in SOC, total N, and exchangeable K in the grass treatment compared with the control treatment. The mixed amendments and Andean alder treatments both displayed significant increases in exchangeable K as well compared with the control condition. It is noteworthy that although not always significant, the canary grass amendments treatment displayed the highest net increases in all soil chemical properties except exchangeable Ca and Mg (Table 2).

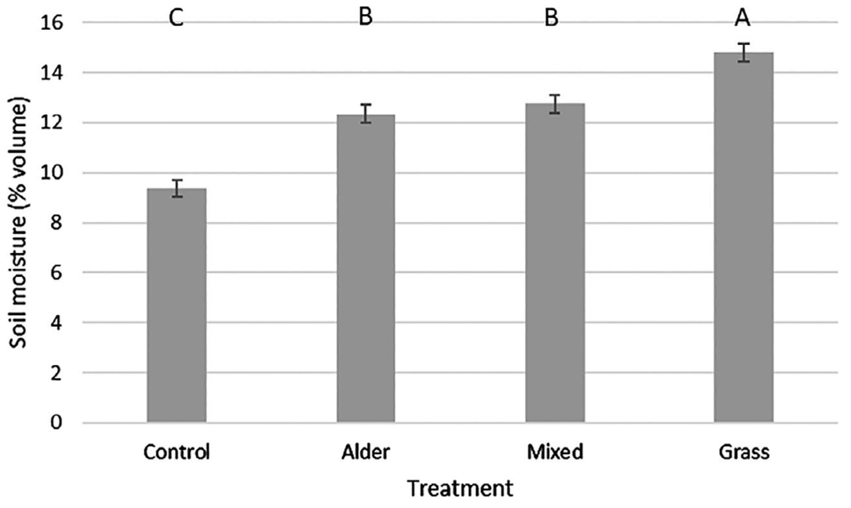

FIGURE 5 Mean soil moisture content measurements by treatment (control, Andean alder, mixed canary grass and Andean alder, and canary grass amendments). Error bars indicate standard error of the mean; letters above bars indicate results from Fisher's least significant difference test, such that treatments with different letters have significantly different means

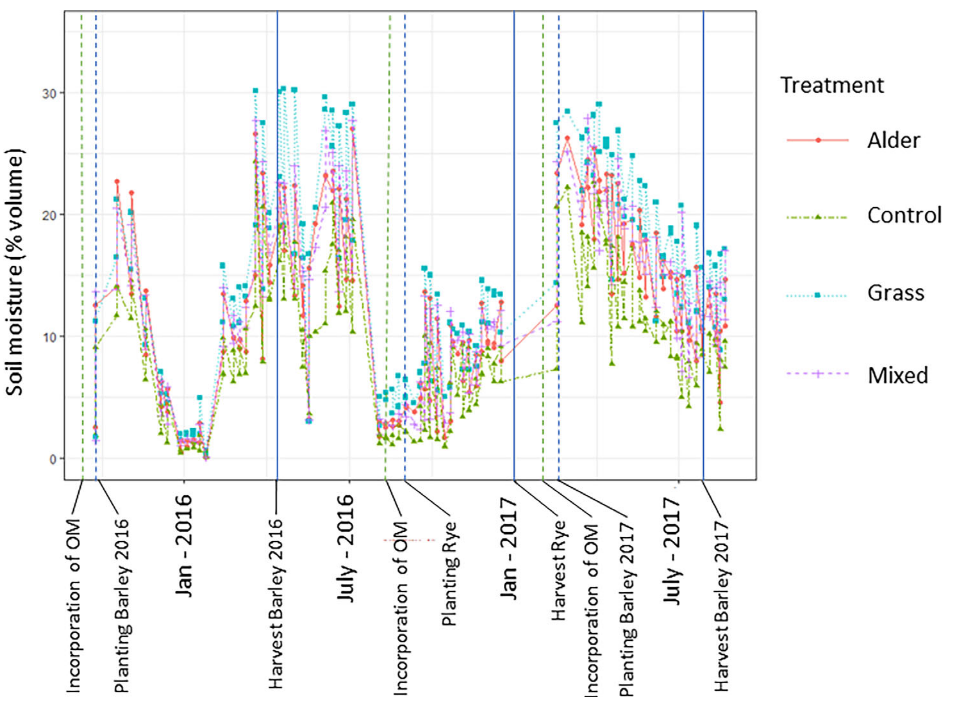

FIGURE 6 Timeline displaying mean soil moisture content measurements by treatment (control, Andean alder, mixed canary grass and Andean alder, and canary grass amendments), with key dates indicated

