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# Soil properties and crop productivity under varying density of planted *Piliostigma reticulatum* (DC) Hochst in Burkina Faso

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**Abstract** *Piliostigma reticulatum is widely distributed in the Sahel and plays an important role in the livelihoods of local communities.* Its uses include livestock feeding and soil management. However, anthropogenic pressure and adverse climatic factors have led to significant variability and a decline in the species' density, impairing its potential for soil management.,. To ensure the sustainable soil management determining the optimal planting density of *P. reticulatum* is essential.. This study employed a completely randomized Fisher block design with four shrub densities (0, 500, 1000, and 2000 shrubs·ha$^{-1}$) in a sorghum-cowpea mixed cropping system. The management method applied to the shrubs was coppicing. The parameters evaluated included shrub aboveground biomass (AGB), soil chemical characteristics and crop productivity (grain, straw, and tops). The results showed that the densities of 1000 and 2000 shrubs ha$^{-1}$ increased AGB production by 59% and 64%, respectively compared to 500 shrubs.ha$^{-1}$. The 2000 shrubs ha$^{-1}$ density enhanced soil organic status with higher levels of organic matter and total nitrogen. Sorghum grain yield increased by 127% and cowpea yield by 56% at 1000 and 2000 shrubs·ha$^{-1}$, respectively, compared to the control (0 shrubs·ha$^{-1}$). A density of 2000 shrubs·ha$^{-1}$ is optimal for sustainable sorghum–cowpea mixed cropping system wtihin Sahelian agroforestry parklands.

**Keywords** Aboveground biomass · Sahel · Soil organic carbon · Sorghum-cowpea association · Shrub regeneration

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## Introduction

Enhancing soil organic status is critical for agricultural productivity and the sustainability of Sahelian agroecosystems. Crop residue restitution has been promoted as a strategy to improve soil organic matter (Castellanos-Navarrete et al. 2014; Koulibaly et al. 2017). However, competing uses for residues such as livestock feed, energy, and soil amendment limit

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their availability (Dugué et al. 2024; Zoungrana et al. 2023). Agroforestry, the practice of deliberately integrating trees and shrubs with crops and/or livestock, particularly using woody species such as *Piliostigma reticulatum*, offers a sustainable alternative for soil management (Bationo et al. 2012; Bonkoungou et al. 1993; Bright et al. 2021; Camara et al. 2021). *Piliostigma reticulatum* provides multiple ecosystem services, including soil fertility improvement, handicraft materials, and cultural and medicinal uses (Bazongo et al. 2024; Roessler et al. 2025; Sehoubo et al. 2023). Its evergreen nature, rapid growth, and high regeneration capacity make it ideal for soil management (Lufafa et al. 2008; Yélémou et al. 2007).

Studies conducted on research stations have shown that *P. reticulatum* aboveground biomass production ranges from 3000 to 6000 kg/ha, depending on its density (Bright et al. 2017; Douzet et al. 2019). Assisted natural regeneration (ANR) is the most common management method in the Sahel. Farmer ANR management such as coppicing and pruning leads to a bushy growth and a tree-like structure respectively (Bationo et al. 2012; Yélémou et al. 2007). The use of biomass from coppicing or pruning for mulching or burial in the soil by tilling has been documented (Bationo et al. 2012; Félix et al. 2018; Gnissien et al. 2022). Furthermore, the enhancement of soil and water conservation techniques by adding *P. reticulatum* leaf litter in zaï pits and half-moon basins has also been highlighted in the sub-Saharan zone (Lahmar et al. 2012).

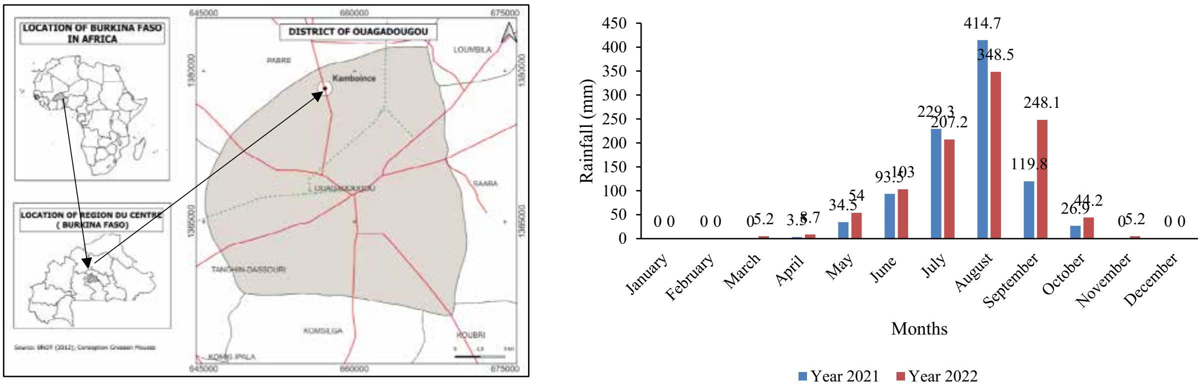
*Piliostigma reticulatum* significantly influences soil functioning in agroecosystems. Its deep root system allows access to water from lower soil layers, reducing competition with crops, while facilitating deep sub-soil water redistribution to upper layers, thereby enhancing drought resilience in both shrubs and associated crops (Kizito et al., 2007, 2012). The species improves soil chemical properties by increasing organic matter content and the availability of essential nutrients, including nitrogen, phosphorus, and exchangeable cations, which enhances crop nutrient uptake (Bright et al. 2017; Dossa et al. 2010; Tyano et al. 2022; Yélémou et al. 2013). In addition, *P. reticulatum* promotes soil biological activity by stimulating microbial communities and their enzymatic functions, accelerating organic matter mineralization (Diakhaté et al. 2016; Diédhiou-Sall et al., 2021). Soil macrofauna activity, such as that of termites and earthworms, is also higher in soils mulched with its aboveground biomass compared to non-mulched soils (Guébré et al. 2020). The impact of *Piliostigma reticulatum* on crop productivity remains controversial. Some studies have demonstrated that the species can enhance crop yields (Bright et al. 2017; Diangar et al., 2024), whereas others report negative effects on crop production (Camara et al. 2024).

