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Effects of amendment of biochar and *Gliricidia sepium* biomass on growth and yield of *Sorghum bicolor* under different agroforestry parklands in Northern Benin

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Abstract Over recent decades, soil fertility across West Africa has progressively declined due to unsustainable land management practices, resulting in reduced agricultural productivity and crop yields. To address this challenge, the adoption of sustainable techniques such as agroforestry has become increasingly critical. This study aimed to evaluate the effects of biochar and *Gliricidia sepium* biomass amendments on the performance of *Sorghum bicolor* within different agroforestry tree species environment. A split-plot experimental design was implemented, comprising three blocks, each associated with a distinct tree species: *Parkia biglobosa*, *Vitellaria paradoxa*, and *Lannea microcarpa*. Within each block, four soil amendment treatments (control, *Gliricidia* biomass, biochar, and *Gliricidia* + biochar) were applied in concentric zones located beneath and outside the tree canopy. A generalized linear mixed-effects model was used to analyze leaf number variation, while a linear mixed-effects model assessed the impact of amendments on sorghum growth and yield parameters. The findings revealed that the spatial position within the agroforestry tree environment significantly influenced sorghum performance. The highest grain yields were recorded under *Parkia biglobosa*, whereas *Vitellaria paradoxa* and *Lannea microcarpa* were associated with reduced plant height, leaf number, and grain weight. Although soil nitrogen content and water retention were not directly measured, the positive effects of the combined amendment are consistent with previously reported improvements in nutrient availability and soil physical properties. Overall, these findings highlight the importance of tree species selection and integrated soil amendment strategies in enhancing sorghum productivity within agroforestry parkland systems on degraded soils.

Keywords Soil fertility · Agroforestry systems · Biochar and *Gliricidia sepium* · *Sorghum bicolor* · Crop yield · West Africa

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Introduction

Over the past few decades, soils in West Africa have experienced a gradual decline in fertility due to

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unsustainable land-use practices, leading to reduced agricultural productivity and crop yields. Agriculture in the region is predominantly rain-fed and subsistence-based and is characterized by inherently low soil fertility (Adebiyi et al. 2019; Doamba et al. 2011; Saidou et al. 2013; Sissoko et al. 2020). Despite these limitations, the agricultural sector contributes approximately 30% to the gross domestic product (GDP) and employs over 50% of the working population (Yabi et al. 2016). In Benin, as in other sub-Saharan African countries, soil fertility degradation is a widespread issue, with its severity varying across localities. Declining soil fertility represents a major constraint to agricultural productivity (Adebiyi et al. 2019; Nambima et al. 2023; Yabi et al. 2012). This degradation is primarily driven by inappropriate agricultural practices, soil erosion, and overgrazing. These factors are further exacerbated by increasing climatic variability, characterized by prolonged dry seasons, intense rainfall events, and strong winds, which collectively accelerate soil degradation processes under changing climatic conditions (Adebiyi et al. 2019; Nambima et al. 2023). To sustain crop production, the application of mineral or organic fertilizers is often required. However, economic constraints faced by smallholder households limit their adoption. Consequently, low-cost alternatives such as the integration of natural woody vegetation into cropping systems offer promising solutions that align with the socio-economic realities of local farmers (Abdou et al. 2014; Tschora and Cherubini 2020). Moreover, agricultural production continues to struggle to meet the demands of a rapidly growing population.

The drivers of soil degradation are both climatic and anthropogenic. The dissemination and adoption of efficient soil fertility management techniques therefore remain major challenges for the sustainable intensification of agro-pastoral production systems (Nacro et al. 2011). Agroforestry, which integrates trees, crops, and livestock within the same land management system, provides numerous environmental and agricultural advantages (Sekhar et al. 2024). This integration of agriculture and forestry is increasingly viewed as a viable strategy for enhancing food security while delivering a wide range of environmental benefits. Accordingly, farmers adopt agroforestry practices to improve crop yields, obtain wood products, and generate income, while building on traditional knowledge to conserve useful species of economic or medicinal value (Sawadogo 2011). Previous studies have shown that associating crops with tree species exhibiting complementary functional traits can enhance agroecosystem multifunctionality (Blesh 2018) and that managing plant community composition represents a promising approach to increasing agricultural productivity (Sauvadet et al. 2020). In some systems, trees provide partial shade that reduces crop physiological stress, pest pressure, and disease incidence, as observed in cocoa-based agroforestry systems (Andres et al. 2016). Nevertheless, excessive shading may also reduce crop growth and yield due to light interception (Sekhar et al. 2024; Sauvadet et al. 2020), highlighting the importance of tree species selection.

In Parallel, biochar has emerged as a promising soil amendment for improving soil fertility, crop yields, and carbon sequestration. Its application increases soil organic carbon (SOC) and total nitrogen (TN) contents and reduces soil bulk density, resulting in significant improvements in crop productivity (Azeem et al. 2019). These benefits are attributed to biochar's high specific surface area and reactive functional groups, which enhance nutrient retention and cation exchange capacity (Kookana et al. 2011; Mounirou 2022; Sohi et al. 2010; Verheijen et al. 2010). Beyond fertility enhancement, biochar contributes to sustainable soil management and climate change mitigation (Allaire and Lange 2013; Mounirou 2022). However, persistent nutrient leaching, widespread land degradation across Africa (Lompo et al. 2021; OCDE 2013; UNEP, 2017), and the limited availability of conventional soil amendments highlight the need for innovative soil management strategies. The use of biochar, alone or in combination with *Gliricidia sepium* biomass, may not only improve soil fertility and biodiversity but also enhance production sustainability while reducing input costs.

Although agroforestry systems and biochar amendments have been widely studied, most previous research has examined their effects independently, with limited attention to their combined impacts under field conditions. Moreover, in West African agroforestry parklands, dominant tree species such as *Parkia biglobosa*, *Vitellaria paradoxa*, and *Lannea microcarpa* differ markedly in canopy structure, shading intensity, and rooting depth, which may strongly influence crop responses to soil amendments. Tree

species–specific interactions between shading, belowground competition, and soil amendment responses therefore remain poorly documented, particularly for sorghum-based systems in Northern Benin.

