Biochar and legumes improve pastures in Brazil: environmental and socioeconomic analysis of three forage grasses in a field experiment

Agnieszka E. Latawiec (a.latawiec@iis-rio.org)
Department of Geography and Environment - Rio Conservation and Sustainability Science Centre, Pontifical Catholic University of Rio de Janeiro, R. Marquês de São Vicente, 225, Gávea, Rio de Janeiro, 22451-000, Brazil https://orcid.org/0000-0003-3036-1870

Aline F. Rodrigues
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

Katarzyna Anna Korys
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

Maiara S. Mendes
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

Marcio Rangel
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

Ana Castro
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

Wenceslau Teixeira
Empresa Brasileira de Pesquisa Agropecuária (Embrapa Solos), R. Jardim Botânico, 1024 - Jardim Botânico, Rio de Janeiro - RJ, 22460-000

Judson F. Valentim
Empresa Brasileira de Pesquisa Agropecuária (Embrapa Acre), Rodovia BR-364, Km 14, Rio Branco - Acre, Brazil, CEP: 69900-970

Ednaldo Araujo
Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agrobiologia), Rodovia BR-465, Km 7, Bairro Ecologia CEP: 23891-000 - Seropédica – RJ

Luiz Fernando Duarte de Moraes
Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agrobiologia), Rodovia BR-465, Km 7, Bairro Ecologia CEP: 23891-000 - Seropédica – RJ

Vinicius Pacheco
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Marcos Mendes
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Cristiano della Picolla
Universidade do Estado de Santa Catarina, Chapeco, Santa Catarina, Av. Madre Benvenuta, 2007, Itacorubi, Florianópolis / SC, 88.035-901 Brazil.
Bernardo Strassburg
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Maciej Kubon
Department of Production Engineering, Logistics and Applied Computer Science, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Poland
Adam Drosik
Faculty of Political Sciences and Social Communication, Department of Social Communication and Journalism, University of Opole, Katowicka 89, 46-061 Opole
Fernanda Gomes
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Brian Reid
School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK
Joana Krieger
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Viviane Dib
International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil
Dariusz Zarzly
Faculty of Electrical Engineering, Automatic Control and Informatics, Opole University of Technology, Prószkowska street 76, 45-758 Opole, Poland

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Research Article

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Authors: Agnieszka E. Latawiec[1,2,3,4*], Aline F. Rodrigues[2], Katarzyna Anna Korys[2], Maiara Mendes[2], Marcio Rangel[2], Ana Castro[2], Wenceslau Teixeira[5], Judson F. Valentim[6], Ednaldo Araujo[7], Luiz Fernando Duarte de Moraes[7], Vinicius Pacheco[2], Marcos Mendes[2], Cristiano della Picolla[8], Bernardo Strassburg[2], Maciej Kubon[9], Adam Drosik[10], Fernanda Gomes[2], Brian Reid[4], Joana Krieger[2], Viviane Dib[2], Dariusz Zarzly[11]

1- Department of Geography and Environment - Rio Conservation and Sustainability Science Centre, Pontifical Catholic University of Rio de Janeiro, R. Marquês de São Vicente, 225, Gávea, Rio de Janeiro, 22451-000, Brazil

2 -International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro, 22460-320, Brazil

3 - Faculty of Mechanical Engineering, Opole University of Technology, Mikołajczyka 5, 45-271 Opole, Poland

4 -School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK

5 – Empresa Brasileira de Pesquisa Agropecuária (Embrapa Solos), R. Jardim Botânico, 1024 - Jardim Botânico, Rio de Janeiro - RJ, 22460-000

6 - Empresa Brasileira de Pesquisa Agropecuária (Embrapa Acre), Rodovia BR-364, Km 14, Rio Branco - Acre, Brazil, CEP: 69900-970

7- Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agrobiologia), Rodovia BR-465, Km 7, Bairro Ecologia CEP: 23891-000 - Seropédica – RJ

8 – Universidade do Estado de Santa Catarina, Chapeco, Santa Catarina, Av. Madre Benvenuta, 2007, Itacorubi, Florianópolis / SC, 88.035-901 Brazil.

9 - Department of Production Engineering, Logistics and Applied Computer Science, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Poland

10 - Faculty of Political Sciences and Social Communication, Department of Social Communication and Journalism, University of Opole, Katowicka 89, 46-061 Opole

11- Faculty of Electrical Engineering, Automatic Control and Informatics, Opole University of Technology, Prószkowska street 76, 45-758 Opole, Poland

***Corresponding author. E-mail address:** a.latawiec@iis-rio.org (A.E. Latawiec)

Abstract

Pasturelands, often degraded, represent most of the converted lands globally. Here we present the results from a field experiment in Brazil where we tested the impact of different soil enhancers on soil quality and productivity of three tropical forages grasses: *Brachiaria (Syn. Urochloa) brizantha* cv. Marandu, *Brachiaria brizantha* cv. BRS Piatã, and *Brachiaria brizantha* cv. BRS Paiaguás. Soil enhancers included: biochar - a carbon-rich product from biomass pyrolysis, moinha, a local charcoal residue, traditional fertiliser containing nitrogen, phosphorus and potassium, lime and forage peanut (*Arachis pintoi* cv. Amarillo). Independent of treatment and *Brachiaria* cultivar, dry matter tended to be greatest in the first harvesting period, decreasing sharply in the second. Considering the total biomass produced over the experiment (sum of four harvests), the highest production (dry biomass) was for Piatã cultivar (14.07 Mg ha^{-1}; treatment with the biochar application rate of 30 Mg ha^{-1}). For Marandu and Piatã, the highest forage biomass increases were observed with the treatment that included biochar at the rate of 30 Mg ha^{-1}. Marandu and Piatã yields generated an income of U$ 1,291 per year and U$ 1,183, respectively. For Paiaguas, the treatment that generated the greatest yield increase was forage peanut forage + 15 Mg ha^{-1} with its total income peak at U$ 991. The results reflected positive changes in soil characteristics such as improvement in cation exchange capacity, pH and nutrient contents. This research was developed in collaboration with the landowners within a bottom-up approach. Views of the landowners regarding land management are included in the discussion. Improved management of tropical pasturelands holds opportunity for more sustainable food production and also ecosystem services protection and recuperation, for example, biodiversity net-gain, water regulation and carbon sequestration.

