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Biochar and Forage Peanut improve pastures: Evidence from a field experiment in Brazil

Agnieszka E. Latawiec[a,b,c,d,*], Aline F. Rodrigues[a,b], Katarzyna A. Korys[b], Maiara Mendes[b], Marcio Rangel[b], Ana Castro[b], Wenceslau Teixeira[e], Judson F. Valentim[f], Ednaldo Araujo[g], Luiz Fernando Duarte de Moraes[g], Vinicius Pacheco[h], Marcos Mendes[b], Cristiano Dela Piccolla[i], Bernardo Strassburg[a,b,j], Maciej Kubon[k], Adam Drosik[l], Fernanda D. Gomes[a,b], Brian Reid[d], Joana M. Krieger[b], Viviane Dib[b], Dariusz Zmarzły[m], Eduardo Carvalho da Silva Neto[b,n]

[a] *Departament 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*
[b] *International Institute for Sustainability, R. Dona Castorina 124, Jardim Botânico, Rio de Janeiro 22460-320, Brazil*
[c] *Faculty of Mechanical Engineering, Opole University of Technology, Mikołajczyka 5, 45-271 Opole, Poland*
[d] *School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK*
[e] *Empresa Brasileira de Pesquisa Agropecuária (Embrapa Solos), R. Jardim Botânico, 1024 - Jardim Botânico, Rio de Janeiro, Rio de Janeiro 22460-000, Brazil*
[f] *Empresa Brasileira de Pesquisa Agropecuária (Embrapa Acre), Rodovia BR-364, Km 14, Rio Branco, Acre CEP: 69900-970, Brazil*
[g] *Empresa Brasileira de Pesquisa Agropecuária (Embrapa Agrobiologia), Rodovia BR-465, Km 7, Bairro Ecologia, CEP: 23891-000 Seropédica, Rio de Janeiro, Brazil*
[h] *Programa de pós-graduação em Ciência, Tecnologia e Inovação em Agropecuária – PPGCTIA / UFRRJ, Pavilhão Central do Campus da UFRRJ, BR 465 km 7, Seropédica, 23.890-000, Brazil*
[i] *Centro de Educação Superior do Oeste, Universidade do Estado de Santa Catarina, R. Beloni Trombeta Zanin, Chapecó, 680E, Santo Antônio, SC, Brazil*
[j] *Re.green Praça Santos Dumont, 70 - 4° Andar Gávea, Rio de Janeiro - RJ, Brazil*
[k] *Department of Production Engineering, Logistics and Applied Computer Science, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Poland*
[l] *Faculty of Political Sciences and Social Communication, Department of Social Communication and Journalism, University of Opole, Katowicka 89, 46-061 Opole, Poland*
[m] *Faculty of Electrical Engineering, Automatic Control and Informatics, Opole University of Technology, Prószkowska street 76, 45-758 Opole, Poland*
[n] *Universidade Federal Rural do Rio de Janeiro, BR-465, Km 7, Campus Seropédica, Seropédica, Rio de Janeiro CEP: 23890-000, Brazil*

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ABSTRACT

Pasturelands, often degraded, represent most of the converted lands globally. It is important to understand how different pasture management approaches can improve soil quality, increase feed production and farmer income. Here, the impact of different soil enhancers on soil quality and productivity of three cultivars of *Brachiaria (Syn. Urochloa)* forage grass is presented. Soil enhancers included: biochar - a carbon-rich product from biomass pyrolysis, moinha (local charcoal residue), traditional fertiliser containing nitrogen, phosphorus and potassium, lime, and forage peanut (*Arachis pintoi* cv. Amarillo). Considering the total biomass produced over the experiment (sum of four harvests), the highest dry biomass production was observed for *Brachiaria brizantha* cv. Piatã (14.1 Mg ha^{-1}) and cv. Marandu (12.7 Mg ha^{-1}), for biochar application of 30 Mg ha^{-1}. Paiaguás had the highest dry matter production (12.4 Mg ha^{-1}) for the treatment with forage peanut plus 15 Mg ha^{-1} of biochar. The increases in dry mass production translated to additional income, as compared with the control, of U$ 1 291, U$ 1 183 and U$ 991 per year for Marandu, Piatã and Paiaguás, respectively. The increases in forage grass productivity were reflected by positive changes in soil characteristics such as improvement in cation exchange capacity, pH and nutrient contents. Improved management of tropical pasturelands holds opportunity for more