*P. reticulatum* appears in fields at different densities, often in a scattered distribution, whether managed through coppicing or pruning (Lahmar et al. 2012; Lufafa et al. 2008). In the context of a decline in woody density in fields due to adverse climatic conditions and anthropogenic pressures (Takenaka et al. 2021; Yaméogo et al., 2019), identifying optimal shrub densities is critical for sustaining soil health in Sahelian agroecosystems. This paper presents the results of the effects of different *P. reticulatum* planting densities on: (i) shrub aboveground biomass production, (ii) soil organic matter and nutrient availability, and (iii) sorghum and cowpea yields in mixed crops.

## Materials and methods

### Study area

The experiment, was established in August 2012 at the Crops-New-Systems experimental station in Kamboinsé, on land provided by the International Institute for Water and Environmental Engineering, in the northern Sudanian zone of Burkina Faso (Gnissien 2024). The geographic coordinates of the site are 2°11′12" and 12°28′35" North latitude, and 1°04′06" and 1°28′49" West longitude (Fig. 1 a). The rainy season occurs from May to October each year, with monthly rainfall varying between 26.9 and 414.7 mm in 2021, and between 44.2 and 348.5 mm in 2022 (Fig. 1 b). According to Fontès and Guinko (1995), the vegetation of the area is dominated by shrub savannah, with species such as *P. reticulatum* (DC) Hochst, *Combretum micranthum* G. Don, and *Diospyros mespiliformis* Hochst. exA. Rich. The trial was established on an epipetal plinthosol with an effective depth of 30 cm (Gnissien 2024). The experiment was set up as part of the Agroecology-based aggradation-conservation agriculture (ABACO) project in




(a)

(b)

**Fig. 1** Location of study aera (**a**) and rainfall and rainy days evolution from 2013 to 2022 (**b**)

2012 and was monitored until 2021 by the Agroecology and Sustainable Intensification of Annual Crops (AIDA) research unit of the Centre de coopération internationale en Recherche Agronomique pour le Développement (CIRAD). Since 2021 Université Nazi BONI (as part of the SustainSahel project) took over the management.

## Experimental design

The experimental design consists of a completely randomised Fisher blocks with four shrub densities corresponding to four treatments: 0, 500, 1000, and 2000 shrubs ha$^{-1}$. Each treatment was replicated four times, with each replication measuring 13.6 m x 10 m. Zaï was the soil tillage technique applied to all treatments. The shrubs were planted by direct seeding in August 2012 with the following spacings: 4 m x 4 m for the 500 shrubs/ha density, 4 m x 2 m for the 1000 shrubs/ha density, and 2 m x 2 m for the 2000 shrubs ha$^{-1}$density.

## *Piliostigma reticulatum* coppicing and productivity

For each plot containing the shrubs, regular coppicing was applied starting in 2015. In June 2015, only one coppicing was performed due to the young age of the shrubs; this number increased to two between 2016 and 2020, during the months of June and August, and to three coppicings in 2021 and 2022, during the months of June, August, and November, respectively. Sorghum (Sorghum bicolor L) was cultivated alone from 2012 to 2017, and from 2018 onward, a sorghum and cowpea (Vigna unguiculata (L.) Walp.) in mixed crops was introduced as the cropping system. The aboveground biomass of the shrubs was used as mulch on the soil in the form of wood and leafy branches after each coppicing. It is also noteworthy that crop residues (sorghum straw, sorghum panicles, and cowpea tops) were returned to the soil as mulch after each harvest. It is also important to note that chemical fertiliser was only applied to the sorghum in 2013.

Aboveground dry biomass was measured in 2021 and 2022. For each coppice, fresh biomass per plant was harvested and weighed. Three samples per plot were oven-dried at 65 °C for 48 hours to determine dry weight. The mean dry weight per plant was then multiplied by the number of plants to estimate dry biomass per plot. The resulting value was then extrapolated to a per-hectare basis using the following formula:

$$AGB = \frac{\text{Biomass weight elementary plot} * 10000}{\text{Plot area}} \quad (1)$$

## Crop productivity

Sorghum and cowpea yields were evaluated for the 2021 and 2022 cropping seasons in accordance with the harvesting protocol that had been instituted since the implementation of the trial in 2012. Sorghum grain and straw yields were evaluated per zaï pit, with five pits selected at random per elementary plot. The cowpea grain and straw yields were evaluated per elementary plot using the whole-plot harvesting technique for each elementary plot. An extrapolation to the hectare was subsequently performed to determine the sorghum and cowpea yields.

### Soil sampling

Soil samples were collected during two campaigns in November 2021 and November 2022 at depths of 0-10 cm and 10-20 cm, respectively. Samples were obtained from each plot at three distinct points along the diagonal at each depth level and were mixed to constitute a composite sample. The samples thus collected were then analysed at the Laboratoire d'Etude et de Recherche sur la Fertilité du sol et les Systèmes de Production (LERF-SP).

### Determination of soil chemical parameters

The soil pH was determined using the potentiometer method of analysis, using soil/water suspensions 1/2,5 (AFNOR,1981). The determination of organic carbon was achieved through the implementation of wet oxidation, a method initially established by Walkley and Black in 1934. The organic matter content was obtained by multiplying the organic carbon content by 1.724 (Pansu and Gautheyrou 2003). The total nitrogen content was determined using the KJELDAHL method (Hillbrand et al., 1953). The Bray I method (Bray and Kurtz 1945) was used to determine available phosphorus. The extraction of available potassium and exchangeable bases (calcium, magnesium, potassium, and sodium) was conducted using ammonium acetate at a pH of 7. The parameters under investigation were determined for the years 2021 and 2022.