The main objective of this study is to assess the effects of biochar and *Gliricidia sepium* biomass incorporation on the growth and yield of *Sorghum bicolor* cultivated under an agroforestry tree environment. Specifically, this study aims to: (i) determine whether biochar and *G. sepium* biomass amendments significantly enhance *Sorghum bicolor* growth and yield; and (ii) evaluate the extent to which these amendment effects are influenced by the surrounding agroforestry tree species.

Based on these objectives, the following hypotheses were tested: (H1) Biochar and *Gliricidia sepium* biomass amendments, applied alone or in combination, significantly enhance the growth and yield of *Sorghum bicolor* compared to unamended soils; (H2) The magnitude of sorghum response to these amendments varies among agroforestry tree species due to differences in canopy characteristics and belowground resource competition; and (H3) The combined application of biochar and *Gliricidia sepium* biomass produces greater improvements in sorghum performance than either amendment applied alone.

Materials and methods

Study environment

This study was conducted in agroforestry parklands of northern Benin, West Africa, precisely in the commune of Cobly, located in the northwestern part of the country along the border with the Republic of Togo. Cobly is bordered to the north by the Commune of Matéri, Boukombé to the south, Tanguiéta to the east, and Togo to the west. The site was selected due to its low soil fertility and vulnerability to climate change and food insecurity (Aleza et al. 2018). Cobly lies within the Sudanian agro-ecological zone, between latitudes 9°45′ and 12°25′ N. In general, the Sudanian zone is characterized below annual rainfall 900 m, with relative humidity ranging from 18% during the harmattan season to 99% in August (Arbonnier, 2009; Ekué et al. 2004). The region experiences pronounced diurnal temperature variations, exacerbated by climatic variability that has led to global warming, intermittent droughts, and intense winds. Temperatures typically range from 24 °C to 41 °C. In addition, the presence of mountain ranges favors more frequent and abundant rainfall in certain high-altitude communes, as emphasized by (Houssou 1998). However, climatic variability has caused major upheavals, resulting in global warming, pockets of drought and violent, intense winds. Temperatures in this zone fluctuate between 24 °C and 41 °C. The landscape of the Sudanian zone is dominated by savannahs and gallery forests, composed of small trees offering moderate ground cover. Evapotranspiration is around 1600 mm (Ekué et al. 2004). The harmattan's effect on the water balance is significant in the dry season. Slash-and-burn agriculture is the most common land use in the area (Ekué et al. 2004). *Sorghum bicolor* ssp bicolor (L.) Moench is an important cereal in cropping systems and diets in many African countries. Alongside maize, it constitutes one of the staple cereals in the Atacora region of Benin, playing a vital role in food security and rural livelihoods (Fig. 1).

Experimental design

The experiment was conducted using a split-plot design with agroforestry tree species as the main-plot factor and soil management practices as sub-plot factors. Three dominant agroforestry parkland tree species were considered as main plots: *Parkia biglobosa*, *Vitellaria paradoxa*, and *Lannea macrocarpa*. For each species, three individual trees with similar diameter at breast height (DBH; mean = 8.25 cm) and located under uniform environmental conditions were selected, resulting in three replicates per tree species. Each individual tree represented one main-plot experimental unit. Within each tree (main plot), subplots were arranged in concentric rings around the tree trunk (Fig. 2) to account for the spatial influence of the canopy and root system. Two sub-plot factors were tested in a factorial arrangement: (i) position relative to the tree canopy with two levels (under crown and outside crown), and (ii) soil amendment with four levels (control, *Gliricidia sepium* biomass, biochar, and *Gliricidia sepium* biomass + biochar). This resulted in eight treatment combinations per tree. The eight sub-plot treatments were randomly assigned within the concentric zones under and outside the canopy for each tree individual. *Sorghum bicolor* was directly sown in planting holes within each sub-plot.