TABLE 2 Mean net changes[a] and standard errors (in parentheses) to soil chemical properties measured before (July 2015) and after the research period (July 2017) presented by treatment (control, Andean alder, mixed canary grass and Andean alder, and canary grass)

	Treatment			
Soil chemical property	Control	Alder	Mixed	Grass
SOC (%)	0.24b (0.06)	0.34ab (0.06)	0.37ab (0.06)	0.46a (0.06)
Total N (%)	0.03b (0.03)	0.03ab (0.03)	0.06ab (0.03)	0.06a (0.03)
Available P (mg kg^{-1})	4.76a (1.11)	4.90a (1.13)	4.90a (1.13)	5.59a (1.13)
Exchangeable K (cmol kg^{-1})	0.05d (0.04)	0.21c (0.04)	0.34b (0.04)	0.43a (0.04)
Exchangeable Ca (cmol kg^{-1})	1.58a (0.70)	2.55a (0.70)	2.57a (0.70)	1.58a (0.70)
Exchangeable Mg (cmol kg^{-1})	−0.42a (0.08)	−0.42a (0.08)	−0.44a (0.08)	−0.49a (0.08)

Note: Fisher's least significant difference test results are presented to the right of the mean net changes, with different letters different at the 5% significance level.

[a]Net changes are calculated based on the soil chemical component measurement before starting the experimental treatments and after the last experimental treatment was conducted (Barley, 2017).

4 | DISCUSSION

4.1 | Hedgerows impacts on erosion in agricultural fields

The hedgerows comprised canary grass and canary grass combined with Andean alder displayed significant potential to decrease soil water erosion (Figure 3). Canary grass strips reduced soil loss by about 60%, whereas the mixed canary grass and Andean alder hedgerow reduced soil loss by about 50% compared with the control. Our results corroborate past research demonstrating that grass strips can be highly effective in controlling erosion (e.g., Donjadee et al., 2010; Tesfaye et al., 2018; Wu et al., 2010; Xiao et al., 2012).

Perhaps more surprisingly, our results exhibited considerably less erosion than observed in other studies from the region. For example, Henry et al. (2013) using ^{137}Cs to estimate erosion at landscape level found average erosion rates of 27 Mg ha^{-1} yr^{-1}, whereas Molina et al. (2008) using direct measurements of accumulated sediment at 'checkdams' at the catchment level found similarly high erosion rates of 22 Mg ha^{-1} yr^{-1}. Erosion found in this study barely reached levels above 1 Mg ha^{-1} yr^{-1} in the control condition, which is similar to the estimated global average rate of soil formation (Pimentel, 2006).

Part of the reason why the levels of erosion observed in this study may have been low could be due to the fact that erosion was assessed at the plot level rather than at the landscape or catchment scale where greater slope lengths can contribute substantially to the erosive energy of overland flow (Kearney et al., 2017b), and water and sediment fluxes are interconnected leading to the possibility of greater erosion losses through gully erosion (Boix-Fayos et al., 2006). Furthermore, the current study also focuses on agricultural land uses, as opposed to other land uses also present in rural landscapes or catchments. In studies examining the effect of different land uses on erosion, it has been found that surface run-off on agricultural land is often low to minimal compared with other land uses, because high infiltration rates are often associated with cultivated soils (Harden, 2001; Harden, 1996; Molina et al., 2007). In a study in the Ecuadorian Andes using rainfall simulators, the compacted surfaces of paths and roads generated much greater run-off volumes, initiated greater run-off at lower rainfall intensities, and produced run-off sooner during a rain event compared with cultivated areas (Harden, 2001). Similarly, Molina et al. (2007), also working in the Ecuadorian Andes, found degraded and abandoned land to generate surface run-off within a few minutes after the start of the rainfall event, whereas surface run-off on arable land was rare. Another reason may be that the cotton filtration method used to remove the soil from the water in the sediment catchment trenches was not fine enough to trap all soil particles. Therefore, soil loss measurements may have been slightly lower from the erosion plots than the actual losses experienced. Notwithstanding this potential experimental bias, it is unlikely that any under-measurement can account for the magnitude of difference in soil erosion measured in the current study compared with those referenced above.

It is therefore important to use caution in extrapolating erosion data from plot level studies, such as this one, to the landscape scale (Boix-Fayos et al., 2006). Instead, the erosion measurements in this study should be taken as a relative measure of the potential for different types of hedgerows to control erosion in this particular context.