### Statistical analysis

Soil parameter data and crop yields were analyzed using R software version 2024.12.0+467. The Shapiro-Wilk test was first applied to assess the normality of the data, ensuring the appropriateness of parametric tests. A two-factor analysis of variance (ANOVA) at a 5% significance level was then conducted to evaluate the effects of shrub density and trial year on the measured variables. Additionally, multiple regression analysis was performed to explore the relationships and interactions between sorghum and cowpea grain yields and the various soil parameters across both cropping seasons. This analysis considered soil data from the 0-10 cm depth, as no significant differences were observed between the data at the 10-20 cm depth.

## Results

The AGB production per *P. reticulatum* shrub was found to be higher at a density of 500 shrubs ha$^{-1}$ (7.86 kg) in comparison to the other densities (Fig. 2 a). However, for AGB production of *P. reticulatum* per hectare, the densities of 1000 shrubs ha$^{-1}$ and 2000 shrubs ha$^{-1}$ resulted in a significant increase in dry aboveground biomass production (6252 kg ha$^{-1}$ for the 1000 shrubs.ha$^{-1}$ density and 6460 kg ha$^{-1}$ for the 2000 shrubs.ha$^{-1}$ density) in comparison to the 500 shrubs ha$^{-1}$ density ($P<0.001$). (Fig. 3 a). The production per shrub and for all shrubs per hectare was not affected by the year (Fig. 2 b and Fig. 3 b).

### Effects of *Piiostigma reticulatum* planting densities on soil organic matter and nutrient levels

Table 1 and Table 2 show that no significant interaction between plant density and year was detected for any of the soil variables measured in the 0-10 cm. However, the 2000-plant density exhibited significantly higher concentrations of OM, N, and K compared with the other densities. This density also showed higher values for all base cations, except for $Ca^{2+}$ under 1000- density, and $Mg^{2+}$, under 500- density.OM, Total N, $K^{+}$ and $Na^{+}$ significantly differ between years.

The results for the 10–20 cm depth clearly show that no significant interaction between plant density and year was detected for any of the soil variables measured (Table 3 and Table 4). Similarly, shrub density did not significantly affect the soil parameters. In contrast, OM, Total N and Av_P significantly differ between years

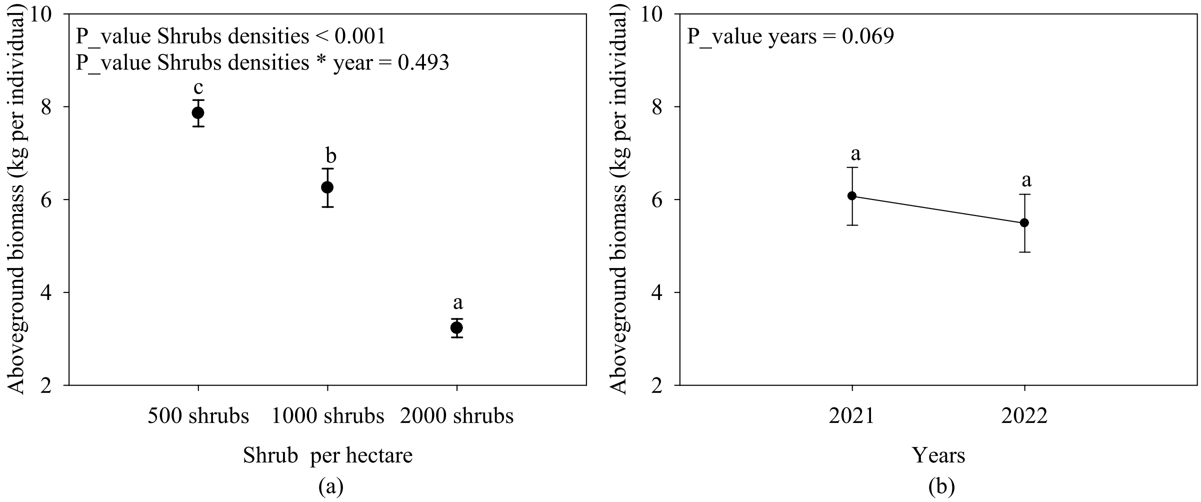



**Fig. 2** Variation of *Piliostigma reticulatum* aboveground biomass per shrub (**a**) and years (**b**). The error bars represent the standard errors within the treatments. Values sharing the same letters are not statistically different at the 5% significance level