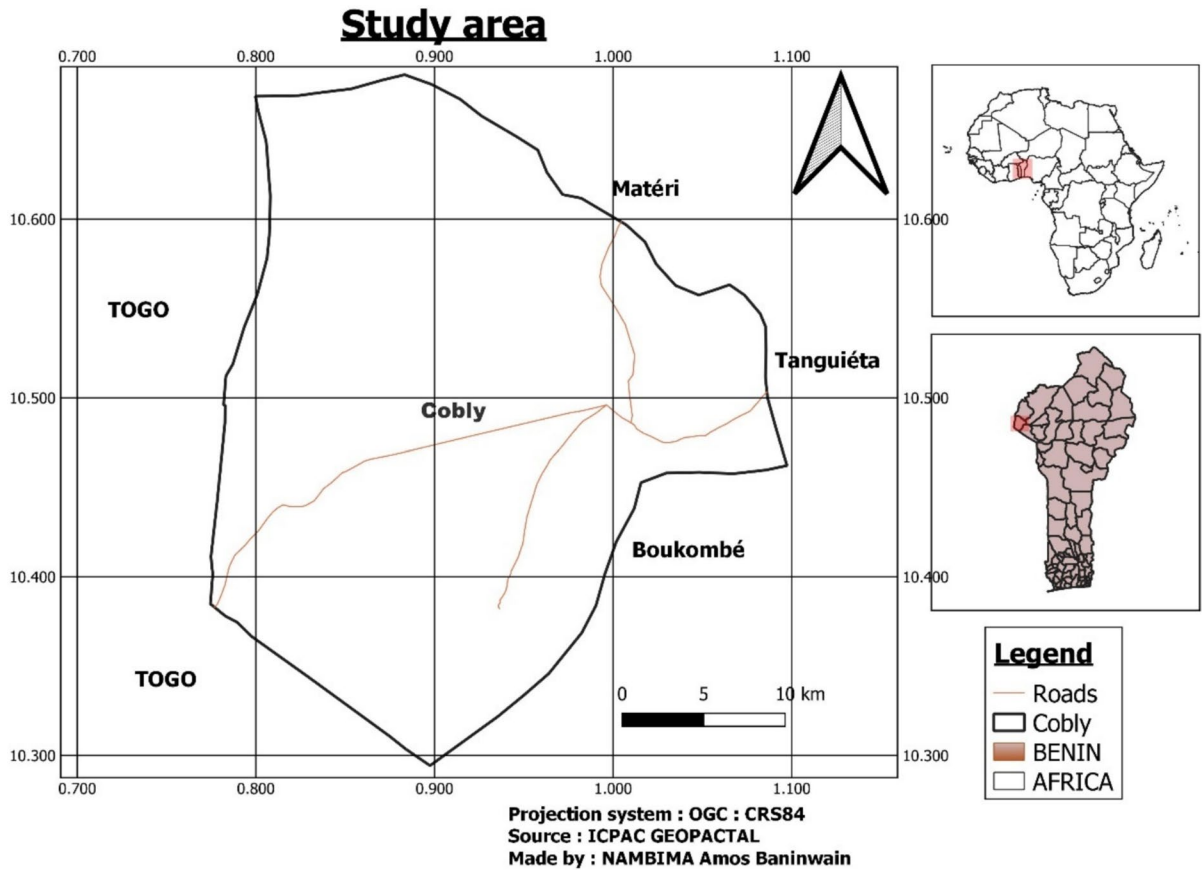


Fig. 1 Map illustrating the study location

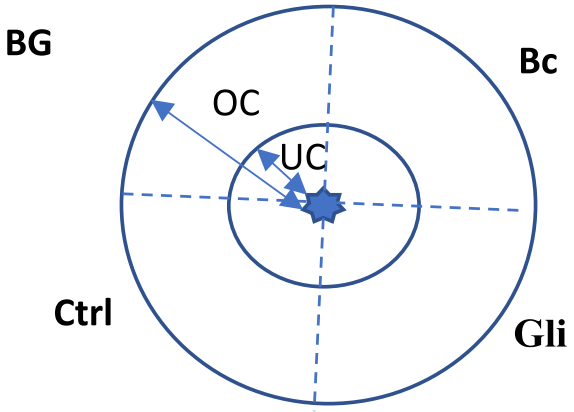


Fig. 2 Experimental plot set on each tree individual

The experiment was conducted over two consecutive cropping seasons using the same tree individuals, with soil amendments reapplied at the beginning of each season. The concentric layout was used to minimize directional bias in crop performance and to clearly distinguish zones influenced by tree canopy and rooting effects.

Rate and method of *Gliricidia sepium* biomass and biochar application

Sorghum bicolor requires an average nitrogen input of approximately 50 kg N ha^{-1} to achieve optimal growth and yield. As a green manure, an annual production of 15 t ha^{-1} of fresh foliar biomass can supply the equivalent of 40–70 kg N ha^{-1} yr^{-1} (Ouedraogo et al. 2023), justifying the use of *Gliricidia sepium* biomass as an alternative nitrogen source. To estimate dry matter content, three samples of 100 g of fresh *Gliricidia* leaf biomass were oven-dried at 105 °C for 48h. The mean dry mass obtained was 14.15 g, corresponding to a dry matter content of 14.15%.

Gliricidia biomass was initially harvested under field conditions and subsequently air-dried under shade in a greenhouse for one month to avoid direct solar radiation, biological attacks, and weather-related losses (Nambima, 2019). During the drying period, the biomass was turned daily to minimize infestation by nematodes, fungi, and mites. Sorghum was planted at a spacing of 0.80 m × 0.50 m, corresponding to a density of 25,000 planting hills ha^{-1}, with two plants per hill. Based on a total application rate of 2 t ha^{-1} of *Gliricidia sepium* biomass, each planting hill received 40 g of biomass. Biochar was applied at a rate of 300 kg ha^{-1}, equivalent to 12 g per planting hill. The biochar used in the experiment was produced from maize (*Zea mays*) crop residues. Both *Gliricidia* biomass and biochar were incorporated 15 days after sowing into planting holes approximately 5 cm deep, placed close to the sorghum plants, and subsequently covered with soil to maximize agronomic efficiency by improving nutrient availability and water retention within the root zone.

Growth and yield measuring

Plant height was measured using a tape measure graduated to the nearest millimeter, from the soil surface at the collar to the tip of the apical leaf during the vegetative stage, and from the collar to the tip of the panicle at heading. Measurements were conducted at 30 and 60 days after sowing (DAS). For each treatment, measurements were taken on three randomly selected Sorghum bicolor plants per plot.

Vegetative growth was further assessed by counting the number of fully expanded leaves per plant and by measuring the length of the largest fully expanded leaf using a tape measure. These parameters were selected because the experiment was conducted under farmer field conditions rather than in a controlled environment, where access to specialized equipment required for direct measurements of leaf area or Leaf Area Index (LAI) was not feasible. Leaf number and the length of the largest leaf are widely used proxy indicators of canopy development in cereal crops and have been shown to correlate with leaf area expansion and biomass accumulation in field-based agronomic studies. Their use therefore provides a practical and reliable approach for assessing crop vegetative performance in smallholder farming contexts. At physiological maturity, panicles were harvested for each treatment, air-dried, and weighed to determine grain yield. Stems were cut at the collar, oven-dried to constant weight, and weighed to estimate aboveground biomass yield. Grain and biomass yields were expressed per treatment and per agroforestry tree species.

Data analysis

Linear mixed-effects models were applied to evaluate the three growth parameters (*Sorghum* height, number of leaves, and length of the largest leaf) and two yield performance parameters (biomass and grain weight), reflecting the nested structure of the data. Given that leaf number is a count variable, generalized linear mixed models (GLMM) with a Poisson distribution were employed. For growth traits, random effects were specified to reflect the hierarchical nesting of individual *Sorghum bicolor* plants within trees, while yield models included only the random intercept of individual trees. Fixed effects included soil amendment, tree species, canopy position (under vs. outside crown), year, and time (for growth data), along with their possible interactions, except those involving time. Model selection was carried out through backward elimination of random effects followed by fixed effects. All models were fitted using restricted maximum likelihood (REML), and model assumptions were evaluated via residual diagnostics. Statistical analyses were performed in R (R Core Team 2021) using the *lmerTest* package (Stegmann et al. 2018).