Key words: biochar, forage peanut, sustainable agriculture, pasturelands, farmers, bottom-up approach

1. Introduction

Degraded and low-productivity pasturelands prevail globally: 80% of agricultural land is dedicated to feed and livestock production but provides less than 20% of the world's food calories (UNCCD, 2022). Degradation of pastures, both planted and natural grasslands drives the decline of their productivity due to poor herd, vegetation or soil management (Feltran-Barbieri and Féres, 2021). Global growth in meat consumption is projected to increase by 14% by 2030 compared to the 2018-2020 base-period average (OECD / FAO, 2021) and along with this increase, the pressure on new production areas is likely to be exacerbated (OECD / FAO, 2015). The advancement of the agricultural frontier, mainly in developing countries in the tropical region, may cause the loss of native forest areas that provide key local and global ecosystem services (Rodrigues et al., 2021).

Brazil is covered by around 160 million hectares of pastures, mostly degraded (Strassburg et al., 2020). In particular, barren abandoned pastures dominate the Atlantic Forest biome. Typically, farmers in this region do not apply fertilisers, soil improvers or rotational grazing (Bertossi et al., 2016; Rocha Junior et al., 2016). Since pasturelands provide a range of products ecosystem services such as meat production and carbon sequestration (Lal, 2004), it is important to understand how different pasture management approaches can increase feed production and soil carbon stocks. Brazil is an important producer and exporter of beef, accounting for almost 20 percent of the world's beef exports, and has the second largest herd of cattle in the world. The country is projected to continue its export growth trajectory over the next decade, reaching 2.9 million metric tons, or 23 percent of total global beef exports by 2028 (USDA, 2019). However, despite its socio-economic importance, the domestic livestock sector, largely based on grass grazing systems, performs well below its potential (Feltran-Barbieri and Féres, 2021; Strassburg et al., 2014).

Biochar is a carbon-rich organic material obtained from biomass by pyrolysis. Biochar may increase agricultural productivity, aid soil restoration and carbon sequestration (Lehmann and Joseph 2009; Castro et al., 2018; Latawiec et al., 2019; Blanco-Canqui et al., 2020; Han et al., 2022). Among soil amendments, biochar is distinguished by its ability to rapidly increase soil carbon sequestration thus contributing to the mitigation of climate change (Blanco-Canqui et al., 2020).

The use of biochar to increase pasture productivity in the tropics has been reported to be promising. Slavich et al. (2013) reported that biochar from feed manure increased pasture productivity by 11%, while Latawiec et al. (2019) showed an average increase of 27% over two years in the production of *Brachiaria brizantha* cv. Marandu, a forage grass commonly used in Brazilian. Meta-analysis by Jeffery et al. (2017) showed that biochar causes an average yield increase of 25% in the tropics. The authors concluded that the effect of increasing biochar yield may be particularly beneficial for agriculture in tropical, nutrient poor and acidic soils. However, studies that investigate the use of biochar to improve fodder grass performance and reduce the negative effects of cattle grazing in tropical regions are still scarce.

Herein the effect of different soil enhancers to improve degraded pasture was evaluated as applied to three different forage grasses in a field experiment in Brazil. The species of the grasses were selected based on the results from our previous experiment (Latawiec et al., 2019), which showed an increased *B. brizantha* Marandu productivity following biochar application. We have now extended this research within a participatory approach together with the landowner on which field the experiment was conducted. The research had three objectives: i) to evaluate forage grass productivity in response to the soil enhancers, ii) to investigate changes in soil and biomass parameters depending on the treatment, and iii) to evaluate the financial benefit to the farmer as ascribed by changes in yield. To our knowledge this is the first study that comprehensively assesses a range of different soil enhancers in pasturelands. The insights gained will contribute to better decision-making by farmers and policymakers that will support improved and more sustainable pastureland management.

2. Material & Methods

2.1 Study site

Field study was conducted in the municipality of Itaguaí, state of Rio de Janeiro - Brazil (22°49'30" S; 43°42'0" W), between November 2015 and March 2017. The climate is tropical rainy with dry season in winter (As) according to Köppen's classification. The average annual temperature ranges from 24 °C to 35 °C, and the average annual precipitation is around 1,300 mm. See supplementary materials (supplementary figure1) for the rainfall and solar radiation during the experiment. The predominant soil in the region is Planosol (de Carvalho et al., 2003).

2.2 Experimental design

This experiment builds upon Latawiec et al. (2019; that reported an increase in the yield of fodder grass *Brachiaria brizantha* cv. Marandu in a pot experiment using biochar) at a field scale. Furthermore, the current research reflected real-world land management relevant to farmers and extended the research to consider a range of grasses commonly used or of interest of farmers. Thereby, we examined *B. brizantha* cv. BRS Piatã, which is used by the owner of the property where the experiment was undertaken, *B. brizantha* cv. Marandu, a forage grass popular in many tropical regions and *B. brizantha* cv. BRS Paiaguás a new drought resistant variety that the landowner was interest to investigate. The experiment consisted of 81 experimental plots. These plots represented each forage grass under the following regimes: control, moinha milled char (type of charcoal, used by the local farmers to enrich soil in carbon and improve soil water retention), limestone, limestone + NPK fertilizer, biochar (15 Mg ha^{-1}), forage peanut (*Arachis pintoi* cv. Amarillo), forage peanut + limestone, forage peanut + biochar (15 Mg ha^{-1}) and biochar (30 Mg ha^{-1}). Each regime was replicated three times for each grass. The harvested grass and soil were collected and measured four times during the 14 months of the experiment (dates are available in supplementary material table1). The management of pasture height and grazing intervals adopted in this study followed practices adopted by the local farmers. The animals were not allowed to graze on the area between forage biomass harvests.

2.3 Biochar production

Gliricidia sepium (Jacq.) Kunth ex Walp., family Fabaceae was used as a feedstock to produce biochar. In the study region, this species must be systematically cut, providing large amounts of organic residue. *G. sepium* has a high biomass production capacity in different tropical conditions up to 800 m altitude. Being a perennial and easily cultivated plant for green manuring (N2 fixation) and mulching, *G. sepium* thicker stalks can be used for biochar production as they often do not have alternative use and may cause undesired shadow for the growth of other plants. *G. sepium* tolerates frequent pruning of about four times per year. A simple 200 l brass kiln was used to produce the biochar. Kiln capacity was 70kg of raw Gliricidia biomass and biomass to biochar efficiency was 30% (see supplementary figure 2 for the photos and details of the kiln). The pyrolysis lasted approximately 10 hours with temperatures around 400 °C. After cooling, biochar was grounded and sieved (< 2 mm) for homogenisation. Biochar was analysed by solid state 13C NMR spectroscopy. Spectra was obtained on a Varian INOVA (11.74 T) spectrometer with 13C and 1H frequencies of 125.7 and 500.0 MHz, respectively. The biochar was considered stable, resilient, and low charge (Latawiec et al., 2019). Carbon content was 60%, H was 2.2% and N was 0.60%.