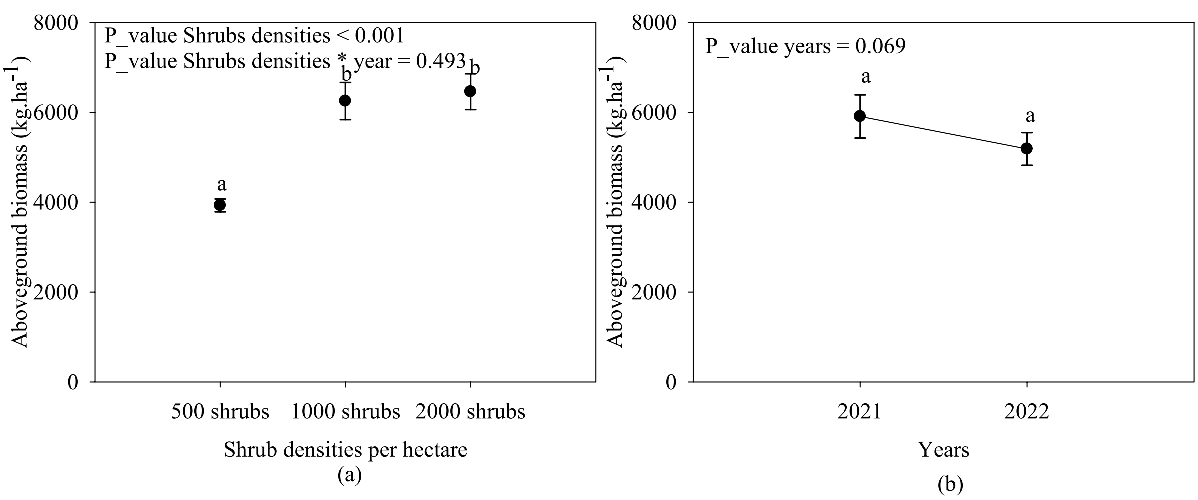



**Fig. 3** Variation of *Piliostigma reticulatum* aboveground biomass according to densities of shrubs (**a**) and years (**b**). The error bars represent the standard errors within the treatments. Values sharing the same letters are not statistically different at the 5% significance level

## Effects of *Piliostigma reticulatum* planting densities on sorghum and cowpea yields

The different densities of *P. reticulatum* resulted in similar sorghum grain and straw yields (**Fig. 4**a). However, the sorghum grain yield (838 kg ha$^{-1}$) and straw yield (3746 kg ha$^{-1}$) were significantly higher in 2022 than in 2021 (**Fig.** 4b). The cowpea grain yield increased with higher densities of *P. reticulatum*. (Tables 5 and 6)The maximum value was recorded at a density of 2000 shrubs ha$^{-1}$ (381 kg ha-1). However, increasing densities had no significant effect on the cowpea fodder yield (**Fig.** 5a). Compared to 2021, the cowpea grain yield significantly increased in 2022 (374 kg ha$^{-1}$), whereas the year did not affect on the cowpea fodder yield (**Fig.** 5b).

**Table 1** Variation in soil organic matter and macronutrient content according to Piliostigma reticulatum density and year at 0–10 cm depth. Legend:Values preceded by the sign ± represent the standard errors within the treatments. Values with the same superscript letters in the same column are not statistically different at the 5% threshold

| | Treatments | pH_Water | OM (%) | Total_N ($g.kg^{-1}$) | Av_P ($mg.kg^{-1}$) | Av_K ($mg.kg^{-1}$) |
|---|---|---|---|---|---|---|
| Shrub densities | 0 shrubs $ha^{-1}$ | 6.23 ± 0.14 $^{a}$ | 0.90 ± 0.07 $^{a}$ | 0.54 ± 0.05 $^{a}$ | 2.05 ± 0.18 $^{a}$ | 76.95 ± 8.88 $^{a}$ |
| | 500 shrubs $ha^{-1}$ | 6.38 ± 0.10 $^{a}$ | 0.92 ± 0.06 $^{a}$ | 0.61 ± 0.05 $^{a}$ | 2.22 ± 0.14 $^{a}$ | 85.83 ± 4.64 $^{a}$ |
| | 1000 shrubs $ha^{-1}$ | 6.33 ± 0.06 $^{a}$ | 0.95 ± 0.06 $^{a}$ | 0.60 ± 0.05 $^{a}$ | 1.99 ± 0.18 $^{a}$ | 88.05 ± 17.22 $^{a}$ |
| | 2000 shrubs $ha^{-1}$ | 6.48 ± 0.12 $^{a}$ | 1.23 ± 0.11$^{b}$ | 0.71 ± 0.06 $^{b}$ | 3.35 ± 0.72 $^{a}$ | 129.00 ± 12.19 $^{b}$ |
| *P*_value Shrub densities | | 0.513 | 0.008 | 0.017 | 0.069 | 0.026 |
| Years | 2021 | 6.36 ± 0.10 $^{a}$ | 0.86 ± 0.05 $^{a}$ | 0.50 ± 0.02 $^{a}$ | 2.31 ± 0.13 $^{a}$ | 93.23 ± 8.72 $^{a}$ |
| | 2022 | 6.35 ± 0.06 $^{a}$ | 1.10 ± 0.06 $^{b}$ | 0.73 ± 0.03 $^{b}$ | 2.50 ± 0.41 $^{a}$ | 96.69 ± 10.23 $^{a}$ |
| *P*_value Years | | 0.881 | 0.003 | < 0.001 | 0.625 | 0.778 |
| *P*_value Shrubs densities *Years | | 0.695 | 0.987 | 0.692 | 0.338 | 0.623 |

**Table 2** Variation in soil exchangeable bases according to *Piliostigma reticulatum* density and year at 0–10 cm depth. Legend: Values preceded by the sign ± represent the standard errors within the treatments. Values with the same superscript letters in the same column are not statistically different at the 5% threshold