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* Corresponding author at: Departament 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.
E-mail addresses: alatawiec@gmail.com, a.latawiec@iis-rio.org (A.E. Latawiec).

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sustainable food production, and for ecosystem services protection and recuperation, for example, biodiversity net-gain, water regulation and carbon sequestration.

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 inadequate 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). 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 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 quality. Brazil is an important producer and exporter of beef, accounting for almost 20 per cent 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 per cent 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 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 increase soil carbon sequestration, thus contributing to climate change mitigation (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 Brazil. A meta-analysis by Jeffery et al. (2017) showed that biochar supported an average (for all analysed crops) yield increase of 25% in the tropics. The authors concluded that biochar 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. This 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 various soil enhancers in pasturelands, linking environmental and socioeconomic analysis to a participatory approach with landowners. The insights gained will contribute to better decision-making by farmers and policymakers that will support improved and more sustainable pastureland management.

2. Material and 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 the 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 (supplementary Figure 1). The region is characterized by predominantly flat relief (0–3% slope), in the geomorphological unit of the coastal plain of Rio de Janeiro. The geology is composed of Neogene and Quaternary fluvial-marine sediments deposited on Precambrian acidic rocks (gneiss, orthogneiss and biotite-hornblende (Pereira et al., 2022). The predominant soil in the region is Dystric Planosol (Carvalho Filho et al., 2003; IUSS Working Group WRB, 2022).

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. The current research reflected real-world land management relevant to farmers and extended the research to a field scale considering a range of grasses commonly used by, or of interest to, farmers. The examined grasses were: *B. brizantha* cv. BRS Piatã, which is predominantly used by the property owner where the experiment was undertaken, *B. brizantha* cv. Marandu, a forage grass widespread in Brazil and in other tropical regions and *B. brizantha* cv. BRS Paiaguás, which is a drought-resistant variety that the landowner was motivated to investigate. The experiment consisted of 81 experimental plots, 3×3m each. These plots represented each forage grass under the following regimes: control, moinha (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 Table 1). 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. *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 (N_2 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.

A simple 200 L brass kiln was used to produce the biochar (Supplementary Figure 2). Kiln capacity was 70 kg of raw *G. sepium* biomass, and biomass to biochar efficiency was 30%. The pyrolysis lasted approximately 10 h with temperatures around 400 °C. After cooling, biochar was ground and sieved (< 2 mm). Biochar was analysed by solid-state ^{13}C NMR spectroscopy. Spectra was obtained on a Varian INOVA (11.74 T) spectrometer with ^{13}C and 1 H 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 above ground dry matter produced by three *Brachiaria brizantha* cultivars over four harvests. Above ground biomass after each harvest (keeping five cm of forage for regrowth) was assessed for wet weight, and for dry weight after drying in the oven for 96 h (at 60 °C). To evaluate the concentration of macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Cu, Fe, Mn, and Zn), 200 g (wet weight) of biomass was collected of each treatment after each harvest and analysed following the protocol by Malavolta et al. (1997). In brief, N determination was performed through sulfuric solubilization, in which 0.2 g of dry sample was used for digestion in 50 ml. Acid sulfate mixture was added (15 ml) and digestion proceeded for 1 h in a digester block, with the temperature up to 335 °C. The samples were then cooled, and the N content determined.

