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Improved Pastures Support Early Indicators of Soil Restoration in Low-input Agroecosystems of Nicaragua

Emily Webster[1] · Amélie C. M. Gaudin[1] · Mirjam Pulleman[2,3] · Pablo Siles[4] · Steven J. Fonte[5]

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Abstract

Pasture degradation hinders livestock production and ecosystem services that support rural smallholder communities throughout Latin America. Silvopastoral systems, with improved pasture cultivars (especially *Brachiaria* spp.) and multipurpose trees, offer a promising strategy to restore soils and improve livelihoods in the region. However, studies evaluating the impact of such systems on pasture productivity and soil health under realistic smallholder constraints are lacking. We evaluated the impact of improved pasture grass and tree establishment on a suite of soil health indicators in actively grazed, low-input, farmer-managed silvopastoral systems. In August 2013, paired pasture treatments (improved grass with trees vs. traditional pastures) were established on nine farms with similar land-use histories near Matagalpa, Nicaragua. On each farm, one treatment was left as traditional pasture with naturalized grass (*Hyparrhenia rufa)*, while the adjacent treatment was sown with the improved grass (*Brachiaria brizantha* cv. Marandu) and planted with tree saplings without fertilizer. In August 2015, we measured standing biomass and a suite of chemical, biological, and physical soil health variables. Improved silvopastoral systems with *B. brizantha* produced more standing grass biomass and supported higher levels of earthworm populations and permanganate oxidizable carbon (POXC) compared to the traditional control. Correlations suggest that earthworms and POXC were associated with incipient improvements to soil aggregate stability and water holding capacity. We report measurable improvements to soil health just two years following the establishment of improved pasture systems under common smallholder management practices and suggest that these systems, even with minimal fertility inputs, have the potential to enhance regional sustainability.

Keywords *Brachiaria brizantha* · Earthworms · Pasture degradation · Permanganate oxidizable carbon · Silvopastoral systems · Soil health

Introduction

Pastures and grassland systems occupy an estimated 70% of the global agricultural land area (FAO 2008) and contribute to 40% of the global gross domestic product (GDP) from agriculture (Galdino et al. 2015). In Central America, 73% of agricultural land is dedicated to livestock production on pastures (Holman et al. 2004). Livestock production accounts for 39% of Nicaragua's agricultural GDP (Holmann et al. 2014). However, pastures in the dry corridor region, where 40% of the national cattle herd is maintained, face high levels of degradation (Szott et al. 2000) primarily due to overgrazing and sub-optimal nutrient management (Dias-Filho et al. 2001; Martinez and Zinck 2004).

Pasture degradation is characterized by reduced pasture grass productivity, discontinuous grass cover, invasion by weeds, and deterioration of soil biological, chemical, and physical properties (Martınez and Zinck 2004). For

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✉ Steven J. Fonte
Steven.Fonte@colostate.edu

[1] Department of Plant Sciences, University of California Davis, Davis, CA 95616, USA

[2] Centro Internacional de Agricultura Tropical (CIAT), Soils Research Area, AA 6713 Cali, Colombia

[3] Department of Soil Quality, Wageningen University, PO Box 47, 6700 AA, Wageningen, The Netherlands

[4] Centro Internacional de Agricultura Tropical (CIAT), Soils Research Area, Apartado Postal LM-172, Managua, Nicaragua

[5] Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80523, USA

example, Müeller et al. (2004) found that pasture degradation was closely related to decreased forage production and increased soil bulk density, while Alegre and Cassel (1996) found that overgrazing pastures decreased earthworm abundance. Others have suggested pasture degradation to impact soil organic matter (SOM) pools and overall soil fertility (Fonte et al. 2014). Therefore, soil degradation limits economic returns and important ecosystem services provided by grassland systems such as carbon (C) sequestration, soil and water conservation, and biodiversity habitat provision (Sala and Paruelo 1997).

Soil health has been defined as the capacity of a soil to function in maintaining (or enhancing) water and air quality, and promoting plant and animal health (Doran 2002). This concept integrates a range of physical, chemical and biological soil properties that vary with soil type, climate, land use, and management (Karlen et al. 2001; Lal 2015). In tropical pasture systems, soil physical health can be measured via aggregate stability, compaction, infiltration and water holding characteristics. Chemical properties associated with soil health include pH, cation exchange capacity (CEC), and nutrient availability of key limiting macronutrients (N, P, K). Additionally, SOM is a widely recognized and important driver of soil health, affecting chemical, biological and physical soil qualities and a range of soil-based ecosystem services (Cardoso et al. 2013), and may be especially relevant for long-term nutrient management in tropical pastures (Fonte et al. 2014). However, the functionality of SOM depends on the contribution of different soil C pools. For example, labile (or active) C pools commonly change more rapidly than total soil C (Culman et al. 2012) and are closely associated with nutrient mineralization and availability, making them sensitive indicators of short-term SOM stabilization and mineralization dynamics (Hurisso et al. 2016).