2.4 Biomass analysis

Forage yield of the experiment was evaluated by summing total aboveground dry matter produced by three *Brachiaria brizantha* cultivars over four harvests. Aboveground biomass after each harvest (keeping five cm of forage for regrowth) was assessed for the wet weight, and again after drying in the oven for 96 hours (at 60° C). We collected 200 g of wet weight of each treatment after each harvest to evaluate the concentration of macronutrients (P, K, Ca, Mg and S, in g kg^{-1}) and micronutrients (Cu, Fe, Mn, and Zn) following the protocol by Malavolta et al. (1997). In brief, N determination was performed through sulfuric solubilization, in which 0.2g of dry sample was used for digestion in 50ml. Acid sulfate mixture was added (15ml) and digestion proceeded for 1 hour in a digester block, with the temperature up to 335°C. Then, the samples were cooled for complete digestion of organic matter and the N content was determined.

2.5 Soil sampling and analysis

Soil samples were collected and analysed at harvest times. The soil samples were homogenized and sieved at 2 mm, and analysed for pH (in H_2O, KCl and $CaCl_2$), organic matter (dag / kg), total N (g / kg), total K (mg / dm^3), total P (mg dm^3), residual P (mg / l), remaining P (mg / l), available Mg (cmol / dm^3), H + Al (cmol / dm^3), Na (mg / dm^3), Ca (cmol / dm^3), SB (cmol / dm3), Cation Exchange Capacity - CEC (effective and potential; cmol / dm3), Zn (mg / dm^3), Fe (mg / dm^3), base saturation - v (%), aluminium saturation - m (%), Mn (mg / dm^3), Cu (mg / dm^3) and soil particle sizes following the methodology from Latawiec et al. (2019). Soil pH values were measured in water (pH H_2O), 0.01 M $CaCl_2$ (pH $CaCl_2$) and 1 M KCl (pH KCl) at 1:2.5 soil/water or solution ratio (Embrapa, 1997). Organic matter was extracted through a solution of $NaCr_2O_7$ and H_2SO_4 (Quaggio and Raij 1979). Potassium (K), Phosphorus (P), residual and remaining P, sodium (Na), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) were extracted by Mehlich^{-1}. Magnesium (Mg) and calcium (Ca) were extracted with 1.0 mol l^{-1} KCl and determined by atomic absorption spectrophotometry. Based on K^+, Ca^{2+}, Mg^{2+}, Al^{3+} and H+Al contents, we calculated sum of bases (SB), potential (T) and effective (t) CEC, base saturation (V) and aluminium saturation (m) indexes according to Embrapa (1997). Total nitrogen was determined using the Kjedahl method. Water holding capacity (undisturbed soil sample ~ 100cc) were equilibrated in the potentials of 0, 3, 6, 33, 1500 kPa in Richards pressures chambers and the volumetric soil moisture determined gravimetrically and transformed to volumetric soil water content. The moisture at 10 kPa were recovered by adjusting the measured data (0, 6, 33 and 1500 kPa) to the van Genuchten (VG) equation (van Genuchten, 1991) then using VG equation to estimate the moisture at 10 kPa. The available soil water was calculated as the difference between volumetric water content at 10kPa minus the volumetric water content at 1500kPa (more detail in supplementary methods 1).

2.6 Statistical analysis

Dry biomass production resulting from the sum of the four harvests was tested in terms of residual normality and homogeneity of variances given by Shapiro-Wilk and Bartlett tests, respectively, followed by F-test and ANOVA ($p<0.05$) (supplementary table 2). When F-test detected significant differences, data was submitted to the Tukey test to compare means (α = 0.05). For the analyses of multivariate data (biomass nutrient concentration and soil parameters), performed Principal Components Analysis (PCA) was performed on each dataset (after treating the presence of outliers, centring and standardizing the variables). A generalized linear model (GLM) was used to evaluate the statistical difference between the treatments and tested their significance after assessing the residuals of this analysis. For the biomass nutrient concentrations, the two most relevant nutrients for each axis were used to analyse their course through time. All analyses were performed in R (R Development Core Team, 2018), using packages easyanova, dplyr, stats, hnp, ggplot2 and ggfortify. The dataset of 0, 3, 6, 10, 33 and 1500 and AW of soil samples with biochar were subjected to an analysis of variance (ANOVA) to test the effects of biochar rates on the soil water retention. When these effects were significant, the means were compared while using Tukey's test ($p < 0.05$). We used repeated ANOVA for soil parameters using Matlab version X (supplementary table 3).

2.7 Biomass valuation and cost-benefit analysis

Biomass valuation was based on Latawiec et al. (2019). Biomass increase was used to calculate the additional US$/ha for each treatment from the potential beef production increase, using Equation (1).

(1) $M=\Delta B\times r\times f\times p$,

in which:

M = additional meat profit.

ΔB = difference of the biomass generated with the treatment in relation to the control.

r = 0.026 = value of the equivalent ton of carcass per ton of dry mass of forage ingested, in a modal system with a complete cycle of meat production for the Atlantic Forest, with an efficiency rate of 100%.

f = forage productivity, value of minimum or maximum productivity (between 10 and 17 Mg DM ha^{-1}) for *Brachiaria brizantha* cv. Marandu, in Mg DM ha^{-1}

p = meat price, in US$, which is the average price of meat in the State of Rio de Janeiro during the experiment period.

2.8 Stakeholder inclusion

The experimental design was performed by researchers together with the landowner on which field the experiment took place. Throughout the duration of the study, the owner was consulted and involved in all experimental procedures undertaken. The researchers had access to all notes regarding cattle raising, soil analysis and financial data of the producer. At the end of the experiment and upon data analysis, we performed a workshop (on the 25th of August 2022) that involved the landowner whose land the study took place on, small-scale biochar producers, researchers, to incorporate their analysis and reality check on the results obtained. Perspectives gained are included and cited accordingly in the discussion section.