2.5. Soil sampling and analysis

Soil samples were collected and analysed at harvest times. The soil samples were homogenized and sieved (2 mm), and analysed for pH, organic matter (dag kg^{-1}), total N (g kg^{-1}), total K (mg dm^3), P (mg dm^3), 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 dm^3), 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 size following the methodology from Teixeira et al. (2017). 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 (Teixeira et al., 2017). Organic matter was extracted through a solution of $NaCr_2O_7$ and H_2SO_4 (Quaggio and van Raij, 1979). Potassium (K), sodium (Na), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) were extracted by Mehlich -1 (Teixeira et al., 2017). Phosphorus (P) was evaluated by three methods - using Mehlich-1 (Teixeira et al., 2017), anion-exchange resins (Raij et al., 2001), and remaining P (Alvarez et al., 2000). 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, sum of bases (SB), potential (T) and effective (t) CEC, base saturation (V) and aluminium saturation (m) indexes were calculated according to Teixeira et al. (2017). Total nitrogen was determined using the Kjedahl method (Tedesco et al., 1995). Water holding capacity (undisturbed soil sample ~ 100 cc) 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 et al., 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 (Supplementary Methods).

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 were submitted to the Tukey test to compare means (α = 0.05). (α = 0.05). For the analyses of multivariate data (biomass nutrient concentration and soil parameters), Principal Components Analysis (PCA) was performed on each dataset. A generalized linear model (GLM) was used to evaluate the statistical difference between the treatments and tested their significance after assessing the residuals. For the biomass nutrient concentrations, the two most relevant nutrients for each axis were used to analyse their trends through time. These analyses were performed in R (R Development Core Team, 2018), using packages easyanova, dplyr, stats, hnp, ggplot2 and ggfortify. To test the effects of biochar on soil water retention, 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). When these effects were significant, the means were compared using Tukey's test ($p < 0.05$). For soil parameters (excluding available soil water) repeated ANOVA was performed using Matlab (Supplementary Table 3).

2.7. Biomass valuation

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 Eq. (1).

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

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} and 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 experiment was designed with the landowner in who's field the experiment took place. Forage grasses choice, use of soil enhancers and doses, biomass collection intervals were dictated by the real-word conditions and according to the practice of the local cattle ranchers. Throughout the study, the owner was consulted and involved in undertaken experimental procedures. Historical data regarding cattle raising, soil analysis and financial data generated by the producer were made available to the research team. At the end of the experiment and upon data analysis, a workshop was held on the 25th of August 2022 with the landowners, small-scale biochar producers and researchers to validate the results obtained and identify future research priorities. Perspectives gained are included and cited accordingly in the discussion section. Further details are provided in the Supplementary materials (Supplementary Figures 3–5).

3. Results

3.1. Forage yield

Forage yield differed among treatments for the cultivars Marandu ($F = 2.55$, $p = 0.047$) and Paiaguás ($F=0.92$, $p = 0.550$) (Fig. 1 and Supplementary Table 4).

When evaluating trends in forage yield per harvest, independent of treatment and *Brachiaria* cultivar, dry matter tended to be greatest in the first harvesting period, decreasing in the second harvesting period (Fig. 1). Cultivar Paiaguás showed an increase in dry biomass production in the fourth harvest, comparing to the second and third harvest. Considering the total biomass produced over the experiment (sum of four harvests, Fig. 2), the highest production of dry biomass for cultivars