Soil macrofauna are also sensitive to soil management and ecosystem engineers (e.g. earthworms, termites, and ants), in particular, can greatly influence SOM turnover, nutrient cycling, and soil physical properties (Lavelle 1997; Rousseau et al. 2013). Their responsiveness to alterations in plant cover and other disturbances make macrofauna abundance and diversity valuable indicators of tropical soil health (Rosenberg et al. 1986; de Valença et al. 2017). Monitoring the response of such indicators to changes in soil management is valuable for providing early assessments of a land use system's capacity to improve soil health and reverse degradation.

As regional and global demand for livestock products continue to increase (McDermott et al. 2010), developing low-input management practices that promote pasture and livestock productivity while reversing degradation is a significant priority (Schroth and McNeely 2011). Research institutions within the tropics have developed sustainable intensification strategies for pasture systems that can simultaneously increase input use efficiencies and productivity per unit of land while minimizing soil erosion, creating positive SOM budgets, enhancing the activity and diversity of soil life, and improving soil structure and hydraulic properties (Rao et al. 2015; Lerner et al. 2017). For example, silvopastoral systems feature multipurpose tree species incorporated with improved pasture grasses such as *Bracchiaria* or *Panicum* spp., which exhibit faster growth rates and higher biomass production potential than naturalized grass species, such as *Hyparrhenia rufa* that was introduced from Africa in the 1800's and spread throughout the region (Garcia et al. 2018; Parsons 1972). In addition to their production value, the vigorous root systems of improved grasses aerate soils, increase SOM accumulation (Fisher et al. 1994) and help improve soil aggregation especially through root-derived aggregates and biopores (Velasquez et al. 2012). Trees within silvopastoral systems can provide multiple benefits including production of timber and non-timber products, increased shade for enhanced animal welfare (Broom et al. 2013), improvements in soil C storage and biological activity (Rousseau et al. 2013; Casals et al. 2014) and provision of high-quality fodder, which can increase meat and milk production and quality (Murgueitio et al. 2011). While fertilization is often recommended to maintain pasture productivity and cover (Vilela et al. 2001; Santos et al. 2015), these recommendations are seldom followed by smallholder farmers (Vera et al. 1998). Therefore, assessing the ability of improved pasture systems to restore degraded land under typical management scenarios (i.e., active grazing and low-inputs) is highly relevant to understand if such practices still offer benefits to soil health and overall farmer livelihoods.

The objective of this study was to utilize an on-farm approach to measure the impact of low-input, improved pasture system establishment (including the planting of multipurpose, agroforestry tree species) on pasture productivity and soil health indicators within working smallholder systems of the region. We sought to improve our understanding of linkages between soil biological, physical, and chemical properties in these systems and their value as early restoration indicators. We hypothesized that improved pasture systems would support increased aboveground pasture grass biomass and that this would be reflected in improvements to soil health.

Methods

Site Characteristics

This research was conducted in the central highlands of Nicaragua, approximately 160 km northeast of Managua

Table 1 Plot characteristics of traditional and improved pasture treatments on nine farms ($n = 18$) near San Dionisio, Nicaragua, sampled in August 2015

Farm	Treatment	Elevation (*m*)	Slope (%)	Soil Texture (% sand/%clay)	Tree Stand Basal Area ($m^2\ ha^{-1}$)	Average Stocking Rate ($kg\ day^{-1}$)
1	Improved	482	15	37/39	2.5	32
	Traditional	479	16	56/24	2.3	191
2	Improved	529	10	47/25	1.6	474
	Traditional	536	25	58/21	1.0	252
3	Improved	755	15	47/32	4.3	658
	Traditional	750	0	45/28	5.4	992
4	Improved	575	24	48/25	4.6	0
	Traditional	567	26	53/22	6.9	831
5	Improved	524	30	38/33	0.0	939
	Traditional	546	28	48/26	0.8	575
6	Improved	713	39	46/25	0.4	916
	Traditional	702	38	53/21	0.2	665
7	Improved	682	24	56/16	1.6	1899
	Traditional	707	36	50/23	1.0	1899
8	Improved	683	26	51/25	2.7	1899
	Traditional	688	11	48/27	3.7	1899
9	Improved	529	32	58/15	2.2	643
	Traditional	534	42	64/11	0.0	1440
	Treatment *p*-value	0.369	0.819	0.069/0.098	0.724	0.355

P-values are presented for treatment comparisons (traditional vs. improved pasture systems) across the nine farms

in the adjoined municipalities of Terrabona and San Dionisio within the Matagalpa Department (12°43′07.03′′ N, 85°55′08.01′′W). The region is largely dedicated to mixed crop-livestock systems with agricultural activities primarily focused on small-scale production of corn, beans, dual-purpose livestock (for meat and milk production), and coffee in the higher altitudes. With a sub-humid tropical savanna climate, average monthly temperatures vary between 22 and 25 °C and annual rainfall averages 1300 mm, with ~85% occurring between May and November (Magaña et al. 1999). Topography is dominated by hilly terrain, with slopes frequently greater than 20%, and elevations ranging from 479 to 755 m (Table 1). Soils are shallow and dominated by Entisols (Murillo and Osorio 1998) with predominantly sandy clay loam textures.