Further research is necessary to assess the hedgerows' potential for controlling other types of erosion processes such as gully erosion and erosion induced by animal-powered tillage. Tillage erosion has been shown to be particularly important in the region of study with soil loss figures in the southern Ecuadorian Andes reported to be between 30 and 186 Mg ha^{-1} yr^{-1} (Dercon et al., 2007). With regard to this type of erosion, another study conducted in Ecuador suggests that grass hedgerows similar to the ones assessed here do have the potential to reduce erosion, through the development of slow-forming terraces (Dercon et al., 2003). However, it should be pointed out that the development of such terraces cause important within field spatial variability in fertility, which implies the need for enhanced fertility management practices (Dercon et al., 2003).

It has been suggested that climate change will expose Andean agroecosystems to more extreme weather events, which in turn could potentially increase water erosion rates (Fonte et al., 2012; Kohler et al., 2014). In this event, erosion control techniques such as those assessed in this study may be important for building greater resilience to the effects of climate change. Furthermore, notwithstanding the low levels of erosion measured here at the agricultural plot level, it is clear that at the landscape level and under other land uses, the region is highly susceptible to erosion given findings from other studies (Harden, 2001; Harden, 1996; Henry et al., 2013; Molina et al., 2007, 2008). As such, we would argue that the use of mixed hedgerows and grass strips under agricultural land uses could play an important role in addressing land degradation caused by erosion, especially when employed more strategically, for example, by considering the overall landscape mosaic and interconnections between land uses. Further research in this regard would be particularly welcome to assess the efficacy of these hedgerows in controlling erosion in other contexts or land uses with greater susceptibility to erosion.

4.2 | Influences of organic amendments on soil fertility and productivity

As hypothesised, our results indicate that canary grass and mixed canary grass and Andean alder hedgerows and their associated organic amendments have the potential to increase soil productivity in terms of both overall biomass and grain yield when incorporated into the soil before planting (Figure 4a,b). This is an important, novel finding in this socioecological context as it suggests that resource-constrained farmers may be able to supplement limited organic agricultural inputs with amendments from canary grass strips to improve their productivity and overall resilience to climate change. The results reflect previous studies with vetiver grass in Africa, which was also shown to increase yields when used as a mulch (Babalola et al., 2007; Okeyo et al., 2014).

In contrast, alder-based organic amendments alone did not significantly improve soil productivity in the time frame of this study. This is surprising given that the scarce research on the use of alder leaf material as organic amendments suggests that it has the potential to increase soil nutrient levels and a range of other soil properties (de Valença et al., 2017; Swanston & Myrold, 1997). Moreover, chemical composition of the leaf material indicated that it was high quality (i.e., low C:N) and was composed of suitable levels of lignin (<15%) and phenols (<4%; Table 1), according to Palm et al. (2001). It is noteworthy, however, that phenols were at the high end (3.65%) of the acceptable levels for direct incorporation with annual crops. In cases with levels of phenols higher than 4% the decision-support tool of Palm et al. (2001) suggests mixing the organic resources with fertilizers or high-quality materials. Indeed, when the Andean alder leaves were mixed with canary grass, biomass production and grain yield were not significantly different to the canary grass alone treatment (Figure 4a,b), although it cannot be discounted that this effect was simply a result of the canary grass amendments included in the mixed amendments treatment. More research is needed to better understand this effect and the minimal quantities of organic amendments necessary to achieve significant improvements in soil productivity. Additionally, future research should consider the potential trade-offs with loss of productivity due to the use of hedgerows on agricultural land.

Although it is not possible with the current experimental design to assess whether the soil productivity improvements observed under the canary grass and mixed organic amendment treatments (Figure 4) were a result of the hedgerows themselves (e.g., through decreased erosion or additional belowground organic matter inputs from roots) or the organic amendments incorporated, it is likely that the additional nutrients these amendments provide (Tables 1 and 2 and Table S4) coupled with their ability to increase soil moisture (Figures 5 and 6, Table S4) are at least partly responsible for these improvements.