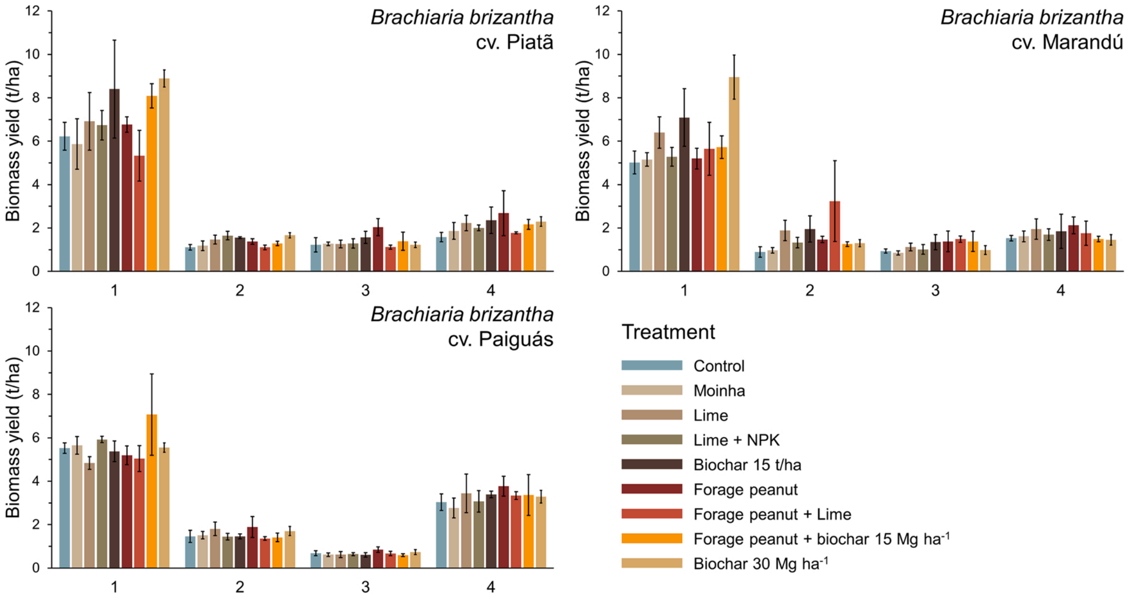

Fig. 1. Dry matter production (Mg ha^{-1}) of three *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Piatã (A), Marandu (B) and Paiaguás (C) under different soil amendment regimes across four consecutive harvests (n = 3).

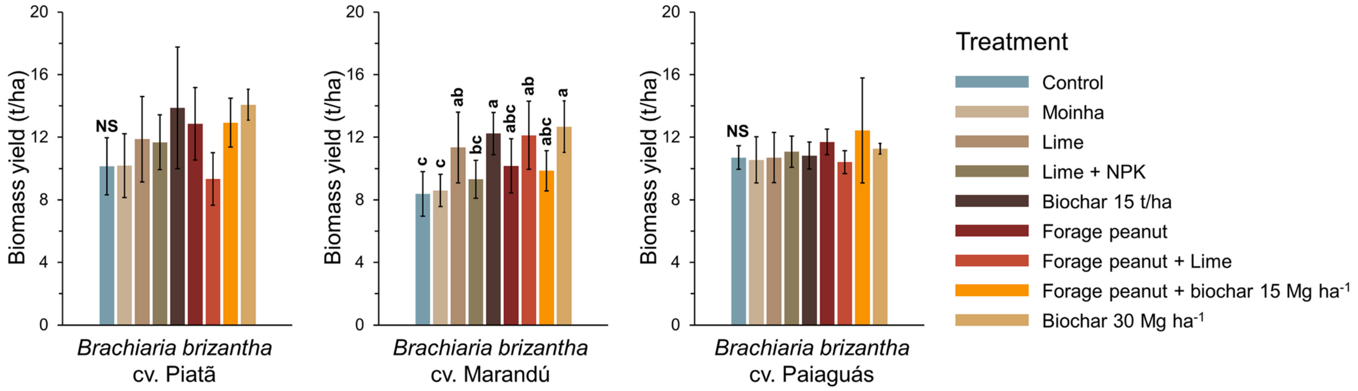

Fig. 2. The sum of four harvests for three forage grasses with standard deviation. Letters above the bars represent significant differences (t-test) while NS means non-significant (n = 3).