Experimental Design

In August 2013, pasture management treatments were randomly assigned to plots on nine farms with similar land use histories located along a 7 km transect. To address the anticipated high between-farm variability in soil properties, we use a randomized complete block design where treatments were assigned to adjacent pastures on each farm (i.e., block). Within each farm, two treatments were established in an area that had been under pasture for at least 6 years with naturalized grass species, varying levels of tree cover (based on preexisting management), and considered to be degraded by the farm owner. An area of 0.7 ha (7000 m^2) was left as traditional pasture, with the naturalized grass species *Hyparrhenia rufa*, while an adjacent area of equal size was sown with the improved *Brachiaria brizantha* cv. Marandu species and planted with trees. To establish *B. brizantha*, glyphosate was applied to the naturalized grass within the treatment area, and afterward seeds were planted at 50 cm by 25 cm spacing. Native tree species were selected for this study based on a participatory process with local farmers to understand preference and use of certain trees within pasture settings. Species including *Cedrela odorata*, *Samanea saman*, *Enterolobium cyclocarpum*, *Caesalpinia velutina*, *Cassia grandis*, and *Cordia alliodora* were selected as timber species, while *Gliricidia sepium*, *Guazuma ulmifolia*, and *Leucaena leucocephala* were included as forage and fuelwood species. Tree species were planted as saplings in April and May 2014, except for *G. sepium* which was propagated using cuttings. In total, 220 trees approximately 1 m tall were planted in each of the silvopastoral treatment plots to achieve a target density of 185 trees ha^{-1} (expecting 40% mortality). Of the planted 220 trees, 120 were timber species (20 individuals per species), while 100 trees were forage and fuelwood (40 *G. sepium*, 30 *G. ulmifolia* and 30 *L. leucocephala*). Planting distance between trees varied according to the presence of existing trees and shrubs at the time of establishment. Fertilizer inputs were not used (according to typical farmer practice) and plots were managed (e.g. weeding, grazing, pruning of trees) by the owner of each farm, with oversight from local International Center for Tropical Agriculture (CIAT) staff.

Soil and pasture biomass measurements were taken 24 months after pasture grass establishment (15 months after tree establishment) during the first 2 weeks of August 2015. Grazing was suspended for at least 15 days prior to field sampling in both treatment plots on all farms. At the time of sampling, each participating farmer was interviewed to gather information on grazing management for each treatment plot, including herd size and composition (i.e. number of calves, heifers, cows, horses) and grazing duration (number of days) for 2014 and 2015. Average daily cattle weight (kg) per plot over the two years was calculated using typical weights for livestock in each category (Table 1; RUTA 2012).

Standing Biomass, Ground Cover, Tree Stand Basal Area

Botanical composition and dry weight standing biomass volume in each plot at the time of sampling were evaluated using the Botanal method (Tothill et al. 1978). Briefly, visual rankings of biomass volume, species composition (% weeds vs. pasture grass), and ground cover (% vegetation cover, exposed soil, rock, plant residue) of 1 m^2 quadrants were made at 50 randomly located points within each plot. Sub-samples of points representing each biomass volume rank from lowest to highest were measured for height, cut to 1 cm above the soil surface, weighed separately, and oven-dried at 60 °C. A regression equation describing the relation between the dry weights and the volume rank was calculated, and used to determine pasture grass, weed and total dry weight standing biomass (Mg ha^{-1}). Ground cover for each treatment plot was determined by taking the average value of each ground cover category (% vegetation cover, exposed soil, rock, plant residue) across the 50 sampled points. The volume of existing and planted trees within each treatment plot was expressed as the stand basal area (SBA m^2 ha^{-1}), calculated by summing up individual basal areas for all trees with a diameter >2.5cm at breast height (1.3 m; West 2009).

Macrofauna Communities

To assess biological, physical and chemical soil health indicators, treatment plots ($n = 18$) were divided into four equal quadrants. Three of these were selected at random for subsampling ($n = 54$). Measurements were conducted within a 1.5-meter radius of the center of each selected quadrant.

In each selected quadrant and treatment plot, soil macroinvertebrate abundance and diversity were evaluated using an adapted version of the Tropical Soil Biology and Fertility (TSBF) method (Anderson and Ingram 1993). A monolith (25 cm × 25 cm × 20 cm deep) was excavated, including surface litter, and soil macroinvertebrates (>2 mm) were hand-sorted in the field and stored in 70% alcohol (or 4% formalin for earthworms). Individuals were then counted and identified to the family level (or subclass in the case of earthworms) for calculation of diversity indices and then grouped at the order level for reporting of abundance. Diversity was calculated using both taxonomic richness (S = number of taxonomic groups) and the Shannon Index (H; Shannon 1948), considering the number of unique taxonomic groups encountered across the three subsample points. Macrofauna abundance was averaged across the three subsample points and reported as individuals m^{-2}.