3. Results

3.1 Forage yield

Forage yield differed among treatments for the cultivars Marandu ($F = 2.55$, $p = 0.047$) and Paiaguás ($F=0.92$, $p= 0.550$) (figure 1 and supplementary table 2).

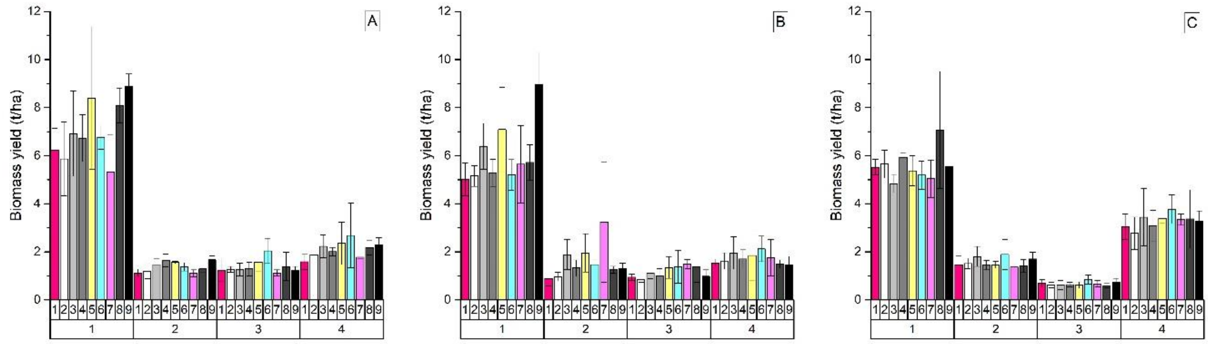

Figure 1. Dry matter production (Mg ha^{-1}) of three *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Piatã (A), Marandú (B) and Paiguás (C) under different soil amendment regimes (1-control, 2 – monha, 3 – lime, 4 – lime +NPK, 5 – biochar Mg ha^{-1}, 6 – forage peanut, 7 – forage peanut + lime, 8 – forage peanut + biochar 15 Mg ha^{-1}, 9 – biochar 30 Mg ha^{-1}) across 4 consecutive harvests (n=3).

When evaluating trends in forage yield per harvest, independently of treatment and *Brachiaria* cultivar, dry matter tended to be greatest in the first harvesting period, decreasing sharply in the second (Figure 1). Cultivar Paiaguás showed a slight decrease in dry biomass production in the third harvest and a sharp increase in the fourth. Considering the total biomass produced over the experiment (sum of four harvests, Figure 2), the highest production of dry biomass for cultivars Marandu and Piatã cultivars was 12.7 and 14.1 Mg ha^{-1}, respectively for the application of biochar at a 30 t/ha rate, while for Paiaguás the highest dry matter production (12.4 Mg ha^{-1}) was due to the use of forage peanut plus application of 15 Mg ha^{-1} biochar (supplementary table 3).

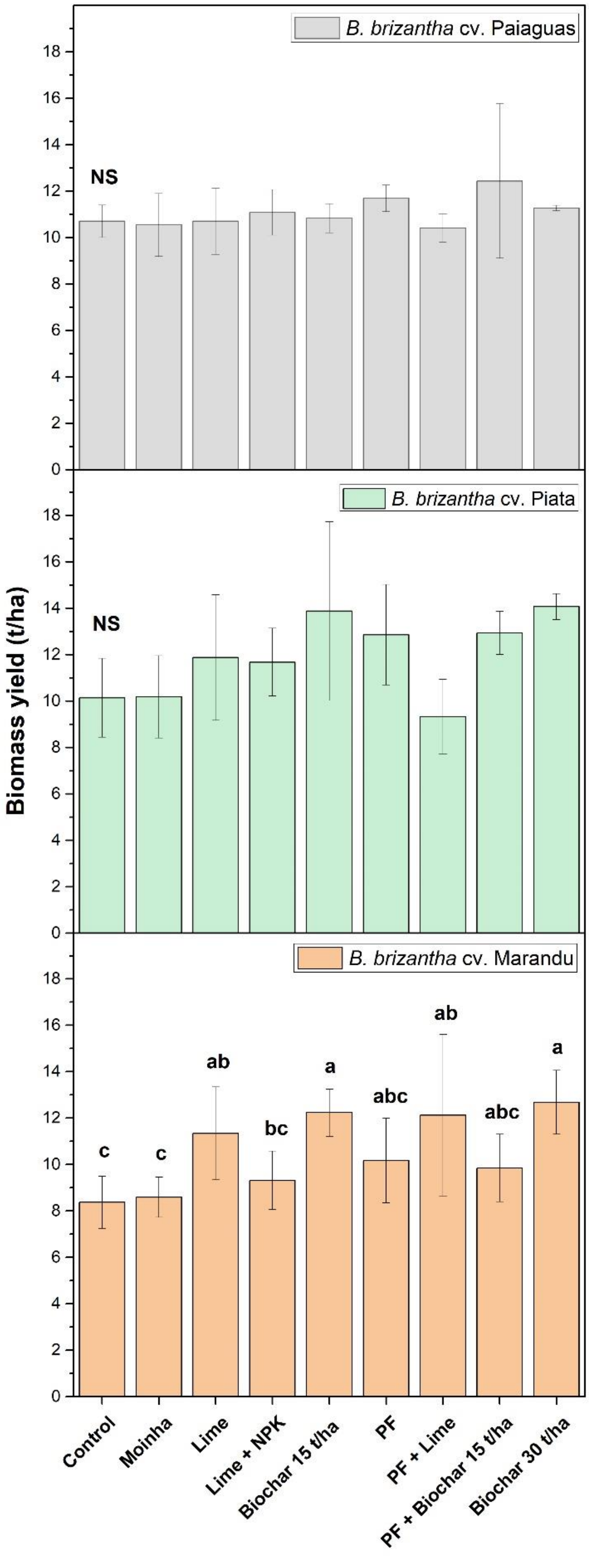

Figure 2. The sum of four harvests for three forage grasses with standard deviation. Letters above the bars represent significant differences (t-test) while NS means non-significant.