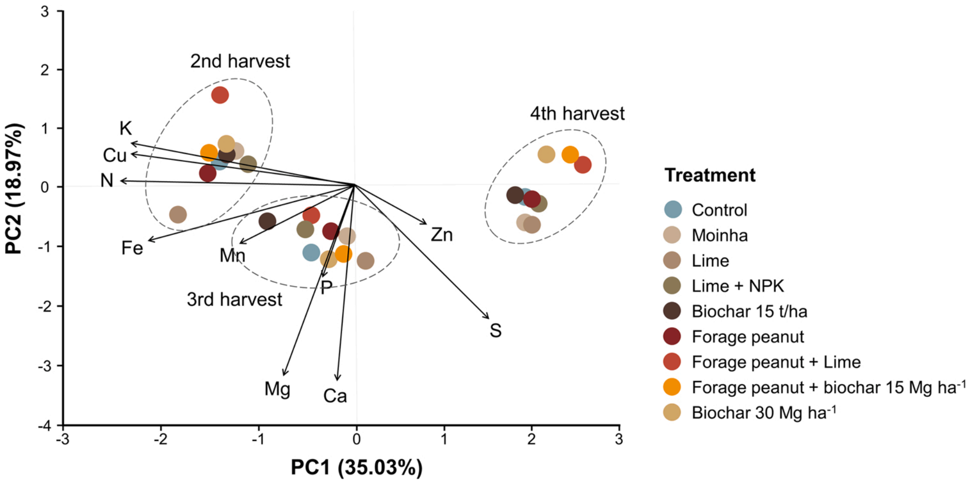

Fig. 3. Principal Components Analysis of aboveground forage biomass nutrient concentration, measured in a field experiment with three different *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Paiguá, Marandu and Piatã). Each point in the figure represents the centroid of three replicates (plots) measured at a given time (harvest) with colours indicating the different treatments. 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.

Piatã and Marandu cultivars was 14.1 and 12.7 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 observed for the forage peanut plus application of 15 Mg ha^{-1} biochar.

3.2. *Nutrients in biomass*

The axis of the first principal component (PC1) explained 35.03% of the variation in the dataset (Fig. 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).

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. This is except for the forage peanut + biochar 15 Mg treatment for the *Brachiaria* cv. Piatã that shows statistically significant differences (p-value = 0.022) (Supplementary Table 5) and the residual analysis reinforces this conclusion. The effect of the treatments over time on nutrient content extracted by the aboveground biomass in PCA considers data of the three *Brachiaria brizantha* cultivars simultaneously. Variation of selected foliar nutrients (N, Cu, Ca and Mg) based on the PCA results through time for three grasses is shown in Figure 6 in Supplementary Materials.

3.3. *Soil analysis*

Fig. 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 Al and Al saturation (m). 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 m. Strong negative correlation of several soil parameters with PC2 was mainly influenced by *Brachiaria brizantha* cv. Piatã and Paiaguás as illustrated by the squares and triangles on the Fig. 4.

The results of generalized linear model for the soil parameters is presented in Table 7 in the Supplementary materials. The treatment with biochar 30 Mg showed statistical differences for all three *Brachiaria brizantha*: Marandu (p-value = 0.032), Piatã (p-value = 0.028) and Paiaguás (p-value = 0.017). Limestone treatment showed statistically significant results for *Brachiaria brizantha* cv. Piatã (p-value = 0.027) and Paiaguás (p-value = 0.026) while Limestone + NPK presented significant differences for *Brachiaria brizantha* cv. Piatã (p-value < 0.001) and Marandu (p-value = 0.010). For all forage grasses, the highest correlation (Pearson) between biomass and nutrients in soil was found for K (r = 0.35; p = 0.0013; Supplementary Table 8). Changes in K in soil over four harvests are presented in Fig. 5. Other selected soil characteristics (V, m, P) for each forage grass over four harvests are presented in Supplementary Figure 7.

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 9). However, the changes were not statistically different (supplementary Table 10). Similar trend was observed for soil organic matter.