Results

Effect of treatments on *Sorghum bicolor* growth

Effect of treatments on Sorghum bicolor plant height

Table 1 presents the statistical analysis of factors influencing the height of *Sorghum bicolor*. The results indicate that time ($p < 0.001$), year (< 0.001), soil amendment (< 0.001), spatial position (< 0.001) are significant determinants of *Sorghum b.* plant height. Moreover, several interaction effects were statistically significant, indicating complex variation patterns. Specifically, the effect of amendment varied across years ($p = 0.023$), and species

Table 1 Effect of amendment, position and time on *Sorghum bicolor* plant height

Term	sumsq	meansq	NumDF	DenDF	F value	*p*.value
Time	2,370,806.807	2,370,806.807	1	431	2121.853	< 0.001
year	211,184.145	211,184.145	1	397	189.008	< 0.001
Species	251.021	125.511	2	6	0.112	0.896
Amendment	552,613.457	184,204.486	3	397	164.862	< 0.001
Position	87,924.514	87,924.514	1	397	78.692	< 0.001
Year:amendment	10,735.604	3578.535	3	397	3.203	0.023
Species:amendment	22,314.993	3719.165	6	397	3.329	0.003
Year:position	5772.125	5772.125	1	397	5.166	0.024
Species:position	8131.493	4065.747	2	397	3.639	0.027
Amendment:position	59,753.675	19,917.892	3	397	17.826	< 0.001
Species:amendment:position	23,492.413	3915.402	6	397	3.504	0.002

($p = 0.003$). Similarly, the influence of position differed by year ($p = 0.024$), species ($p = 0.027$), and traitment ($p < 0.001$). Additionally, both position and treatment effects varied significantly across species ($p = 0.002$). These findings highlight the intricate interplay between temporal, biological, and environmental factors in shaping sorghum growth dynamics.

Table 1 summarizes the mixed-effects ANOVA results for *Sorghum bicolor* plant height. The analysis indicates that time of measurement, cropping year, soil amendment type, and spatial position relative to the tree canopy all had a highly significant effect on sorghum plant height ($p < 0.001$). In contrast, tree species alone did not exert a significant main effect on plant height ($p = 0.896$).

Several interaction effects were statistically significant, highlighting the context-dependent nature of sorghum growth responses. In particular, the effect of soil amendment varied significantly across years (year × amendment; $p = 0.023$) and tree species (species × amendment; $p = 0.003$). Similarly, the influence of spatial position differed according to year (year × position; $p = 0.024$), tree species (species × position; $p = 0.027$), and soil amendment (amendment × position; $p < 0.001$). A significant three-way interaction among tree species, soil amendment, and spatial position ($p = 0.002$) further indicates that the combined effects of these factors jointly shaped sorghum height responses. While Table 1 identifies the statistically significant sources of variation, the magnitude and direction of these effects are presented in subsequent figures and tables, which allow a detailed interpretation of treatment-specific responses.

Figure 3 demonstrates strong and consistent effects of soil amendment, agroforestry tree species, crown position, and temporal factors on Sorghum bicolor plant height. Importantly, the magnitude of height differences among treatments is substantial and varies with species, position, and year.

Across all three tree species (Lannea microcarpa, Parkia biglobosa, and Vitellaria paradoxa), sorghum plants grown outside the tree crown (OC) were consistently taller than those grown under the crown (UC), regardless of soil amendment. Under Lannea microcarpa, mean sorghum height outside the crown increased from approximately 265 cm in the control to ~ 300 cm with biochar, ~ 365 cm with *Gliricidia sepium*, and ~ 405 cm with the combined *Gliricidia* + biochar treatment. This corresponds to an absolute increase of ~ 140 cm, or approximately 53%, between the control and the combined amendment. Under the crown, sorghum height ranged from ~ 250 cm (control) to ~ 335 cm (*Gliricidia* + biochar), indicating a reduction of about 70 cm compared with the outside-crown position. Under Parkia biglobosa, which exerted the weakest shading effect, sorghum height outside the crown increased from ~ 275 cm (control) to ~ 385 cm (*Gliricidia* + biochar), representing a gain of ~ 110 cm (≈40%). Under the crown, height ranged from ~ 265 to ~ 345 cm, corresponding to an average reduction of ~ 40 cm relative to outside-crown conditions. Under Vitellaria paradoxa, the lowest sorghum heights were observed, particularly under the crown. Outside the crown, plant