| | Treatments | $Ca^{2+}$ (cmolc $kg^{-1}$) | $Mg^{2+}$ (cmolc $kg^{-1}$) | $K^{+}$ (cmolc $kg^{-1}$) | $Na^{+}$ (cmolc $kg^{-1}$) | SEB (cmolc kg-1) |
|---|---|---|---|---|---|---|
| Shrub densities | 0 shrubs $ha^{-1}$ | 2.79 ± 0.31 $^{a}$ | 0.91 ± 0.09 $^{a}$ | 0.14 ± 0.02 $^{a}$ | 0.03 ± 0.01 $^{a}$ | 3.87 ± 0.40 $^{a}$ |
| | 500 shrubs $ha^{-1}$ | 3.20 ± 0.26 $^{a}$ | 1.22 ± 0.13 $^{b}$ | 0.19 ± 0.02 $^{b}$ | 0.07 ± 0.02 $^{b}$ | 4.68 ± 0.39 $^{ab}$ |
| | 1000 shrubs $ha^{-1}$ | 3.62 ± 0.48 $^{b}$ | 0.98 ± 0.07 $^{a}$ | 0.20 ± 0.02 $^{b}$ | 0.05 ± 0.01 $^{ab}$ | 4.86 ± 0.52 $^{b}$ |
| | 2000 shrubs $ha^{-1}$ | 4.57 ± 0.55 $^{b}$ | 1.44 ± 0.21 $^{b}$ | 0.31 ± 0.03 $^{c}$ | 0.09 ± 0.02 $^{b}$ | 6.41 ± 0.79 $^{c}$ |
| *P*_value Shrub densities | | 0.039 | 0.044 | < 0,001 | 0.019 | 0.029 |
| Years | 2021 | 3.25 ± 0.28 $^{a}$ | 1.01 ± 0.07 $^{a}$ | 0.24 ± 0.02 $^{b}$ | 0.04 ± 0.01 $^{a}$ | 4.54 ± 0.38 $^{a}$ |
| | 2022 | 3.85 ± 0.35 $^{a}$ | 1.26 ± 0.12 $^{a}$ | 0.18 ± 0.02 $^{a}$ | 0.08 ± 0.01 $^{b}$ | 5.37 ± 0.48 $^{a}$ |
| *P*_value Years | | 0.170 | 0.076 | 0.017 | 0.003 | 0.151 |
| *P*_value Shrub densities *Years | | 0.798 | 0.622 | 0.937 | 0.936 | 0.977 |

**Table 3** Variation in soil organic matter and macronutrient content according to *Piliostigma reticulatum* density and year at 10–20 cm depth. Legend: Values preceded by the sign ± represent the standard errors within the treatments. Values with the same superscript letters in the same column are not statistically different at the 5% threshold

| | Treatments | pH_water | OM (%) | Total_N ($g.kg^{-1}$) | Av_P ($mg.kg^{-1}$) | Av_K ($mg.kg^{-1}$) |
|---|---|---|---|---|---|---|
| Shrub densities | 0 shrubs $ha^{-1}$ | 6.08 ± 0.13 $^{a}$ | 0.69 ± 0.06 $^{a}$ | 0.42 ± 0.04 $^{a}$ | 1.40 ± 0.27 $^{a}$ | 64.37 ± 7.23 $^{a}$ |
| | 500 shrubs $ha^{-1}$ | 6.08 ± 0.06 $^{a}$ | 0.79 ± 0.06 $^{a}$ | 0.54 ± 0.05 $^{a}$ | 1.56 ± 0.41 $^{a}$ | 61.66 ± 5.52 $^{a}$ |
| | 1000 shrubs $ha^{-1}$ | 6.18 ± 0.06 $^{a}$ | 0.82 ± 0.06 $^{a}$ | 0.49 ± 0.05 $^{a}$ | 1.76 ± 0.48 $^{a}$ | 78.88 ± 13.76 $^{a}$ |
| | 2000 shrubs $ha^{-1}$ | 6.26 ± 0.11 $^{a}$ | 0.87 ± 0.11 $^{a}$ | 0.51 ± 0.06 $^{a}$ | 1.77 ± 0.22 $^{a}$ | 93.60 ± 8.07 $^{a}$ |
| *P*_value Shrub densities | | 0.527 | 0.154 | 0.055 | 0.751 | 0.105 |
| Years | 2021 | 6.13 ± 0.07 $^{a}$ | 0.65 ± 0.03 $^{a}$ | 0.38 ± 0.01 $^{a}$ | 2.24 ± 0.22 $^{b}$ | 76.77 ± 6.27 $^{a}$ |
| | 2022 | 6.17 ± 0.07 $^{a}$ | 0.94 ± 0.05 $^{b}$ | 0.60 ± 0.03 $^{b}$ | 1.01 ± 0.16 $^{a}$ | 72.49 ± 7.77 $^{a}$ |
| *P*_value Years | | 0.749 | < 0.001 | < 0.001 | < 0.001 | 0.665 |
| *P*_value Shrub densities *Years | | 0.930 | 0.629 | 0.720 | 0.297 | 0.917 |

**Table 4** Variation in soil exchangeable bases according to *Piliostigma reticulatum* density and year at 10–20 cm depth. Legend: Values preceded by the sign ± represent the standard errors within the treatments. Values with the same superscript letters in the same column are not statistically different at the 5% threshold

| | Treatments | $Ca^{2+}$ (cmolc $kg^{-1}$) | $Mg^{2+}$ (cmolc $kg^{-1}$) | $K^{+}$ (cmolc $kg^{-1}$) | $Na^{+}$ (cmolc $kg^{-1}$) | SEB (cmolc $kg^{-1}$) |
|---|---|---|---|---|---|---|
| | 0 shrubs $ha^{-1}$ | 2.91 ± 0.33 [a] | 0.90 ± 0.10 [a] | 0.14 ± 0.02 [a] | 0.04 ± 0.01 [a] | 3.99 ± 1.26 [a] |
| Shrub densities | 500 shrubs $ha^{-1}$ | 3.87 ± 0.38 [a] | 1.15 ± 0.11 [a] | 0.14 ± 0.02 [a] | 0.05 ± 0.01 [a] | 5.21 ± 0.48 [a] |
| | 1000 shrubs $ha^{-1}$ | 4.03 ± 0.49 [a] | 0.96 ± 0.09 [a] | 0.19 ± 0.03 [a] | 0.05 ± 0.01 [a] | 5.48 ± 0.75 [a] |
| | 2000 shrubs $ha^{-1}$ | 3.94 ± 0.52 [a] | 1.07 ± 0.18 [a] | 0.22 ± 0.05 [a] | 0.07 ± 0.01 [a] | 5.30 ± 0.76 [a] |
| *P*_value Shrub densities | | 0.263 | 0.524 | 0.300 | 0.150 | 0.316 |
| Years | 2021 | 3.93 ± 0.32 [a] | 1.08 ± 0.06 [a] | 0.19 ± 0.02 [a] | 0.04 ± 0.00 [a] | 5.37 ± 0.44 [a] |
| | 2022 | 3.52 ± 0.31 [a] | 1.05 ± 0.11 [a] | 0.11 ± 0.03 [a] | 0.05 ± 0.01 [a] | 4.73 ± 0.43 [a] |
| *P*_value Years | | 0.281 | 0.364 | 0.381 | 0.056 | 0.237 |
| *P*_value Shrub densities *Years | | 0.448 | 0.548 | 0.750 | 0.881 | 0.371 |