Aggregate Stability

Adjacent to each macrofauna pit, a soil sample (25 cm × 5 cm × 20 cm deep) was extracted and kept cool for aggregate fractionation. Field moist soil was passed through a 12 mm sieve by gently breaking soil clods by hand along natural fracture lines, and air-dried. Subsamples were separated into four water-stable size fractions: large macroaggregates (>2000 µm), small macroaggregates (250–2000 µm), microaggregates (53–250 µm), and the silt and clay fraction (<53 µm) according to Elliott (1986). In brief, soil size fractions were isolated by placing 50 g of the air-dried, 12 mm sieved soil on top of a 2000 µm sieve and submerging it in deionized water for slaking. After 5 min, the sieve was moved up and down in an oscillating motion for 50 cycles over a 2 min period. Soil remaining on the sieve (large macroaggregates) was rinsed into a pre-weighed aluminum pan. Material passing through the 2000 µm sieve was transferred to a 250 µm sieve and sieved for another 2 min in the same manner to isolate small macroaggregates. Material passing through the 250 mm sieve was then transferred to a 53 µm sieve and the process repeated once more to separate microaggregates from the silt and clay fraction. All fractions were oven-dried at 60 °C and mean weight diameter (MWD) was calculated following van Bavel (1950) by summing the weighted proportions of each aggregate size class.

Soil Compaction

Bulk density was measured, as an indicator of compaction, by inserting a ring (5 cm diameter) horizontally into the soil profile at 3–8 cm and 13–18 cm depths. Bulk density was calculated as the proportion of soil dry weight per fresh soil volume after correcting for stone content (>2 mm) according to Page-Dumroese et al. (1999). Average penetration resistance (PR) was also measured to 20 cm depth at four points located within 1 m of the macrofauna pit using a hand-held static cone penetrometer (Eijkelkamp, Model 06.01.SA, the Netherlands).

Infiltration and Water Retention

Gravimetric and volumetric soil water content were determined from the bulk density samples. Soil matrix infiltration capacity was measured using a Minidisk Tension Infiltrometer (Decagon Devices; 4.5 cm diameter and pressure head of −2.0 cm). For each measurement, a flat space was located and surface litter carefully removed to ensure full contact between the infiltrometer and the soil. Measurements were taken every 30 s over a 5-min period and unsaturated surface hydraulic conductivity (SHC) was calculated according to manufacturer guidelines (Decagon 2014). Plant available water (PAW%), generally understood as the difference in water potential between field capacity and permanent wilting point, of the soils (0–20 cm depth) was estimated based on equations proposed by Saxton et al. (1986), using values of soil texture, organic matter (calculated by multiplying organic C values by the van Bemmelen constant, 0.58), and bulk density at each sample point.

Soil Chemical Properties

Sub-samples of the 12-mm sieved and air-dried bulk soils were crushed and sieved to 2-mm and analyzed for texture (Bouyoucos 1951), pH (water, 2.5:1), effective cation exchange capacity (CEC; Thomas 1982), and available phosphorus (P; Olsen and Sommers 1982) at LAQUISA laboratory (Leon, Nicaragua), and for permanganate oxidizable C (POXC; Weil et al. 2003) at the University of California, Davis. POXC is considered a relatively active and/or labile pool of C that responds rapidly to changes in management and can reflect longer-term changes in total SOM (Culman et al. 2012). Additional sub-samples of bulk soil were ground and analyzed for total C and N by combustion using an Elementar Vario EL Cube or Micro Cube elemental analyzer at the University of California, Davis.

Statistical Analysis

Soil biological, physical, and chemical properties and associated sub-indicators were compared using ANOVA with pasture system as fixed variable and with the nine farms considered as blocks and treated as a random variable. Mean values of the three sub-sample points for each treatment plot were averaged to obtain one value per plot ($n = 18$) and statistical analysis were conducted on these means. Natural log and power transformations were applied as needed to meet the assumptions of normality and homoscedasticity. Bivariate regression analysis and Pearson correlation coefficient (r) were used to elucidate the relationships between earthworm abundance, soil properties, biomass and ground cover. Analysis was conducted using the Agricolae and lmerTest packages within the R environment (R Core Team 2015) and differences at $p < 0.05$ were considered significant.

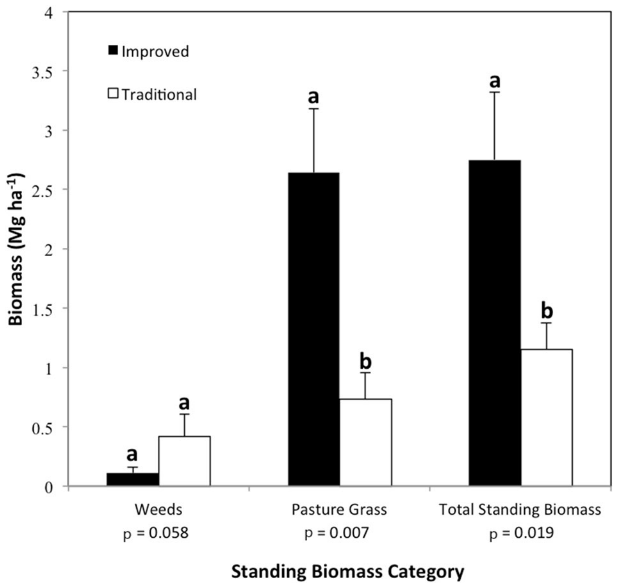

Fig. 1 Composition of standing pasture biomass production in traditional and improved pasture treatments on nine farms ($n = 18$) near San Dionisio, Nicaragua, sampled in August 2015. Error bars represent one standard error of the mean. Means in the same biomass category followed by the same letter are not significantly different by ANOVA ($p < 0.05$)