3.4. *Biomass valuation*

Brachiaria brizantha cv. Marandu, showed the greatest income increase, as compared with control, over the four harvests for the treatment 30 Mg ha^{-1} (Table 1). This 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 (increase by 51%). Piatã obtained the second largest income, with biochar 30 Mg ha^{-1}, reaching its maximum level of total income at US $ 1 183, with a total average of US $ 940 (39% increase as compared with control). Paiaguás treatment generated its greatest income for forage peanut + 15 Mg ha^{-1} of biochar (increase by 16% with respect to control) with its total income peak at US $ 991, having a total average of US $ 787.

4. Discussion - potentials, challenges and solutions

In this paper evidence is provided on the influence of soil enhancers on restoration of degraded pasturelands. Over four harvests, we observed statistically significant differences in biomass growth between treatments for *B. brizantha* cv. Marandu. Among treatments, the application of biochar produced from *Gliricidia sepium* led to benefits in plant biomass production and correlated with K increase in soil (Pearson Correlation Coefficients, Supplementary Table 8; concentrations of the nutrients in the biomass are presented in Supplementary Tables 11a-e). 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 51% increase (compared to control) in income for Marandu, 39% income increase for Piatã for 30 Mg ha^{-1} of biochar and 16% increase in income for the treatment of forage peanut with 15 Mg ha^{-1} for Paiaguás. Paiaguás is drought resistant which in combination with biochar may potentialize a range of soil ecosystem services

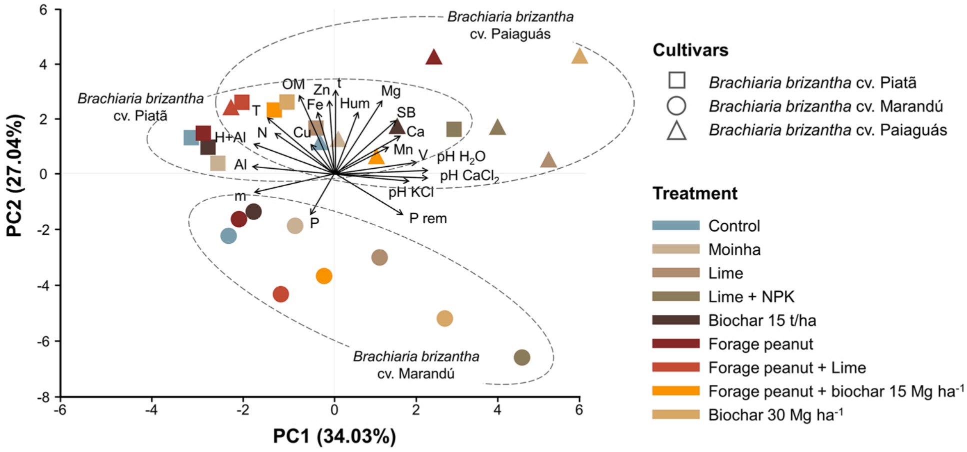

Fig. 4. Principal Components Analysis of soil chemical parameters measured in a field experiment with three different *Brachiaria brizantha* cultivars (*Brachiaria brizantha* cv. Paiaguás, Marandu and Piatã). Each point, square and triangle in the figure represents the mean (n = 3) of every treatment at the end of the experiment for *Brachiaria brizantha* cv. Marandu, Piatã and Paiaguás, respectively, and their colours indicate the different treatments. Vectors' length and direction indicate the magnitude and loading in which the soil variables contribute to the ordination, respectively. Values between the brackets indicate the percentage of the variation in the original dataset that is explained by axes PC1 and PC2.