**Table 5** Variation of sorghum grain yield and straw yield according to *Piliostigma reticulatum* densities and years. The error bars represent the standard errors within the treatments. Legend: Values sharing the same letters are not statistically different at the 5% significance level

| | Treatements | Grain yield | Straw yield |
|---|---|---|---|
| | 0 shrubs.$ha^{-1}$ | 393.50 ± 75.18 [a] | 1726.77 ± 549.98 [a] |
| Shrubs densities | 500 shrubs.$ha^{-1}$ | 515.51 ± 175.21 [a] | 2250.45 ± 642.78 [a] |
| | 1000 shrubs.$ha^{-1}$ | 892.61 ± 352.83 [a] | 2656.31 ± 845.92 [a] |
| | 2000 shrubs.$ha^{-1}$ | 616.64 ± 228.41 [a] | 2712.00 ± 885.21 [a] |
| *P*_value densities | | 0.448 | 0.572 |
| | Years | Grain yield | Straw yield |
| | 2021 | 371.41 ± 45.35 [a] | 926.29 ± 171.53 [a] |
| | 2022 | 837.71 ± 211.94 [b] | 3746.47 ± 492.95 [a] |
| *P*_value years | | 0.046 | < 0.001 |
| *P*_value years*densities | | 0.620 | 0.850 |

**Table 6** Variation of cowpea grain yield and straw yield according to *Piliostigma reticulatum* densities (a) and years (b). The error bars represent the standard errors within the treatments. Legend: Values sharing the same letters are not statistically different at the 5% significance level

| | Treatements | Grain yield | Cowpea tops yield |
|---|---|---|---|
| | 0 shrubs | 244.76 ± 25.38 [a] | 188.70 ± 38.71[a] |
| Shrubs densities | 500 shrubs | 377.99 ± 28.72 [b] | 320.99 ± 4.45 [a] |
| | 1000 shrubs | 348.73 ± 28.50 [b] | 364.66 ± 63.98 [a] |
| | 2000 shrubs | 380.82 ± 41.89[b] | 433,22 ± 94.88 [a] |
| *P*_value densities | | 0.012 | 0.068 |
| | Years | Grain yield | Cowpea tops yield |
| | 2021 | 302.60 ± 20.96 [a] | 382.76 ± 61.19 [a] |
| | 2022 | 373.55 ± 27.25 [b] | 271.02 ± 29.24 [a] |
| *P*_value years | | 0.027 | 0.088 |
| *P*_value years*densities | | 0.699 | 0.427 |

## Relationships between soil nutrient levels and sorghum and cowpea yields

Table 7 shows significant correlations between sorghum grain yield, cowpea grain yield and most of the soil nutrients ($P < 0.001$) and this is true for

**Table 7** Results of the multiple linear regression of sorghum grain yield as a function of soil nutrient levels and cowpea grain yield

| | Estimate | Std. error | Pr(>\|t\|) | Significance level |
|---|---|---|---|---|
| Intercept | 1873.8364 | 1744.8059 | 0.293524 | |
| pH_Water | − 358.8253 | 286.8974 | 0.223097 | |
| OM | − 1639.5826 | 730.8075 | 0.034359 | 0.05 |
| Total N | 3419.4495 | 1032.9484 | 0.002937 | 0.01 |
| Av_K | 0.4528 | 3.3659 | 0.894097 | |
| Av_P | − 189.2260 | 89.4900 | 0.045050 | 0.05 |
| SEB | 424.1603 | 106.6160 | 0.000556 | 0.001 |
| Cowpea grain yield | − 3.4077 | 1.2135 | 0.009742 | 0.01 |
| $R^2 = 0.6792$; $P$_value = 0.0001041 | | | | |

67.92% of the observations. Thus, the increase in sorghum grain yield was associated with significant increases in Total N ($P<0.01$) and SBE ($P<0.001$). However, the increase in sorghum grain yield also led to significant decreases in OM content ($P<0.05$), Av_P ($P<0.05$) and cowpea grain yield ($P<0.01$).

## Discussion

### *Piliostigma reticulatum* aboveground biomass production

The aboveground biomass production of *P. reticulatum* per plant at a density of 500 shrubs ha$^{-1}$ was twice that at a density of 2000 shrubs ha$^{-1}$. This was due to the greater spacing between shrubs at the 500 shrubs ha$^{-1}$ density, which were less affected by competition for air, water and essential nutrients for growth compared to the 2000 shrubs ha$^{-1}$ density, where competition is expected to be more intense and reduces the potential for biomass production per plant. In China, Taimoor et al. (2019) also observed higher aboveground biomass production per plant at low densities of *Cunninghamia lanceolata* (Lamb) Hook compared to high densities. According to the same authors, individuals in the lower density plots had larger diameters at breast height and longer root lengths than those in the high density plots. The higher total aboveground biomass production per plot at the 2000 shrubs ha$^{-1}$ density is probably related to the higher number of shrubs. An increase in aboveground biomass production with increasing density of *P. reticulatum* was highlighted by Douzet et al. (2019) in the same study design as ours. The level of biomass production at 1000 and 2000 shrubs ha$^{-1}$ densities is comparable to that obtained by Bright et al. (2017) and Bright et al. (2021) respectively for the same species at 1000 shrubs ha$^{-1}$ density and for *G. senegalensis* at a density of 1500 shrubs ha$^{-1}$ in Senegal. Furthermore, the biomass produced by the 1000 and 2000 shrubs ha$^{-1}$ densities could represent an alternative to the use of crop residues for soil mulching, thus reducing the competition for their other uses, as highlighted by previous studies (Dugué et al. 2024; Tesfay et al. 2024). These residues could thus be used exclusively for fodder needs and/or organic fertiliser production. This is particularly relevant because, except for the 500 plants ha$^{-1}$ density, which according to previous studies (Kafando et al. 2023; Somé et al. 2016) produced an aboveground biomass yield similar to the sorghum straw yield of about 3900 to 4200 kg ha$^{-1}$ under farmer conditions, the 1000 and 2000 shrubs ha$^{-1}$ densities provide a greater amount of biomass. Thus, the biomass production by the 1000 and 2000 shrubs ha$^{-1}$ densities are in line with the recommendations of Lahmar et al. (2012), who proposed the use of woody shrub biomass as a key factor for the adoption of conservation agriculture in the Sahel.