Results

Pasture Management and Production

Stocking rates varied considerably between farms but did not differ significantly between pasture treatments (Table 1; $p = 0.355$). Similarly, while tree stand basal area varied greatly by farm, significant differences between pasture treatments were not observed ($p = 0.724$). Total standing biomass of ground vegetation was 2.4 times greater in improved (2.75 Mg ha^{-1}) compared to traditional pastures (Fig. 1; $p = 0.019$). Improved pastures also had significantly higher levels of pasture grass contributing to the total standing biomass ($p = 0.007$). While weed biomass was nearly four times higher in traditional pastures, this effect was only marginally significant ($p = 0.058$). No significant treatment effects were observed on ground cover composition. Vegetation cover in improved pastures averaged 72% compared to 73% in traditional pastures, while exposed soil averaged 18% in improved pastures compared to 17% in traditional pastures. Plant residue and rock represented 5% each of ground cover in both treatments (data not shown).

Table 2 Mean abundance and density of prominent soil macrofauna taxa in traditional and improved pasture treatments on nine farms ($n = 18$) near San Dionisio, Nicaragua, sampled in August 2015

Macrofauna order or subclass	Common Name	Improved (Ind m^{-2})	Traditional (Ind m^{-2})	Density (% of total)	*p*-value
Oligochaeta	Earthworms	56.9 (*20.8*)	27.3 (*11.1*)	16.8	**0.028**
Araneae	Spiders	5.3 (*2.0*)	10.1 (*4.4*)	3.1	0.405
Chilopoda	Centipedes	5.3 (*3.6*)	2.4 (*1.6*)	1.5	0.488
Coleoptera	Beetles (adults & larvae)	42.1 (*7.6*)	35.0 (*6.2*)	15.4	0.544
Diplopoda	Millipedes	2.4 (*1.3*)	4.2 (*1.9*)	1.3	0.195
Diptera	Flies & mosquitoes (larvae)	5.3 (*2.2*)	1.8 (*0.9*)	1.4	0.563
Hemiptera	True bugs	3.6 (*1.8*)	7.7 (*2.2*)	2.2	**0.023**
Hymenoptera	Ants	88.0 (*33.3*)	102.0 (*25.4*)	37.8	0.458
Isopoda	Pillbugs, slaters	7.1 (*4.6*)	0.6 (*0.6*)	1.5	0.097
Isoptera	Termites (adults & larvae)	25.5 (*8.9*)	36.7 (*14.9*)	12.4	0.466
Lepidoptera	Butterflies & moths (larvae)	8.9 (*4.6*)	10.7 (*5.1*)	3.9	0.674
Species Richness (S)		7.6 (*0.8*)	7.4 (*0.6*)	–	0.796
Shannon Index (H)		1.8 (*0.1*)	1.8 (*0.2*)	–	0.826
Total Abundance		255.4 (*40.6*)	245.9 (*29.9*)	–	0.877

Values in parentheses and in italics represent the standard error of the mean

See supplementary Table 1 for groups representing less than 1% of overall density

Bold indicates significant at $p < 0.05$

Macrofauna Communities

A total of 66 macrofauna families were identified across 20 orders (Table 2). *Hymenoptera* (ants, 37.8%), *Oligochaeta* (earthworms, 16.8%), *Coleoptera* (beetles, 15.4%), and *Isoptera* (termites, 12.4%) were the most dominant taxonomic groups overall, representing 82.4% of all individuals. Improved pasture systems significantly increased earthworm abundance, with an average of 27.3 ind m^{-2} in traditional pastures compared to 56.9 ind m^{-2} in improved pastures ($p = 0.028$). Of the earthworms sampled, 95.1% were endogeic (identified by a lack of pigmentation), while 4.9% were pigmented and therefore likely anecic or epigeic taxa. Traditional pastures had more than twice the abundance of *Hemiptera* (true bugs) than improved pastures (7.7 vs. 3.6 ind m^{-2}; $p = 0.023$), but overall this group occurred in very low numbers. No significant differences were observed for other macrofauna groups.

Soil Chemical, Physical and Water Retention Variables

Establishment of improved pastures did not affect pH, CEC, C, N or available P, but significantly increased POXC ($p = 0.033$; Table 3). Among the soil physical variables, management had the most significant impact on estimated PAW %, which was significantly higher in improved compared to traditional pastures ($p = 0.048$; Table 3). While not significant, improved pastures tended to have slightly higher levels of gravimetric and volumetric water content at the time of sampling. Given the subtle differences in soil moisture, we also tested water content as covariate in the analysis of PR, but this factor was not significant and did not reveal significant treatments differences.