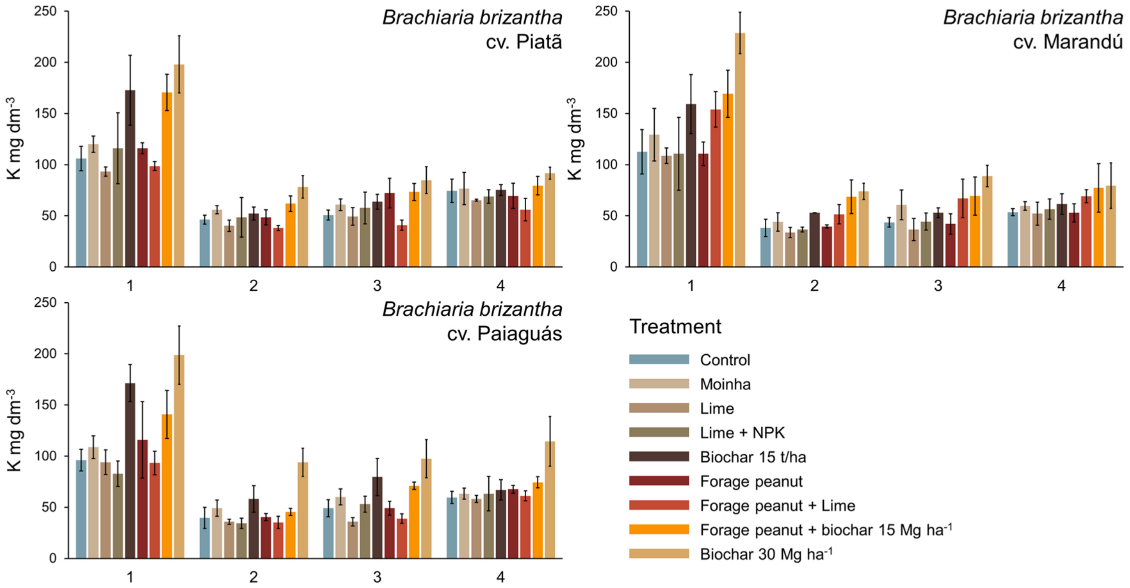

Fig. 5. Changes in soil K over four harvests for different treatments (n =3) for the three Brachiaria cultivars.

Table 1
Income generation by treatment.

		Treatment	Maximum Total Yield (USD)	Average total income (USD)	Average variation of income (USD)
Marandu	1°	Biochar 30 Mg ha^{-1}	$ 1 291	$ 1 025	$ 557
	2°	Biochar 15 Mg ha^{-1}	$ 1 246	$ 990	$ 521
Paiaguás	1°	Forage Peanut + biochar 15 Mg ha^{-1}	$ 991	$ 787	$ 110
	2°	Forage Peanut	$ 932	$ 740	$ 63
Piatã	1°	Biochar 30 Mg ha^{-1}	$ 1 183	$ 940	$ 11
	2°	Biochar 15 Mg ha^{-1}	$ 1 167	$ 927	$ 10

benefits. Even though our data does not show significant difference between this treatment and the control, from the point of view of the farmer, these yield increases (as the sum of the harvests) will deliver additional income.

Biochar has been shown to help water regulation in soils (Razzaghi et al., 2020) and may bring other benefits, such as, regulating soil acidity, increasing soil carbon, and improving soil structure (Matuštíka et al., 2020; Song et al., 2022). Here, for instance, we observed a pH increase, base saturation increase, P increase and Al decrease. Al decreases are favourable as Al is phytotoxic (with its greater availability being linked to low soil pH). At the end of the experiment, PCA on soil parameters showed negative correlation between pH and Al concentration (Fig. 4). The treatment effect on the soil parameters was statistically significant for biochar 30 Mg ha^{-1}, limestone and limestone + NPK for all three *Brachiaria brizantha* cultivars. Remaining P (P rem) that represents the soil capacity to fix P, showed that when soil pH increased, the P rem also increased (both are in the positive part of the PC1; more P may be available to plants; Fig. 4). Treatments such as biochar 30 Mg ha $^{-1}$ and lime increased soil pH, and also P rem. The increase in soil nutrients when using recycled, nationally-produced soil enhancers is of wider relevance to mitigating reliance on imported NPK fertilizers.