3.2 Nutrients in biomass

The axis of the first principal component (PC1) explained 35.03% of the variation in the dataset (Figure 3) and was negatively correlated mainly with N, K, and Cu. Loadings of the variables included in the PCA are in Supplementary table 4. The axis of the second principal component (PC2) explained 18,97% of the data variation and was negatively correlated mainly with Mg and Ca. The third principal component (PC3) (figure not shown) explained 13,11% of the dataset variation and was positively correlated mainly with Zn (loading=0.67).

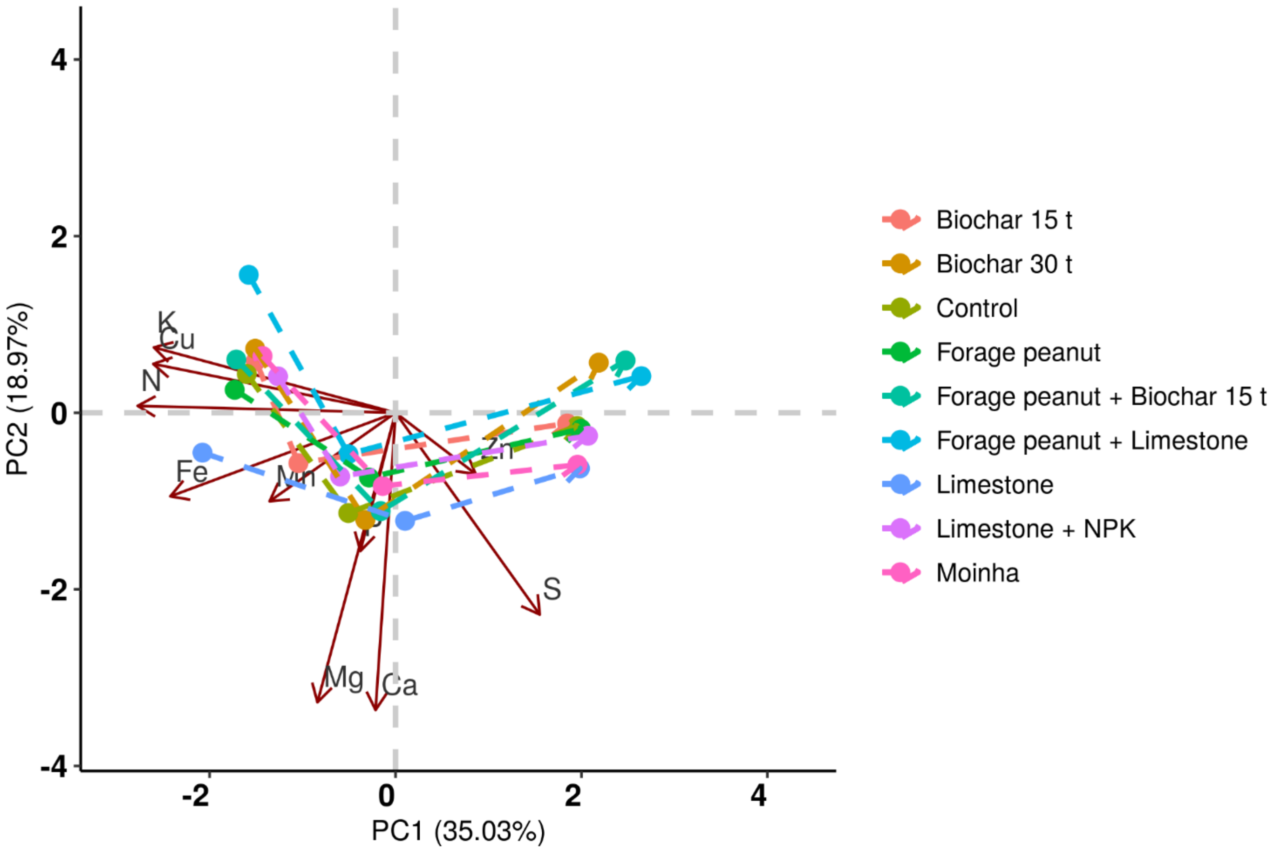

Figure 3. Principal Components Analysis of aboveground forage biomass nutrient concentration, measured in a field experiment with three different *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Paiguá, Marandú and Piatã). Leaf nutrient concentration was measured in four different times (harvests) for each cultivar. Each point in the figure represents the centroid of three replicates (plots) measured at a given time, their colours indicate the different treatments and the dashed lines connecting the centroids indicate the changes in nutrient contents through time (harvests), with arrows indicating nutrient contents measured at the last harvest. Vectors indicate the leaf nutrient variables included in the PCA, and their length and direction indicate the magnitude and direction in which they contribute to the ordination, respectively. Values between brackets indicate the percentage of the variation in the original dataset that is explained by axes PC1 and PC2.

The effect of treatment on leaf nutrient content was not consistent, since treatments were closely grouped in the PCA, with no clear pattern of treatment effect across the different harvesting period (supplementary table 5). Except for the Forage Peanut + Biochar 15 Mg treatment for the *Brachiaria* cv. Piatã that shows statistically significant differences (p-value = 0.022) (5upplementary table 5) and the analysis of the residues reinforces this conclusion.

The effect of the treatments over time on nutrient content extracted by the aboveground biomass revealed by PCA considers simultaneously data of the three *Brachiaria brizantha* cultivars. The dashed lines within PCA results (Figure 2) indicate that all treatments presented a similar pattern of changes in leaf nutrient content through harvests. Variation of selected foliar nutrients based on the PCA results through time for three grasses is shown in Figure 3 in Supplementary Materials. For the three cultivars, the contents of N, Cu, Ca and Mg were higher in the Control and moinha treatments 1 (supplementary figure 3).

3.3 Soil analysis

Figure 4 presents the results of a PCA on soil parameters at the end of the experiment. Loadings of the variables included in the PCA are in Supplementary table 6. The PC1 explained 34.03% of the variation in the dataset and was positively correlated mainly with pH and base saturation (V), and negatively correlated mainly with m and Al (supplementary table 6). The second axis of PCA (PC2) explained 27.04% of the variation and was mainly negatively correlated with curve 0.10 and Mg while having a weaker positive correlation with remaining P and Al saturation (m).

Besides explaining a quarter of the data variation, several soil parameters had a strong negative correlation with PC2. This trend was mainly influenced by *Brachiaria brizantha* cv. Piatã and Paiaguás as observed through the points, squares and triangles (figure 4) that represent each replicate for *Brachiaria brizantha* cv. Marandú, Piatã and Paiaguás, respectively, at the end of the experiment.