Relationships between Prominent Soil Parameters

Earthworm abundance was positively correlated with MWD (Table 4). POXC was positively correlated with total N, MWD, PAW, and vegetation cover, and inversely related to BD (0–10 cm). Calculated PAW was positively related to MWD and vegetation cover. Weed biomass volume was positively correlated with amount of bare soil (%) in each plot. Additionally, MWD was positively correlated with vegetation cover.

Discussion

The development of agroecosystems that sustain productivity and help to restore degraded soils in actively managed low-input pastures is a fundamental challenge for improving rural livelihoods throughout much of the tropics. Careful evaluation of alternative systems and improved

Table 3 Mean values of soil physical, chemical, and water retention variables in traditional and improved pasture systems on nine farms ($n = 18$) near San Dionisio, Nicaragua, sampled in August 2015

Soil Variables	Improved	Traditional	*p*-value
Chemical			
pH	6.43 (*0.08*)	6.41 (*0.08*)	0.794
C (g kg^{-1})	24.4 (*1.7*)	22.1 (*2.5*)	0.167
N (g kg^{-1})	2.79 (0.16)	2.32 (0.175)	0.898
POXC (mg kg^{-1})	779 (*47*)	678 (*59*)	**0.033**
P (mg kg^{-1})	6.22 (*1.56*)	5.28 (*1.20*)	0.127
CEC (MEQ 100 g^{-1})	41.7 (*2.74*)	40.4 (*2.89*)	0.533
Physical			
MWD (µm)	401 (*301*)	411 (*376*)	0.485
BD 0-10 cm (g cm^{-3})	1.06 (*0.03*)	1.09 (*0.02*)	0.515
BD 10-20 cm (g cm^{-3})	1.07 (*0.03*)	1.00 (*0.02*)	0.099
PR Avg 0-20 cm (mPa)	233 (*12*)	230 (*11*)	0.783
Water retention			
GWC 0-10 cm (cm^{3}H$_2$0 cm^{-3} soil)	0.281 (*0.023*)	0.271 (*0.021*)	0.667
GWC 10-20 cm (cm^{3}H$_2$0 cm^{-3} soil)	0.340 (*0.022*)	0.306 (*0.026*)	0.131
VWC 0-10 cm	0.296 (*0.021*)	0.293 (*0.020*)	0.900
VWC 10-20 cm	0.360 (*0.018*)	0.306 (*0.025*)	0.056
PAW (%)	12.3 (*0.4*)	11.1 (*0.6*)	**0.048**
SHC (mm min^{-1})	0.228 (*0.057*)	0.281 (*0.065*)	0.456

C total carbon, *N* total nitrogen, *POXC* permanganate oxidizable carbon, *P* available phosphorus, *CEC* cation exchange capacity, *MWD* mean weight diameter, *BD* bulk density, *PR* penetration resistance, *GWC* gravimetric water content, *VWC* volumetric water content, *FC* field capacity, *PAW* plant available water, *SHC* surface hydraulic conductivity

Values in parentheses and in italics represent the standard error of the mean

Bold indicates significant at $p < 0.05$

understanding of their impacts on soil health is critical for supporting restoration processes and informing management and policy decisions in smallholder agriculture. Our findings address the short-term restoration potential of improved pasture systems and suggest that small improvements to key soil chemical (POXC), biological (earthworm abundance), and physical (PAW%) components of soil health can be detected within two years after establishment.

Primary Production Impacts on Ecosystem Services

The observed increase in aboveground biomass production with improved pasture establishment compared to naturalized grass species supports previous findings (Andrade et al. 2008; Santos et al. 2015; Garcia et al. 2018). We note that the farmers participating in this study identified greater productivity and resilience to drought as key advantages of the improved pasture systems considered here. Similarly, participatory evaluations of improved pasture varieties elsewhere in the region found that farmers favored *Brachiaria* grass species for their growth, soil cover, color, and perceived palatability (Garcia et al. 2018). These benefits highlight why farmers are willing to adopt improved pasture grass cultivars (Holmann et al. 2004).

We also note that weed pressure was greatly reduced in improved pastures, likely due to increased vigor of *Brachiaria*. This is important since colonization by less desirable species likely yields inferior quality forage and is often cited as a stage in the pasture degradation process (Dias-Filho et al. 2001). The positive correlation between weed production and exposed soil highlights the importance of maintaining vegetation cover to prevent colonization of undesirable species. We note that significant differences in tree stand basal area and density (of trees >2.5 cm at breast height) were not detected at the time of sampling, and thus, trees are not likely to be responsible for observed differences between the treatments. However, we suspect that as the agroforestry system becomes more established the trees planted will begin to exert a greater influence on soil and ground vegetation characteristics.