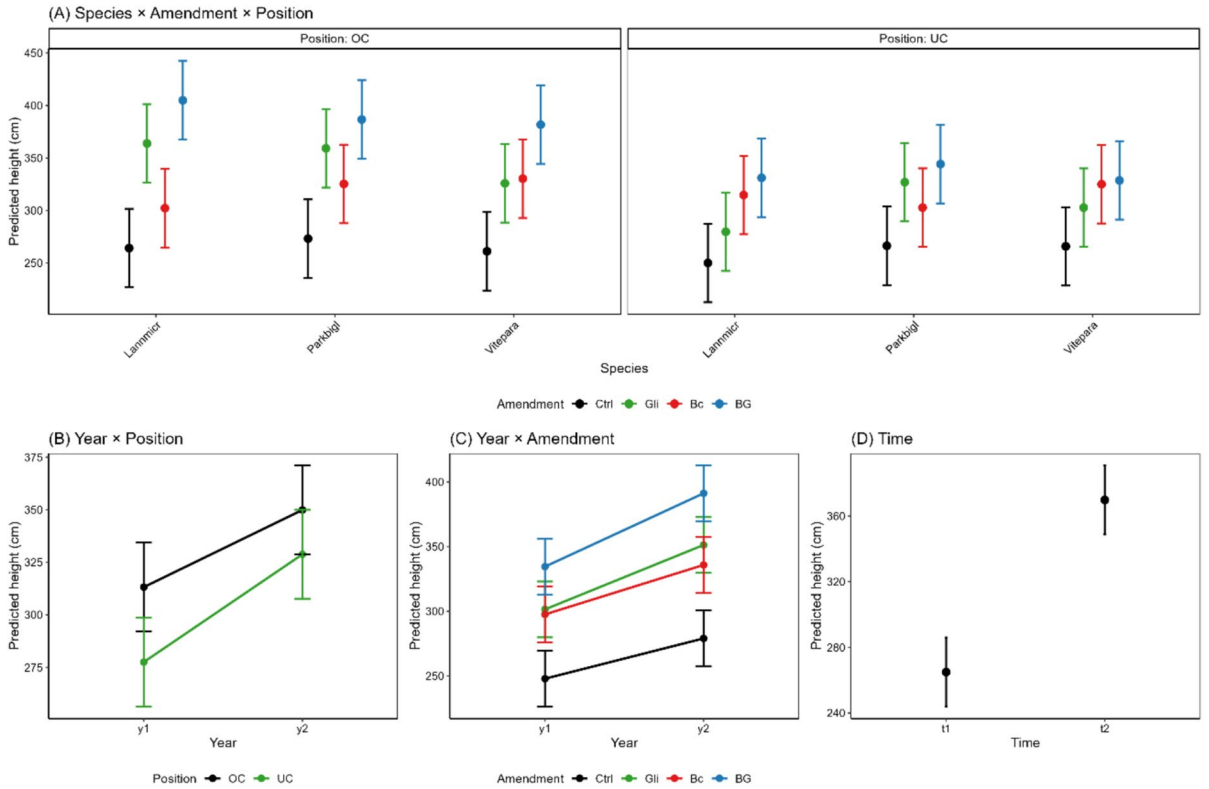


Fig. 3 Effect of amendment, position, time and year on *Sorghum bicolor* plant height

height increased from ~ 260 cm (control) to ~ 380 cm (*Gliricidia* + biochar), an increase of ~ 120 cm (≈46%). Under the crown, heights ranged from ~ 265 to ~ 330 cm, again highlighting the combined effects of shading and amendment. Across all species and positions, the *Gliricidia* + biochar treatment consistently produced the tallest plants, followed by *Gliricidia* alone, biochar alone, and the control.

From the first year (y_1) to the second year (y_2), sorghum height increased at both positions. Outside the crown, mean height increased from ~ 315 to ~ 350 cm (+ 35 cm; ≈ 11%), while under the crown it increased from ~ 275 to ~ 330 cm (+ 55 cm; ≈ 20%). Despite this greater relative increase under the crown, sorghum plants remained consistently taller outside the crown in both years.

Sorghum height increased from year one to year two for all amendments, but the magnitude of increase differed among treatments. The control increased from ~ 250 to ~ 280 cm (+ 30 cm; ≈ 12%), *Gliricidia* from ~ 300 to ~ 350 cm (+ 50 cm; ≈ 17%), biochar from ~ 295 to ~ 335 cm (+ 40 cm; ≈ 14%), and the combined *Gliricidia* + biochar treatment from ~ 335 to ~ 395 cm (+ 60 cm; ≈ 18%). This indicates that the combined amendment not only resulted in the greatest absolute plant height but also exhibited the strongest inter-annual response.

Plant height increased significantly between the two measurement times, from approximately 260 cm at t_1 to ~ 370 cm at t_2, corresponding to an increase of ~ 110 cm (≈ 42%), reflecting normal crop growth dynamics and supporting the strong time effect identified in the ANOVA.

Effect of amendments and time on Sorghum bicolor leaf length

Table 2 shows the various parameters affecting *Sorghum* leaf length. Time, position, amendment and year are the factors that have a significant impact ($p < 0.001$) on *Sorghum* leaf length. From one amendment to another, the variation in *Sorghum* leaf length is not the same for the same position ($p < 0.001$).

Table 2 Effect of amendments and time on *Sorghum bicolor* leaf length

Term	sumsq	meansq	NumDF	DenDF	F value	*p*.value
Time	2845.630	2845.630	1	431	201.213	< 0.001
Position	292.524	292.524	1	409	20.684	< 0.001
Species	17.736	8.868	2	6	0.627	0.566
Amendment	1385.472	461.824	3	409	32.655	< 0.001
Year	1254.537	1,254.537	1	409	88.708	< 0.001
Position:amendment	513.370	171.123	3	409	12.100	< 0.001
Species:amendment	510.906	85.151	6	409	6.021	< 0.001

Similarly, across amendments, the variation is not the same for the same species.

Figure 4 illustrates the effects of soil amendment, agroforestry tree species, crown position, year, and time on the length of the largest fully expanded leaf of *Sorghum bicolor*. Beyond qualitative trends, the magnitude of differences among treatments is substantial and varies according to species and spatial position.

Across all tree species, sorghum leaf length increased progressively from the control to biochar, *Gliricidia sepium*, and the combined *Gliricidia* + *biochar* amendment. Under *Lannea microcarpa*, mean leaf length increased from approximately 95 cm in the control to ~ 98 cm with biochar, ~ 93 cm with *Gliricidia*, and ~ 103 cm with *Gliricidia* + biochar. Compared with the control, the combined amendment increased leaf length by ~ 8 cm (≈ 8%), whereas *Gliricidia* alone slightly reduced leaf length by ~ 2 cm (≈ 2%), indicating a species-specific response. Under *Parkia biglobosa*, leaf length ranged from ~ 99 cm (control) to ~ 104 cm (*Gliricidia* + biochar),