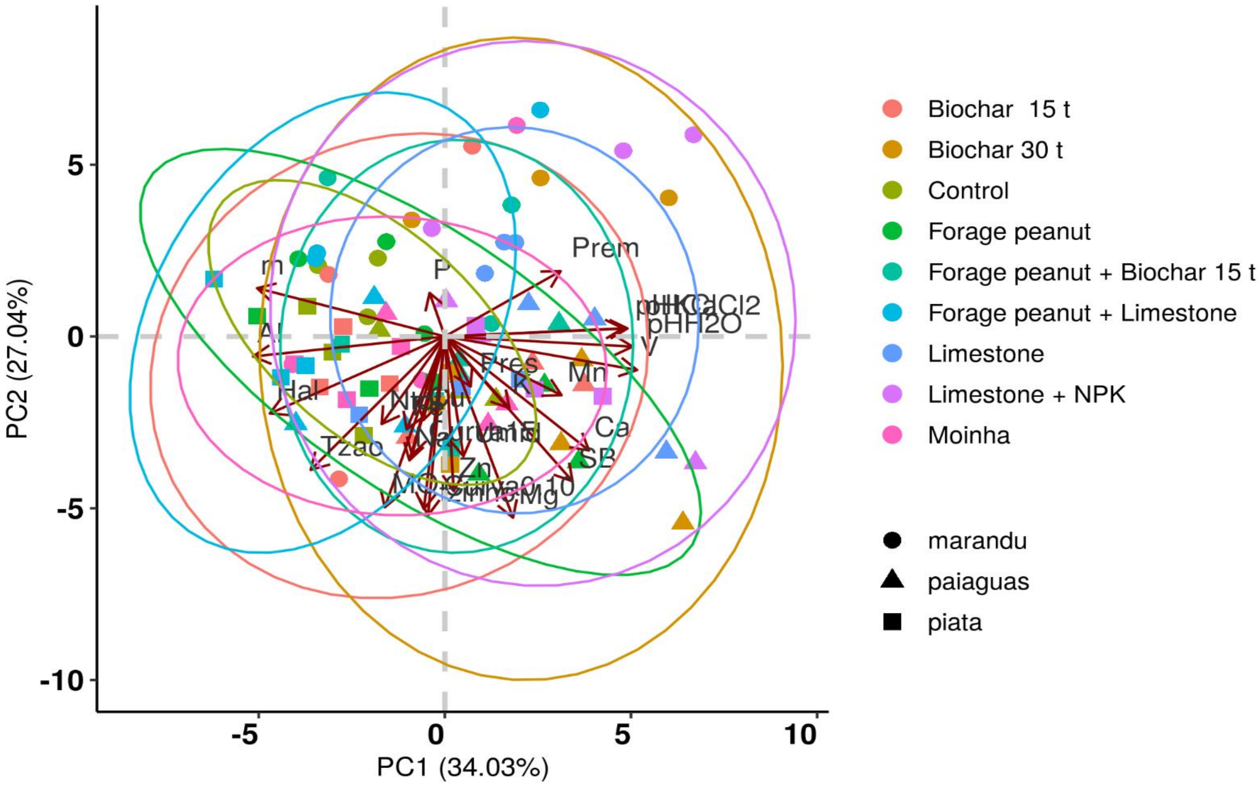

Figure 4. Principal Components Analysis of soil chemical parameters measured in a field experiment with three different *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Paiaguás, Marandú and Piatã). Each point, square and triangle in the figure represents a replicate (plot) for *Brachiaria brizantha* cv. Marandú, Piatã and Paiaguás, respectively, and their colours indicate the different treatments. Vectors indicate the soil variables included in the PCA, and their length and direction indicate the magnitude and direction in which they contribute to the ordination, respectively. Values between brackets indicate the percentage of the variation in the original dataset that is explained by axes PC1 and PC2.

The effect of treatment on the soil parameters is presented in table 7 in supplementary materials. The treatment with Biochar 30 Mg showed statistical differences for all three *Brachiaria brizantha*: Marandú (p-value = 0.032), Piatã (p-value = 0.028) and Paiaguás (p-value = 0.027). Limestone and Limestone + NPK also were statistically different for two *Bachiarias*. Limestone showed statistically significant results for *Brachiaria brizantha* cv. Piatã (p-value = 0.027) and Paiaguás (p-value = 0.026) and Limestone + NPK presented significant differences for *Brachiaria brizantha* cv. Piatã (p-value < 0.001) and Marandú (p-value = 0.010). For all forages, the highest correlation (Pearson) between biomass and nutrients in soil was found for K (r=0.35; p=0.0013; supplementary materials). Changes in K in soil over four harvests are presented in figure 5. Other selected soil characteristics (V, m, P) for each forage over four harvests are included in supplementary materials (supplementary figure 4) along with the results from repeated ANOVA.