### Effects of *Piliostigma reticulatum* planting densities on soil

The density of 2000 shrubs ha$^{-1}$ of *Piliostigma reticulatum* improved the organic status and nutrient levels of the soil, particularly in the 0–10 cm layer, compared to other densities. This may be due to the higher production of aboveground biomass, which, through decomposition and mineralization processes, enriches the soil with these nutrients. A denser root system, with a larger contact surface area due to the high number of shrubs, will also mobilize more nutrients in the soil. A more developed rhizosphere at the density of 2000 shrubs ha$^{-1}$ would also stimulate enzymatic activities through rhizodepositions, leading to faster decomposition and mineralization of organic matter. This is in line with the findings of Diakhaté et al. (2016) and Diédhiou-Sall et al. (2021), who attributed the increase in soil organic carbon (C_org) and nutrients such as $NO_3^-$ and $NH_4^+$ to a higher intensity of enzymatic activities in the rhizosphere of *P. reticulatum*. The high organic matter content in the soil under the 2000 shrubs ha$^{-1}$ density leads to the formation of a more stable clay-humic complex, which retains more exchangeable bases, as evidenced by the levels of these bases. Our results on the beneficial effect of the high aboveground biomass dose (6.4 t ha$^{-1}$) at the 2000 shrubs ha$^{-1}$density on soil parameters confirm those of Félix et al. (2018), who reported that a dose of 12 t ha$^{-1}$ of *P. reticulatum* biomass improves soil organic carbon and total nitrogen levels compared to a dose of 3 t ha$^{-1}$. Mayenlo et al. (2022) also showed that the highest levels of organic matter and total nitrogen were recorded under high densities of woody plantations. This contradicts the findings of Duan et al. (2019) and Selvalakshmi et al. (2022), who reported a decrease in these contents and a loss of soil quality with increasing densities of *Cunninghamia lanceolata* (Lamb.) Hook. and *Pinus kesiya Royle* ex Gordon. Duan et al. (2019) attributed the improvement of the soil's organic status at lower densities of woody species to the presence of other herbaceous species and undergrowth plants with high biomass production potential, which were absent under the high density. Results for the 10–20 cm depth clearly show that the high density of *P. reticulatum* does not improve the organic status and exchangeable base levels in the soil and the levels are lower compared to those in the 0–10 cm layer. Mulching, along with more intense macrofaunal activity in the surface horizon and the limitation of soil depth by the plinthite, accumulates organic matter and soil nutrients in the 0–10 cm layer at the expense of the 10–20 cm layer (Bazongo et al. 2024; Gnisien et al., 2023).

The organic status and nutrient availability in 2022 were undoubtedly improved compared to the 2021 campaign. This is most likely due to the progressive accumulation of organic matter over the years as a result of the regular and continuous practices of coppicing and mulching. It may also be clear that the high rainfall amount in 2022 favoured significant decomposition and mineralization of organic matter. This is in direct contrast with the findings of Barthès et al. (2015) and Félix et al. (2018), who reported a decline in soil nutrient levels over time in the same agro-ecological zone when amended with *P. reticulatum* wood and leafy branches. Our results also differ from those of Matias et al. (2011), who showed a decline in soil nutrient levels under high rainfall conditions in the Mediterranean region. The difference in our results compared to those of Barthès et al. (2015) and Félix et al. (2018) could be associated with the presence of woody species in our study, which led to an additional nutrient input. These authors only used biomass to mulch the soil, which is why their results are different from ours. The presence of shrubs, beyond just mulching with woody biomass, is therefore essential for improving the organic status and nutrient availability of soils. The contrast between our results and those of Matias et al. (2011) may be related to the higher temperatures associated with the tropical climate in our study, which would promote faster decomposition and mineralization of organic matter compared to the temperate climate, characterized by lower temperatures that could reduce the rate of decomposition under high rainfall conditions.

Additionally, according to the national soil fertility standards (BUNASOLS, 1990), the density of 2000 shrubs ha$^{-1}$ showed an average level of OM (1.0–2.0%) and Total N (0.06–0.10%), while the other densities presented lower levels (0.5–1.0% for OM and 0.02–0.06% for Total N). The level of Av_K was definitively high at the density of 2000 shrubs ha$^{-1}$ (100–200 ppm) and moderate at the other densities (50–100 ppm). The higher biomass production associated with greater root activity could explain the improvement in soil fertility in terms of OM, total N and available K at a density of 2000 shrubs ha$^{-1}$ compared with other densities. Regardless of the density, the levels of Av_P and SBE were very low (< 5 ppm) and low (1–6 meq / 100 g), due to a possible lack of these nutrients in the woody biomass and soil. The OM and Total N contents reached an average level compared to the lower levels recorded in 2021, according to the same national standards. In contrast, regardless of the year, the Av_P and SEB levels were consistently very low and low, respectively.