With regard to soil moisture levels average soil moisture levels were significantly higher in all three treatments receiving organic amendments compared with the control (Figures 5 and 6). In mountainous rain-fed agricultural systems, which are expected to experience more erratic precipitation patterns in the coming years (Kohler et al., 2014), application of such amendments may help resource-constrained farmers further build resilience to climate change beyond the use of the hedgerows as techniques to control erosion. Given the critical relationship between soil water storage, soil aggregation, and SOC (Bronick & Lal, 2005), the increased levels of soil moisture in the experimental conditions are likely a result of the increased levels of SOC incorporated through the organic amendments. SOC levels tended to increase in all treatments compared with the control, significantly so for the canary grass alone treatment (Table 2). These increased levels of SOC following the incorporation of in situ sourced organic amendments reflects the findings of Félix et al. (2018) who found that although the ramial woody amendments that they incorporated did not provide sufficient nutrients to balance the nutrient outflows, they did lead to higher yields and levels of SOC than the control condition. It is important to highlight that hedgerows and grass strips may not produce sufficient quantities of organic amendments to satisfy all carbon and nutrient input requirements (Félix et al., 2018). Indeed, it is unlikely that the quantities of the OM inputs used in this experiment (16.5 Mg ha^{-1} fresh weight) would be feasibly produced by hedgerows grown around an agricultural field, with a recent study suggesting that a different species of canary grass produced between 4.5 and 9.5 Mg ha^{-1} yr^{-1} dry matter (or around 30 Mg ha^{-1} yr^{-1} fresh weight; Pocienė et al., 2013). Instead, our results should be placed within the context of identifying farming practices that have the potential to increase overall access to carbon and nutrient resources as mechanisms to supplement rather than replace current input patterns. This potential is particularly useful in mountainous landscapes where the development of soil conservation practices such as slow-forming terraces can lead to important soil fertility gradients at the field level (Dercon et al., 2003). An increased access to organic amendments means that less fertile parts of the field may be targeted with additional inputs, although still being able to provide lower level inputs to the other areas. Moreover, the potential to harvest the amendments in situ may be able to address some commonly observed landscape scale fertility gradients, where far-fields receive fewer inputs than fields located closer to homesteads (Fonte et al., 2012; Vanek & Drinkwater, 2013).

Finally, although our results indicate that out of the three experimental conditions, canary grass strips performed the best both in terms of erosion control, soil humidity, and for improving soil productivity; on other metrics, it is likely that the other hedgerows would perform better. For example, mixed hedgerows and other agroforestry techniques with important ligneous components have been shown to be particularly valuable for C sequestration (Albrecht & Kandji, 2003; Palma et al., 2007; Takimoto et al., 2008), vegetative richness and diversity (Deckers et al., 2004; Kearney et al., 2017a; Smukler et al., 2010), and for supporting macrofauna abundance and diversity (Pauli et al., 2011; Rousseau et al., 2013). When factoring in these ecosystem components, it would appear that mixed hedgerows with canary grass and Andean alder may be optimal, providing the potential for erosion control, sources of organic amendments, C sequestration, and improved biodiversity. Furthermore, although it was not explicitly assessed in the current research, it would be important to investigate the possible competition between the hedgerows and crops grown for nutrient and water resources. For example, given that Andean alder trees have the potential to fix N, mixed hedgerows may perform better in the long term.

5 | CONCLUSIONS

Our results demonstrate that hedgerows comprised canary grass, and canary grass together with Andean alder have the potential to provide important benefits for small-scale farmers by minimising land degradation due to water erosion and by aggrading soils through the incorporation of organic amendments harvested from these hedgerows. The erosion control potential of canary grass strips and mixed canary grass and Andean alder hedgerows decreased water erosion in the plots by between 50% and 60%. However, we also found that annual erosion at the plot scale in agricultural fields was rather low suggesting that water erosion may not be the greatest driver of land degradation for agricultural land uses in this landscape or at this scale. Nevertheless, we argue that erosion control structures such as those tested in this study may be effective for other types of erosion, such as tillage or gully erosion, or adjacent to other land-use types that may experience greater erosion rates, although more research is necessary to assess these possibilities.

Canary grass and mixed canary grass and Andean alder leaf amendments increased both biomass production and grain yield in this study. Canary grass appears to be a particularly high-quality organic amendment being able to boost soil productivity by itself. Andean alder leaf amendments on the other hand, appear to be less effective, needing to be incorporated with higher quality organic material or composted. It is likely that the agricultural production benefits were, at least partly, a result of the nutrient inputs from the organic amendments as well as their ability to improve soil moisture levels by increasing SOC.

In conclusion, although hedgerows may not be able to produce sufficient quantities of organic resources to satisfy all nutrient input requirements, their potential to supplement existing inputs in a resource constrained socioecological context mean that they should be strongly considered as an option for improved agricultural management. Not only can these extra resources enable farmers to target additional inputs to low fertile areas within fields, but the potential to harvest the amendments in situ is an additional benefit to address commonly observed landscape scale soil fertility gradients where distant fields receive fewer inputs than fields located closer to homesteads.

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SUPPORTING INFORMATION

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