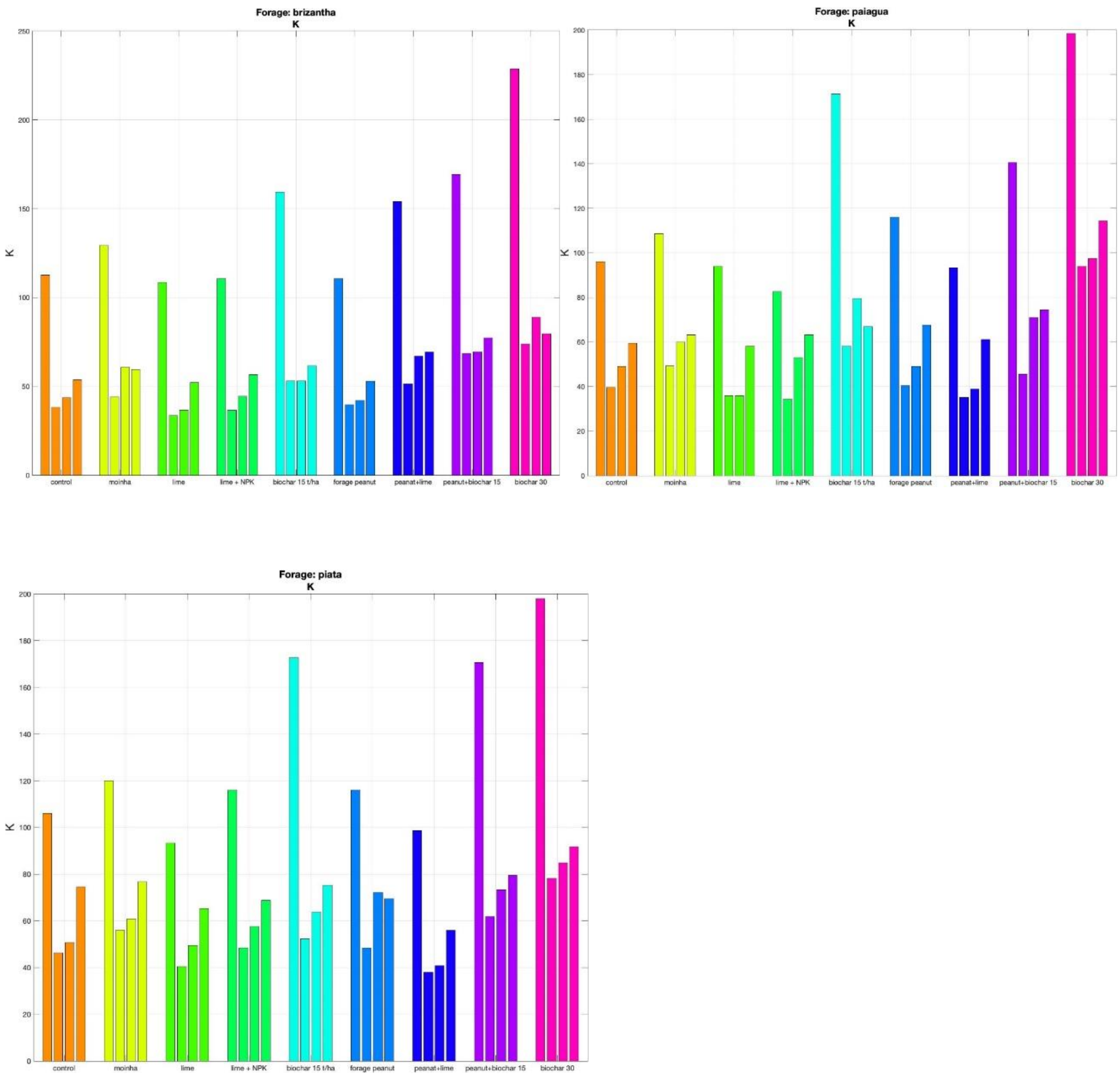

Figure 5. Changes in soil K over four harvests for control (orange), moinha (yellow), lime (light green), lime + NPK (dark green), biochar 15 Mg ha^{-1} (azure), forage peanut (light blue), forage peanut + lime (dark blue), forage peanut + biochar 15 Mg ha^{-1} (purple), biochar 30 Mg ha^{-1} (pink). Among soil parameters, soil K was most correlated with biomass increase for the three forage grasses.

Regarding water holding capacity for biochar samples, the addition of 15 and 30 Mg ha^{-1} showed to improve water soil holding capacity at 0, 3, 6, 10 and 1500 kPa and available water (AW). The data showed a good adjustment to the VG equation with high R^2 and low values of RMSE (supplementary table 8). However, the enhancements were not statistically different (supplementary table 9).

3.4 Biomass valuation

Brachiaria brizantha cv. Marandú, showed the greatest biomass and income over the four harvests (Table 1). The biochar 30 Mg ha^{-1} treatment generated a maximum income of US$ 1,291, average total income of US$ 1,025 and its variation compared to the control test was positive at US $ 557. Piatã obtained the second-best result, with his best treatment being biochar 30 Mg ha^{-1}, which reached its maximum level of total income at US $ 1,183, with a total average of US $ 940 and a control variation of US $ 262. Paiaguas treatment generated the best results for Forage Peanut + 15 Mg ha^{-1} with its total income peak at US $ 991, having a total average of US $ 787 and with a control variation of US $ 110. Raw data and calculations are available on request.

Table 1. Income generation by treatment

		Treatment	Maximum Total Yield (USD)	Average total income (USD)	Average variation of income (USD)
Marandu	**1º**	Biochar 30 Mg ha^{-1}	$ 1.291,23	$ 1.025,39	$ 557,28
	2º	Biochar 15 Mg ha^{-1}	$ 1.246,21	$ 989,64	$ 521,53
Paiaguás	**1º**	Forage Peanut + biochar 15 Mg ha^{-1}	$ 991,40	$ 787,28	$ 109,95
	2º	Forage Peanut	$ 932,26	$ 740,33	$ 62,99
Piatã	**1º**	Biochar 30 Mg ha^{-1}	$ 1.183,35	$ 939,72	$ 10,58
	2º	Biochar 15 Mg ha^{-1}	$ 1.166,82	$ 926,60	$ 10,05

4. Discussion – potentials, challenges and solutions

In this paper evidence is provided on the impact of soil enhancers on restoration of degraded pasturelands. Over the four cutting seasons, we observed significant differences in the biomass growth between treatments for Brachiaria Marandu. This increase translated to income increases for the farmer. Among treatments, the application of *Gliricidia sepium*-made biochar led to benefits in plant biomass production and correlated with K increase in soil (Pearson Correlation Coefficients, supplementary table 10) and concentration of the nutrients in the biomass (supplementary tables 11a-f). Applying 30 Mg ha^{-1} of biochar for *B. brizantha* cultivars Marandu and Piatã, or growing forage peanut + 15 Mg ha^{-1} biochar for cultivar Paiaguás gave the greatest increase in the forage grass biomass. These uplifts in yield represent 34% increase in biomass for Marandu, 28% increase for Piata for 30 Mg ha^{-1} of biochar and

14% increase in biomass for the treatment of forage peanut with 15 Mg ha^{-1} for Paiaguaias (with respect to the control, supplementary table 12). Paiaguás is drought resistant which in combination with biochar may potentialize a range of ecosystem services. Even though our data does not show significant difference between this treatment and control, from the point of view of the farmer, this increase is significant (sum of the cuts of biomass) given the direct increase in the income. Furthermore, biochar has been shown to help water regulation in soils (Razzaghi et al., 2020) and may bring other benefits like regulating soil acidity, increasing soil carbon, and improving soil structure (Matuštíka et al., 2020; Song et al., 2022). Here, for instance, we observed pH increase, base saturation increase, aluminium decrease, and phosphorus increase. The expected and desired, due to toxicity to plants, aluminium immobilisation can be linked to pH increase. The increase in soil nutrients when using recycled, nationally-produced soil enhancers has another crucial benefit. Brazil is a country that depends on nitrogen, phosphorus and potassium fertilisers, including these originating in politically unstable countries. It is a great challenge to increase the national offer for soil enhancers: both mineral and organic in soils due to fast decomposition rates.