### Effects of *Piliostigma reticulatum* planting densities on crop yields

The increase in organic matter and nutrient levels due to high shrub densities did not result in an increase in sorghum yields compared to low densities. However, for cowpea, there was a clear increase in grain yield with high shrub density. The absence of yield improvement in sorghum under high shrub planting density may be due to competition between the shrubs and the crop for water and nutrients. This is likely intensified by the shallow soil depth, which restricts sorghum, a crop known for its dense and deep root system, from accessing deeper soil layers (Chantereau et al. 2013). Our results on sorghum yields align with those obtained by Yélémou et al. (2014) in a similar agro-ecological context, showed that increasing amounts of *P. reticulatum* aboveground biomass did not improve sorghum yields. There are different from those of Félix et al. (2018) which showed an increase of sorghum yield with hight amounts (12 t $ha^{-1}$) of *P. reticulatum* aerial biomass. Camara et al. (2024) in Senegal found a decrease in sorghum grain yield with increasing density of *P. reticulatum* with arborescent growth habit. A more pronounced competition effect between shrubs and crops, due to the absence of pruning practices on *P. reticulatum* plants (Camara et al. 2024), could negatively affected sorghum production at high densities. Improvement in cowpea yield at hight density may be attributed to it shallow rooting system and prostrate growth habit, which reduce susceptibility to competition. In addition, its nitrogen-fixing capacity could contribute to maintaining grain yield even under higher *P. reticulatum* densities. Furthermore, the presence of *P. reticulatum* has been shown to enhance nutrient availability and uptake (Dossa et al. 2010; Diédhiou-Sall et al., 2021), which may further support cowpea productivity. Finally, improvement in cowpea yield is linked to better hydraulic redistribution induced by the presence of *P. reticulatum*, as demonstrated by Bogie et al. (2018) in the association of *P. reticulatum* with pearl millet. Our findings are consistent with those of Diang et al. (2024) in Sénégal, which also reported an improvement in cowpea yield at high *P. reticulatum* planting density (1200–1500 $shrubs.ha^{-1}$).

The improvement in crop productivity, particularly grain and straw yields of sorghum and grain yield of cowpea in 2022, could be attributed to more abundant and better distributed-rainfall, which improved both nutrient (mainly organic matter and total nitrogen), water and mineral nutrition of the crops. The positive impact of increased rainfall on sorghum and cowpea productivity has been widely emphasised in the literature ( Ikazaki et al. 2024; Ikpe et al. 2024; Sanou et al. 2023). However, the sorghum grain yields obtained in our study were below the potential yield of the variety, which could be explained by the deficiency of assimilable phosphorus in the soil, whose important role in improving sorghum productivity has been highlighted (Kouyaté and Sermé, 2021; Tonitto and Ricker-Gilbert 2016).

### Relationships between sorghum, cowpea grain yields, and soil nutrients

The decrease in sorghum yield with the increase in cowpea yield would be due to the competitive effect between the two crops, which was detrimental to sorghum. The decrease in organic matter content with the increase in sorghum grain yield could be related to the mineralization of organic matter leading to the release of nutrients in favour of sorghum. Then a higher uptake of available phosphorus by sorghum due to it key role in grain formation compared to other nutrients (Schlegel and Bond 2020) may explain the decline in soil phosphorus level. The increase in total nitrogen content despite the increase in sorghum grain yield could be due to low nutrient use efficiency by sorghum due to the arid climate (Salehin et al. 2020). The first hypothesis we could propose regarding the increase in exchangeable base (EB) content with the increase in sorghum grain yield is that these nutrients play a less important role in grain development compared with assimilable phosphorus. Furthermore, orthophosphate ions, which are retained by $Ca^{2+}$ and $Na^{+}$ ions through calcium orthophosphate and sodium orthophosphate complexes (Dossa et al. 2010; Dubus 1997;), would release these ions during their uptake by the plants, which could explain the increase in EB content with the increase in sorghum yield and the decrease in assimilable phosphorus content.

## Conclusion

Overall, our work demonstrated the positive influence of *P. reticulatum* density on the soil and, to some extent, on the crop, mainly through coppicing and mulching of its aerial biomass. The planting density of 500 shrubs ha$^{-1}$ resulted in the highest aboveground biomass yield per individual *P. reticulatum* shrub. In contrast, the higher densities produced the greatest total biomass per hectare. Soil parameter results showed that the 2000 shrubs ha$^{-1}$ density improved overall the soil organic status and nutrient availability compared to other densities, especially at the 0-10 cm depth. The study also showed that treatments with shrubs significantly increased cowpea grain yield compared to the control without shrubs, although the presence of shrubs did not improve sorghum productivity or increase cowpea straw yield. Adopting densities of 1000 or 2000 shrubs ha$^{-1}$ of *P. reticulatum* could be an interesting alternative to promote conservation agriculture in the face of crop residue availability problems. Our results suggest that adopting a density of 2000 shrubs ha$^{-1}$ in farmers' fields, combined with two coppicing practices during the rainy season, could ensure sustainable soil management in Sahelian agroecosystems and improve their productivity. However, phosphorus sources in the form of fertilizer or organic amendments should be added to the soil, as it is deficient in this element, which is essential for proper crop production. Given the limitation of the soil depth (30 cm) in the experimental plot, which could reduce the potential of *P. reticulatum*, we suggest that studies on species densities be carried out on other soil types without such limitations to further understand the potential for biomass production and soil fertility improvement. To better understand the influence of *P. reticulatum* densities on organic matter mineralisation processes, studies on microbial communities and enzymatic activities should be carried out.

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**Data availability** Data will be made available on request.

**Declarations**

**Conflict of interest** The authors declare no competing interests.



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