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 has the potential to improve soil quality and increase yields, while also providing 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 a 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 gain traction and the schemes of payments for soil carbon sequestrations are verified, the biochar production costs would be leveraged. Biochar, as a stable form of carbon has particular relevance to carbon storage permanence, contributing to global goals to combat climate change and achieve the obligations of the Paris Agreement (Latawiec et al., 2019, Kenoor et al., 2021). Given the growing prospect of voluntary market payments for ecosystem services (including carbon sequestration), a robust assessment of soil carbon net-gains and the permanence of these gains would be an appropriate extension to the research. This data would underpin a better-informed farmer-centric cost-benefit appraisal of change. Breakeven and cost-benefit analysis would also be beneficial as the income increase may not be significant between the 15 and 30 Mg of biochar (Table 1). Future research should also include a dimension relating to payments for ecosystem services (including, but not limited to soil carbon net-gain) to the farmers in Brazil.

Given its palatability, the continuous addition of legumes to pasturelands may lead to selective grazing, with overgrazing of the legume and undergrazing of the associated grass (Andrade et al., 2006). 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 the 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. With more diverse pasture being more resilient to stress, including climate change (Peterson et al., 2020; Sattler et al., 2018), such grazing management would be important to futureproofing pasturelands. Combination of biochar with legume may bring important benefits beyond the biomass increase, given the increased nutritional value of forage peanut to cattle. Incorporating legumes to pasturelands also enriches low-fertility tropical soils with biologically fixed nitrogen, thus potentially reducing costs linked to nitrogen fertilizer purchase (Shelton et al., 2005; Simeão et al., 2017; Tamele et al., 2018).

Sustainable agricultural practices cannot 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., 20142019). However, despite potential benefits that alternative solutions to better land management may bring, understanding farmer decision-making is fundamental for the adoption of beneficial agricultural practices (Latawiec et al., 2014, Latawiec et al., 2017a; Latawiec et al., 2017b). As case-in-point, during the validation workshop it was stressed that despite the potential benefits of Paiaguás cultivar with respect to climate change adaptation (wherein episodes of drought are becoming more frequent) (Beloni et al., 2018), farmers were reluctant to reform their pastures and move away from the traditionally planted grasses. Biochar was, however, perceived as a potential alternative to moinha and the farmers expressed interest in applying biochar as a means to improve soil quality. Similar obstacles are reported with respect to practical incorporation of legumes in the pastures. Potential leverage-point solution is engaging with a representative farmer, who is respected and heard by the farmers' community to show the benefits of more sustainable pasture management.

Limitations of this study include the duration of the research as the availability of the pasture was dictated by the availability of the land provided by the farmer. When designing the experiment, there was a trade-off dictated by financial resources between the diversity of the treatments and the number of replicates. Given the interest of the farmers and maximum diversification of the treatments, three replicates were implemented, possibly leading to elevated standard deviation. However, from the farmer's standpoint, who considers a sum of harvests rather than statistical significance, this approach was considered appropriate. In addition, although the cost of biochar used in this experiment has been published (Latawiec et al., 2019), the cost-benefit analysis was not performed since such analysis would bring another level of complexity entailing further expert engagement. The labour costs to produce biochar can be significant (Latawiec et al., 2019) and depending on the target plant productivity, payback time assumed, discount rates, possible subsidies, scenarios of future profits from target plant, management scheme (e.g. organic production or not), carbon-price, among other variables required for cost-benefit analysis, biochar may or may not be profitable to the farmers as compared with other soil enhancers (Latawiec et al., 2019; Latawiec et al., 2021). Regarding a possible spillover effect, biomass residues used for biochar production from *Gliricidia sepium,* a perennial and easily cultivated plant for green manuring and mulching, are abundant in the region where the experiment took place and do not compete with other alternative uses.

5. Conclusions

This paper presents a participatory approach wherein the landowner was involved in the design of the research, 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, a diagnosis of problems related to soil management should be performed and solutions evaluated based on feasible actions and goals for all actors involved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108534.

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