Greater vegetation cover was positively correlated with estimated plant available water (Table 4), a trend which has been reported in other grazing systems (Alegre and Cassel 1996; Martınez and Zinck 2004), likely due to extensive root biomass and structure of the pastures. Standing biomass and plant litter can also enhance infiltration by mitigating raindrop impact on the soil surface, while reducing erosion and runoff (Sepúlveda and Nieuwenhuyse 2011). Therefore, increased primary productivity and water holding characteristics exhibited by the improved pasture treatments indicate an enhanced potential for improved water dynamics and erosion control.

While greater aboveground biomass is critical for forage production, reducing weed competition and erosion control, it is also a source of belowground inputs that, in turn, enhance production. In tropical pastures grazed by ruminants, rates of nutrient utilization are usually 10-40% (Wetselaar and Ganry 1982), and return of plant nutrients to the soil via litter is usually greater than returns via excreta (Thomas 1982). Thomas and Asakawa (1993) found improved pasture species (e.g., *Brachiaria* or *Panicum*) to have higher biomass N content and decompose more rapidly than naturalized species. Additionally, while roots were not measured in this study, others have found that root biomass for *B. brizantha* is greater than *H. rufa* (Andrade et al. 2008) suggesting that improved pastures can provide substantial nutrient inputs through their root systems (Fisher et al. 1994). Larger biomass inputs provide living tissues, an additional source of carbon (C) for belowground communities, which facilitates nutrient availability and cycling. Increased biomass, residue return and high-quality forage in improved

Table 4 Pearsons correlations between predominant soil variables under degraded and improved pasture treatments on nine farms ($n = 18$) near San Dionisio, Nicaragua, sampled in August 2015

Variable	POXC	C	N	MWD	BD 0–10 cm	PAW	Worms	Grass biomass	Weed biomass	% Veg cover	% Bare soil	Clay (%)
POXC	1											
C	0.89^{a}	1										
N	0.86^{a}	0.98^{a}	1									
MWD	0.64^{a}	0.50^{b}	0.47^{b}	1								
BD 0–10 cm	-0.66^{a}	-0.76^{a}	-0.74^{a}	−0.34	1							
PAW	0.86^{a}	0.83^{a}	0.85^{a}	0.71^{a}	-0.63^{a}	1						
Worms	0.46	0.27	0.25	0.58^{b}	−0.02	0.37	1					
Grass biomass	0.26	0.35	0.44	0.02	−0.07	0.32	0.31	1				
Weed biomass	−0.20	−0.14	−0.17	−0.12	−0.12	−0.08	−0.32	−0.29	1			
% Veg cover	0.66^{a}	0.51^{b}	0.41	0.50^{b}	−0.45	0.52^{b}	0.39	0.12	−0.31	1		
% Bare soil	-0.51^{b}	−0.35	−0.28	−0.40	0.14	−0.36	−0.38	−0.02	0.57^{b}	-0.84^{a}	1	
Clay (%)	0.44	0.50^{b}	0.47	0.33	−0.43	0.55^{b}	0.42	0.38	−0.14	0.44	−0.30	1

POXC permanganate oxidizable carbon, *C* total carbon, *N* total nitrogen, *MWD* mean weight diameter, *BD* bulk density, *PAW* plant available water

[a] Significant at $p < 0.01$

[b] Significant at $p < 0.05$

pastures provide adequate livestock nutrition (Peters et al. 2013) and help maintain critical ecosystem services necessary to develop productive low-input pastures.

Implications for Belowground Properties

Improved pasture treatments produced relatively small, albeit important changes to key soil properties, indicating early signs in ecosystem restoration. Improved pastures appeared to support earthworm populations, which are sensitive to changes in their environment and soil conditions including amounts and quality of organic matter inputs, pH, soil moisture and temperature (Lee 1985; Edwards and Bohlen 1996). The significant increase in earthworm density may be due to the increased quality and quantity of organic matter provisioned by *B. brizantha*, as organic matter is an essential resource for earthworms (Ampoorter et al. 2011; Velásquez et al. 2012). Others have shown that availability of high-quality (N-rich) organic matter contributes to increased earthworm abundance and growth rates (García and Fragoso 2003; Velásquez et al. 2012). Recent literature suggests that glyphosate-based herbicides can reduce the activity and reproduction of earthworms (García-Pérez et al. 2014). However, others have suggested that these effects are more likely to be an issue for surface feeding earthworms (i.e., epigeics and anecics) and less of a problem for the endogeic earthworms that dominated our study (Gaupp-Berghausen et al. 2015). We note that even if earthworms were affected by glyphosate application during the establishment of *B. brizantha* pastures, this only reinforces the notion that earthworms are early indicators of soil restoration because this treatment supported considerably higher earthworm abundance.