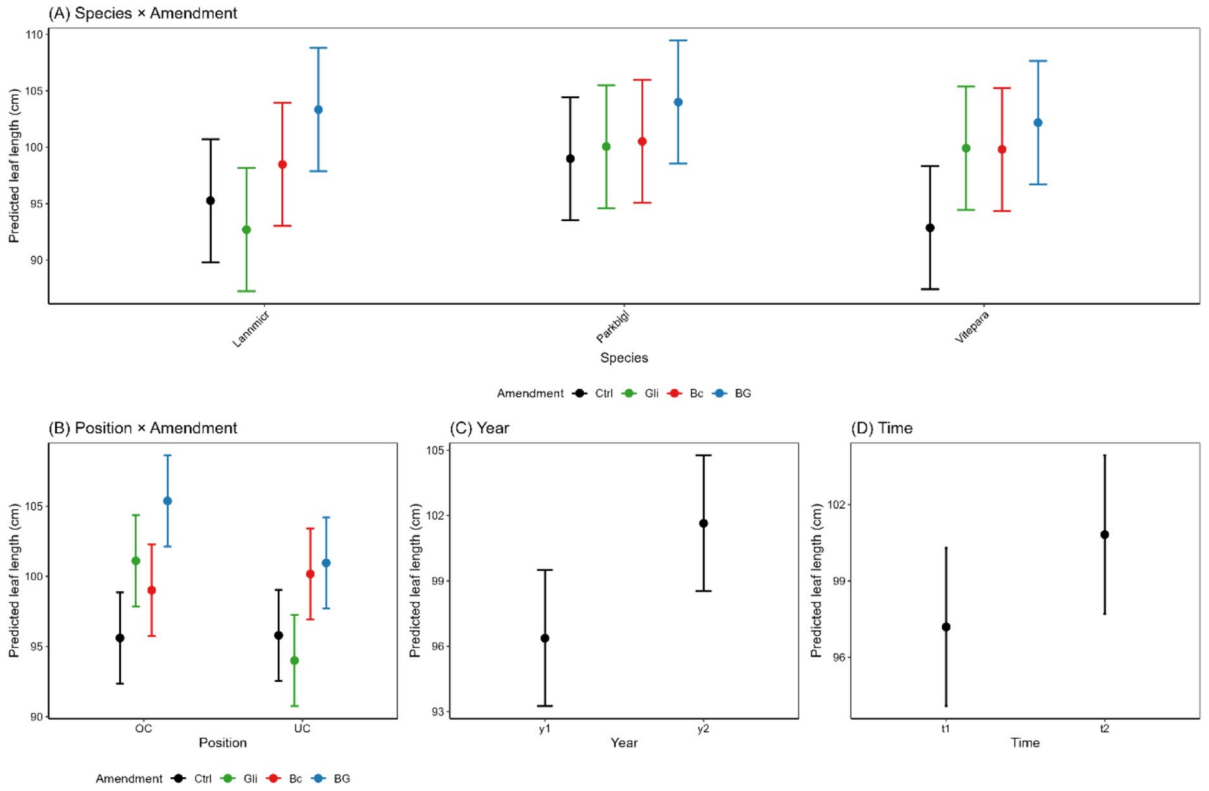


Fig. 4 Effect of amendment, position and time on *Sorghum bicolor* leaf length

corresponding to an increase of ~ 5 cm (≈ 5%). Both biochar and *Gliricidia* alone produced intermediate values (~ 100–101 cm), confirming that *Parkia biglobosa* provided the most favorable conditions for leaf expansion across all amendments. Under *Vitellaria paradoxa*, leaf length increased from ~ 93 cm (control) to ~ 102 cm (*Gliricidia* + biochar), an increase of ~ 9 cm (≈ 10%). Biochar and *Gliricidia* alone increased leaf length by ~ 7 cm (≈ 7%) relative to the control. Across all species, the *Gliricidia* + biochar treatment consistently produced the longest leaves, while the control resulted in the shortest leaf lengths.

Figure 4B shows that, for most amendments, sorghum plants grown under the crown (UC) exhibited slightly longer leaves than those grown outside the crown (OC). Across treatments, leaf length under the crown exceeded outside-crown values by approximately 2–4 cm (≈ 2–4%). An exception was observed for the biochar treatment, where leaf length was similar between positions, with a marginal increase of ~ 1 cm under the crown. This suggests that biochar application may partially mitigate the negative effects of shading on leaf elongation.

From the first year (y_1) to the second year (y_2), sorghum leaf length increased significantly. Mean leaf length increased from approximately 96–97 cm in y_1 to ~ 102 cm in y_2, corresponding to an increase of ~ 5–6 cm (≈ 5–6%). This trend was observed across all amendments, including the control, indicating a strong inter-annual environmental effect.

Figure 4D highlights a strong temporal growth effect. Leaf length increased from approximately 97 cm at t_1 to ~ 101 cm at t_2, representing a gain of ~ 4 cm (≈ 4%), consistent with normal crop development between measurement times.

Effect of time, amendment and position on Sorghum bicolor leaves number

Table 3 highlights the main factors influencing variation in *Sorghum* leaf number throughout the experiment. Time ($p < 0.001$), year ($p < 0.001$), amendment type ($p < 0.001$) and position under the tree ($p = 0.033$) all had a statistically significant effect on this variation.

Table 3 illustrates the influence of various parameters on the variation in the number of *Sorghum* leaves. It appears that between two measurement periods (t1 and t2), the number of leaves increases significantly.

Table 3 Effect of amendments on *Sorghum bicolor* leaf number

Term	nby	AIC	LRT	*p*.value
< None >		4246.202		
Time	1	4370.022	125.820	< 0.001
Year	1	4319.762	75.560	< 0.001
Amendment	3	4332.156	91.954	< 0.001
Position	1	4248.752	4.550	0.033

additionally, a significant increase in the number of leaves was observed from one year to the next. Among the soil amendments, the Biochar + *Gliricidia* treatment resulted in the highest number of leaves, whereas the control treatment recorded the lowest values. furthermore, the number of leaves was significantly greatest outside the shading system compared to those under shade, suggesting a negative impact of shading on *Sorghum* leaf development.

Effect of amendment on *Sorghum bicolor* above-ground dry biomass yield and grain yield

Analysis results show that *Sorghum* dry weight above-ground biomass yield varies significantly with year, position and amendment.

Yearly cumulative effect

Both weight parameters showed substantial year effects. Total weight above-ground biomass yield increased from 63 to 75 g ($F_{1,41^3} = 226.16$, $p < 0.001$) representing a 19% increase while grain yield increasing from 13 g in first year to 20 g in second year ($F_{1,^3 99} = 416.32$, $p < 0.001$) representing 54% of increase. These changes exceeded normal annual fluctuation, suggesting a genuine cumulative effect of the amendments over the first two years.