Regarding the dose of biochar, our results support those from previous studies. Uzoma et al. (2011) reported that the use of biochar in rates of 15 and 20 Mg ha^{-1} significantly increased the yield of maize grain by 150 and 98% respectively, compared to the control while Bista et al. (2019) examined the response of soil properties and wheat growth to four rates of biochar (0, 11.2, 22.4 and 44.8 Mg ha^{-1}). The use of biochar increased the biomass of wheat roots and shoots; however, these responses were observed at rates of biochar below 22.4 Mg ha^{-1}. Efficient biochar production and application can not only improve soil quality and increase yields, but also provide opportunities for additional income, thus generating agronomic and economic benefits (Oni et al., 2019; Yaashikaa et al., 2020). In our experiment the biochar was produced at small-scale which is costly and the financial benefits from biomass increase may not compensate the costs incurred (Latawiec et al., 2019). Nevertheless, if carbon trading continues to grow and the schemes of payments for soil carbon sequestrations are enforced, the costs would be leveraged with additional contribution to global goals to combat climate change and achieve the Paris Agreement goals (Latawiec et al., 2019). In addition, even though the biochar production may be performed in conducive conditions (Latawiec et al., 2019) to engage with other landowners to scale up production at smaller scale – even if it is associated with significant positive side effects such as diminished pollution, there is slow pick up of biochar production. Understanding farmer decision-making is therefore fundamental for the adoption of better agricultural practices (Latawiec et al., 2017a, Latawiec et al., 2017b).

It should also be noted that given its palatability, continuous addition of legumes to pasturelands may lead to selective grazing leads, with overgrazing of the legume and under grazing the associated grass. This could in turn affect the botanical composition of the pasture and contribution of the legume to the total biomass available in the next grazing cycle. Over longer periods, management strategies that allow for selective grazing may impact persistence of the most palatable forage species in mixed swards. On the other hand, the use of well-planned rotational grazing can reduce the risks of selection and overgrazing. A study conducted by Andrade et al. (2006) showed higher percentage of Forage Peanut under higher grazing intensities. Its prostrate and stoloniferous growth habit, with growing points protected from grazing, impart high grazing resistance to this legume species. In that, more diverse pasture is more resilient. Combination of biochar with legume may bring important benefits, beyond the biomass increase given the increased soil carbon stocks and nutritional value of forage peanut to cattle. Incorporating legumes to pasturelands also enriches low-fertility tropical soils with biologically fixed nitrogen, reducing purchase costs of nitrogen fertilizer and contributing to a more sustainable livestock production (Shelton, 2005; Simeão et al., 2017, Tamele et al., 2018).

Sustainable agricultural practices can not only positively influence the yield and nutritional quality of forage crops but can also help mitigate the negative impact of animal production on the environment (Capstaff and Miller, 2018; Latawiec et al., 2014a, 2017, 2019,). However, despite the range of potential benefits that alternative solutions to better land management may bring there are challenges that need to be addressed so these solutions are adopted in practice (Latawiec et al., 2017b . It is highlighted that farmers behaviour is difficult to change in general and bringing them to the discussion is a significant challenge. As case-in-point the farmer who hosted this experiment is resistant to change; even though Paiaguaias may be more adapted to changing climate (wherein episodes of drought are becoming more frequent), he is accustomed to Piatã and is not inclined to reform his pasture. Biochar was however perceived as a potential alternative to moinha and the farmer expressed interest in applying it as a means to improve his soil within a follow-up study. Similar obstacle was noted with respect to practical adoption of legumes in the pastures. Potential solution suggested by researcher involved in promoting better agricultural practices was engaging with a representative farmer, respected and heard by the community. Showing that the practice works is more valuable than convincing with theories, even by renowned scientists.

5. Limitations and future studies

Limitations of our study include the duration of the study. Even though we managed to conduct the first, to our knowledge, large-scale field experiment in Brazil of this type, the availability of the pasture was dictated by the availability of the patches by the farmer. When designing the experiment, we also faced a trade-off (dictated by financial resources) between diversity of the treatments and the number of replicates. Given the interest of the farmers we opted for maximum diversification of the treatments and three replicates, which in field conditions sometimes lead to elevated standard deviation. However, from the farmer standpoint who considers a sum of harvests rather than the medium, we find this approach more relevant.

One of the aftermaths of this study is a detailed analysis of carbon sequestration in the treatments that are of the interest of the farmer and may bring future benefits from the payments for ecosystem services. In this research, we were limited to biochar stability analysis (Latawiec et al., 2019) as financial resources did not include fractional analysis of stable carbon in soil. This follow up research is being currently conducted by our team. Given wider interest of the landowners in Brazil to use biochar, both in agriculture and restoration, we encourage future research on this topic with a possible inclusion to carbon market and additional benefits from the payments for ecosystem services to the farmers, especially small and medium scale ones that need most diversification of the income.

6. Conclusions

This paper presents a participatory approach wherein the landowner was involved in the design of this research, he was active throughout the execution of the experiment and was involved in the analysis and interpretation of the results. Indeed, for science to be considered in practice it is necessary that soil management practices are developed together with rural communities. Such an approach facilities two way knowledge exchange wherein scientists and farmers both benefit from their experience and insights. Building strategies with farmers, incorporating their knowledge, and contributing to their economic development is a way of improving their self-esteem and, at the same time, expanding and valuing academic knowledge. Together with farmers, we must build a diagnosis of problems related to soil management to experiment and evaluate solutions based on pragmatic indicators for all actors involved. For this to happen, it is necessary to use methodologies that facilitate communication and dialogue between farmers, scientists, and practitioners.

Once gone, soils are difficult to recover for future generations. Due to the foundational role of soils in the environment, pastures degradation poses threats not only to the soil environment but also to other planetary systems (Keenor et al., 2021). Poor pasture management can lower their productivity, resulting in reduced biomass yields, impoverished soil fertility and carbon content, and increased erosion. It is necessary to take urgent measures to improve soil quality, especially in developing countries, where food and nutrition security strategies are a major social investment. We believe that our work presented here adds to the existing body of knowledge regarding sustainable management of organic residues and pragmatic alternatives for more sustainable pasture management in Brazil and elsewhere.

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