Besides being sensitive indicators of soil change, earthworms are ecosystem engineers that can greatly affect a range of soil health parameters. Through their burrowing, consumption, and excretion activities, earthworms enhance soil porosity, hydraulic conductivity and infiltration (Andriuzzi et al. 2015), impact nutrient turnover and movement (Fonte et al. 2010) and facilitate the incorporation of SOM into the soil and the formation of macroaggregates (Scullion and Malik 2000; Fonte et al. 2007). The correlation between earthworms and aggregate stability (MWD) suggests that earthworms are beginning to drive improvements to soil structure. Greater rooting capabilities of *B. brizantha* compared to the naturalized grass (Andrade et al. 2008) likely contribute to increased levels of rhizosphere aggregates and plant available water (Fonte et al. 2014), as evidenced by the correlations between water holding properties and MWD with vegetation cover. Therefore, the combined impact of pasture grass and earthworms likely enhance a range of key soil properties that support improved soil structure and water dynamics which contribute to the restoration of these soils. We note that the most abundant *Hemiptera* taxa were *Pentatomidae*, *Thyreocoridae*, and *Reduviidae* (data not shown), which are characterized as herbivores known to feed on and live in the reproductive parts of host plants (Panizzi and Grazia 2015). While abundances were significantly higher in traditional pastures, the overall density of this group was low (Table 2) and the observed differences are likely not to be too important.

Improved pastures demonstrated significantly higher POXC, which has been identified as a sensitive indicator of management-induced changes in SOM (Culman et al. 2012) and a good predictor of SOM stabilization relative to other soil C fractions (Hurisso et al. 2016). POXC plays a significant role in key soil functions, such as nutrient cycling and availability, microbial N turnover and supply, soil aggregation, and soil C accumulation (Weil and Magdoff 2004). Improved pastures likely supplied a more continuous deposition of organic matter in the form of leaf litter and roots, which would provide labile C inputs to stimulate microbial activity and nutrient cycling (Geraei et al. 2016). The positive correlation between POXC and vegetation cover and its inverse correlation to exposed soil further illustrates the importance of greater primary production on POXC. POXC was positively linked to aggregate stability (MWD) and inversely correlated to compaction (BD) of the topsoil. This suggests a close connection between soil physical health and labile carbon. Similar results were found by Stine and Weil (2002), who reported that POXC was positively correlated with macroaggregates (1–4 mm) and porosity (the inverse of BD) across fields under different tillage systems in Honduras. This trend supports the idea that soil C influences soil functional properties, which in turn have the potential to affect a range of soil-based ecosystem services.

It should be noted that many of the variables we measured did not change in the short time frame considered in this study and this is to be expected for soil parameters such as pH, total C and N, CEC, and compaction, which are known to change over relatively longer time intervals and with more extreme management shifts. Furthermore, the limited number of farmers considered in this study (nine total) may have inhibited our ability to detect more subtle changes in soil parameters, due to a lack of statistical power. As mentioned above, we suspect that changes in soil parameters would become more evident with time, especially with the establishment of trees in the improved pastures and continued degradation of the traditional pastures.

Implications for Pasture Restoration Efforts

Improvements in primary production and subsequent impacts on sensitive soil health indicators (macrofauna, POXC) indicate that low-input improved pastures have the potential to make short-term advances in reversing degradation. Correlations between these sensitive indicators and additional properties of soil health (MWD, BD 0–10 cm, PAW) are also apparent, but more time may be needed for additional treatment effects to materialize. Additionally, the young nature of these agroforestry systems is reflected by a lack of significant differences in SBA and the small size of the planted trees at the time of sampling, with many of them not yet reaching 2.5 cm at breast height. We suspect that with additional time these trees will become more established and produce significant effects on a range of soil properties (Rousseau et al. 2013; Casals et al. 2014). Previous research has evaluated pasture restoration with fertilized treatments and suspended grazing (Santos et al. 2015), but few have examined restoration potential under actively grazed pastures with minimal inputs. Our results indicate that even without fertilizer additions and under active grazing, improved pasture systems with *B. brizantha* produced sufficient biomass to initiate improvements in key biological, chemical, and water holding properties. These findings provide evidence that strategies for restoration and intensified production may not be mutually exclusive, which is important in ensuring the economic feasibility of such practices for smallholder farmers of the region. Despite these promising results, management factors ultimately play a significant role in determining long-term pasture productivity. Further study of the long-term impacts on indicators of soil health and pasture grass production under continued grazing of unfertilized pastures is important as this remains a common practice in smallholder tropical pasture systems. Research has emphasized the need for maintenance fertilizer and appropriate stocking rates to sustain *Brachiaria* pastures (Vilela et al. 2001). Therefore, evaluating the effects of fertilization and appropriate stocking rates in future research efforts will be helpful in formulating management recommendations that promote sustained productivity and restoration efforts in the long-term.

Conclusion

Restoring degraded tropical pastures is critical for ensuring the sustained provision of ecosystem services and farmer incomes. Our research confirms that earthworm populations and labile carbon (POXC) are sensitive indicators of early restoration efforts and are useful variables for restoration monitoring, especially given their roles in subsequent improvements to soil structure and water holding dynamics. This in turn may lead to greater and more consistent forage production, creating a positive soil-plant feedback cycle for maintaining long-term productivity of low-input pasture systems. While careful fertility and grazing management are likely important for long-term pasture restoration and productivity (Vilela et al. 2001), our findings indicate that short-term improvements to soil health variables are possible under low-input and active grazing management practices common to smallholder farmers of the region.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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