Amendment effect

Amendment effects were highly significant for both total dry weight above-ground dry biomass yield ($F_{3,41^3} = 67.52$, $p < 0.001$) (Table 4) and grain weight grain yield ($F_{3,^3 99} = 96.36$, $p < 0.001$) (Table 5). The biochar + gliricida combination produced the highest yields with 85 g total weight above-ground biomass yield and 27 g grain weight yield, corresponding to

Table 4 Effect of amendment, position and year on *Sorghum bicolor* biomass gain

Term	sumsq	meansq	NumDF	DenDF	F value	*p*.value
Year	14,863.787	14,863.787	1	413	226.157	< 0.001
Species	629.308	314.654	2	6	4.788	0.057
Amendment	13,312.241	4437.414	3	413	67.517	< 0.001
Position	6896.010	6896.010	1	413	104.925	< 0.001
Year:amendment	1753.861	584.620	3	413	8.895	< 0.001
Species:position	2998.755	1499.377	2	413	22.813	< 0.001

Table 5 Effect of amendment, position and year on *Sorghum bicolor* seed weight

Term	sumsq	meansq	NumDF	DenDF	F value	p.value
Species	2.282	1.141	2	6	5.386	0.046
Amendment	61.251	20.417	3	399	96.360	< 0.001
Year	88.211	88.211	1	399	416.321	< 0.001
Position	15.257	15.257	1	399	72.009	< 0.001
Species:amendment	2.897	0.483	6	399	2.279	0.036
Species:year	2.485	1.242	2	399	5.863	0.003
Amendment:year	2.082	0.694	3	399	3.275	0.021
Species:position	9.218	4.609	2	399	21.752	< 0.001
Species:amendment:year	10.625	1.771	6	399	8.358	< 0.001

increase of 33% and 62% respectively, compared to the controls in year 2.

Critical year × amendment interactions (total weight above-ground biomass yield: $F_{3,413} = 8.90$, $p < 0.001$; grain weight yield: $F_{3,399} = 3.28$, $p = 0.021$) revealed that cumulative effects were most pronounced in treatments involving organic amendments.

Crown position effect

Species' crown effects were significantly affected both total dry weight above-ground dry biomass yield ($F_{1,413} = 104.93$, $p < 0.001$); and grain weight yield ($F_{1,399} = 72.01$, $p < 0.001$), with higher yields observed outside trees crowns. However, significant species × position interactions revealed species-specific patterns where Parkia's crown didn't reduce yield performance. The significant three-way interaction for grain yield weight (species × amendment × year: $F_{6,399} = 8.36$, $p < 0.001$) indicated the complex variation in yield that can occur along factors changes.

Effect of amendment, position and year on Sorghum bicolor dry weight

Table 4 shows that the dry weight above-ground dry biomass yield of *Sorghum* varies significantly with year ($p < 0.001$), amendment ($p < 0.001$) and position in relation to the crown ($p < 0.001$). The table also shows that, within the same year, variations in dry weight above-ground dry biomass yield differ from one amendment to another ($p < 0.001$). Furthermore, the variation in dry weight above-ground dry biomass yield of *Sorghum* according to position (under or outside the head) is not uniform within the same species ($p < 0.001$).

Figure 5 demonstrates that the dry weight above-ground dry biomass yield of *Sorghum b.* varies significantly depending on the type of amendment applied, the year of cultivation and the species, particularly outside the hops zone. For a given amendment, *Sorghum* dry weight above-ground dry biomass yield is significantly higher in the second year than in the

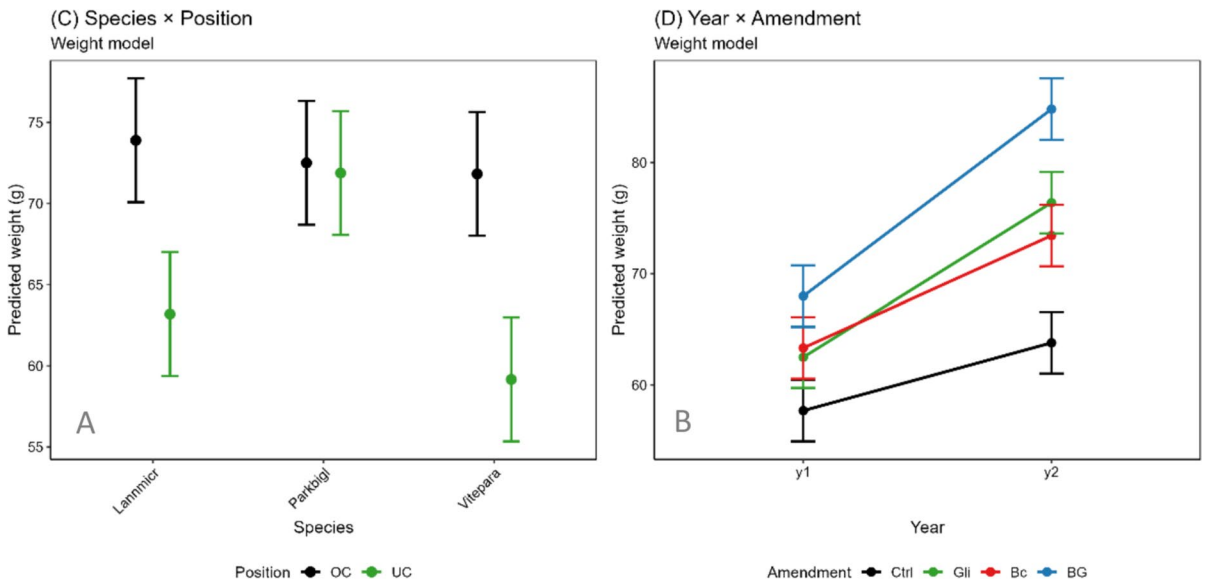


Fig. 5 Effect of amendment, position and year on *Sorghum bicolor* dry weight

first (Fig. 5B). Moreover, the Biochar amendment combined with *Gliricidia* proved the most effective, recording the highest dry weights, while the control showed the lowest performance. No significant difference in dry weight above-ground dry biomass yield was observed between (Fig. 5A). in contrast, *Parkia biglobosa* stood out with the best *Sorghum* dry weights, followed by *Lannea microcarpa* and *Vitellaria paradoxa*. These findings suggest that shading of *Parkia biglobosa* has a less negative impact on *Sorghum* biomass compared with the other species studied, particularly *Vitellaria paradoxa*.

Effect of amendment, position and year on Sorghum bicolor grain weight

Table 5 shows that *Sorghum* grain weight grain yield varies significantly with species ($p = 0.046$), amendment type ($p < 0.001$), year ($p < 0.001$) and position relative to the tree ($p < 0.001$). Several significant interactions were also observed. Within the same species, grain weight grain yield variation differed according to the amendments applied ($p = 0.036$). For the same species, yields also varied from one year to the next ($p = 0.030$). For a given amendment, grain yield also varied across years ($p = 0.021$). The position in relation to the tree influenced differently on the yield depending on the species considered ($p < 0.001$). Furthermore, a significant interaction between year, amendment and species, was observed, indicating that grain yields vary in a complex way depending on the combination of these factors ($p < 0.001$). These fundings highlight the importance of jointly considering tree species, amendment, year and position when interpreting *Sorghum* performance.

Figure 5 illustrates the effects of agroforestry tree species, crown position, year, and soil amendment on the above-ground dry biomass yield of *Sorghum bicolor*. In contrast to a purely descriptive interpretation, clear quantitative differences among treatments and factors are evident.

Figure 5A shows that crown position strongly influenced sorghum above-ground dry biomass, with consistently higher biomass outside the crown (OC) than under the crown (UC) across all tree species. Under *Lannea microcarpa*, sorghum biomass outside the crown averaged approximately 74 g plant^{-1}, while under the crown it decreased to ~ 63 g plant^{-1}, representing a reduction of ~ 11 g (≈ 15%) due to shading. Under *Parkia biglobosa*, biomass outside the crown reached ~ 73 g plant^{-1}, compared with ~ 72 g plant^{-1} under the crown, indicating only a ~ 1 g (≈ 1–2%) reduction. This minimal difference confirms that *Parkia biglobosa* exerts the least negative shading effect on sorghum biomass. Under *Vitellaria paradoxa*, biomass declined from ~ 72 g plant^{-1}

outside the crown to ~ 59 g plant^{-1} under the crown, corresponding to a reduction of ~ 13 g (≈ 18%), the strongest shading effect observed among the species. Overall, these results demonstrate that tree species modulate the magnitude of biomass reduction under canopy cover, with *Parkia biglobosa* being the most favorable species for sorghum biomass production.

Figure 5B highlights strong inter-annual and amendment effects on above-ground dry biomass yield. Across all amendments, sorghum biomass increased substantially from the first year (y_1) to the second year (y_2). In the control treatment, biomass increased from approximately 58 g plant^{-1} in y_1 to ~ 63 g plant^{-1} in y_2, representing an increase of ~ 5 g (≈ 9%). For *Gliricidia sepium*, biomass increased from ~ 60 to ~ 76 g plant^{-1}, corresponding to a gain of ~ 16 g (≈ 27%). Biochar alone resulted in an increase from ~ 62 to ~ 73 g plant^{-1}, a gain of ~ 11 g (≈ 18%). The combined *Gliricidia* + *biochar* treatment showed the strongest response, with biomass increasing from ~ 68 g plant^{-1} in y_1 to ~ 84 g plant^{-1} in y_2, representing an increase of ~ 16 g (≈ 24%). Compared with the control in the second year, this combined amendment increased biomass by approximately 21 g plant^{-1} (≈ 33%).

Discussion

Sorghum bicolor growth variation according to amendment, position and year

Analysis of experimental data reveals that *Sorghum* growth measured by plant height, length and number of leaves, is significantly influenced by several factors: time (development stage), year of cultivation, type of amendment applied, and position relative to the tree crown. The progression in plant height from one-time t1t_1t1 to another t2t_2t2 reflects continuous and significant growth, highlighting to *Sorghum*'s sensitivity to environmental and agronomic conditions throughout its vegetative cycle (Fig. 6).

Among the tested treatments, the amendment combining *Gliricidia sepium* biomass and biochar consistently produced the most favorable growth outcomes across both cropping seasons. Plant height, leaf length and number of leaves were significantly higher with this amendment than with other amendments. This superior performance is attributed to the complementary properties of the two amendments: the nitrogen-rich *Gliricidia s.* biomass promotes leaf growth and plant vigor; and the biochar improves soil structure, water retention capacity and nutrient availability, creating a favorable environment for root development and efficient nutrient uptake. Supporting evidence from Kouyate et al. (2021) demonstrated that *Gliricidia* biomass significantly increased maize growth parameters (biomass and diameter at the collar of corn plants) in the second year of application. Similarly, Ouedraogo et al. (2023) report that *Gliricidia sepium* contains high levels of nitrogen (3.8%), potassium (23 g/kg), calcium (9 g/kg), and magnesium (4 g/kg). Thus, Ouedraogo et al. (2023) contributing to improved biomass yields in both maize and Sorghum when used as a soil amendment. In contrast, control plots without plots showed the lowest growth performance, underscoring the limiting effects of nutrient-poor soils on Sorghum development.

Regarding the effect of relative position to tree crowns, the best growth results (height and number of leaves) were observed outside the tree crown, i.e. in areas exposed to direct sunlight. Shading generated by tree crowns, particularly those of *Vitellaria paradoxa* and *Lannea microcarpa*, limits light penetration, thus reducing photosynthesis and slowing growth. However, under *Parkia biglobosa*, *Sorghum* plant height remained significantly higher than under the other tree species, which could be explained by its more aerated crown structure, allowing better light transmission. This suggests that moderate shading of *Parkia biglobosa* may be less restrictive for *Sorghum* growth than those with denser canopy. These results confirm and extend the observations made by several authors who have studied the effect of tree shade on crop productivity in Sudanian zones. Gbemavo et al. (2010) reported a significant reduction in the capsular yield of cotton under the *Vitellaria paradoxa* canopy, accompanied by a marked drop in plant density. This reduction in yield under tree cover is attributed to a reduction in incident light, a key factor in photosynthesis and therefore in crop growth and production. Similarly, Zomboudre et al. (2005) reported that maize plant height and number of leaves were significantly higher outside tree crown than under them. This trend suggests that the shade cast by crowns, particularly those with dense foliage, creates a microclimate less favorable to optimal plant growth, notably by limiting available light and modifying the

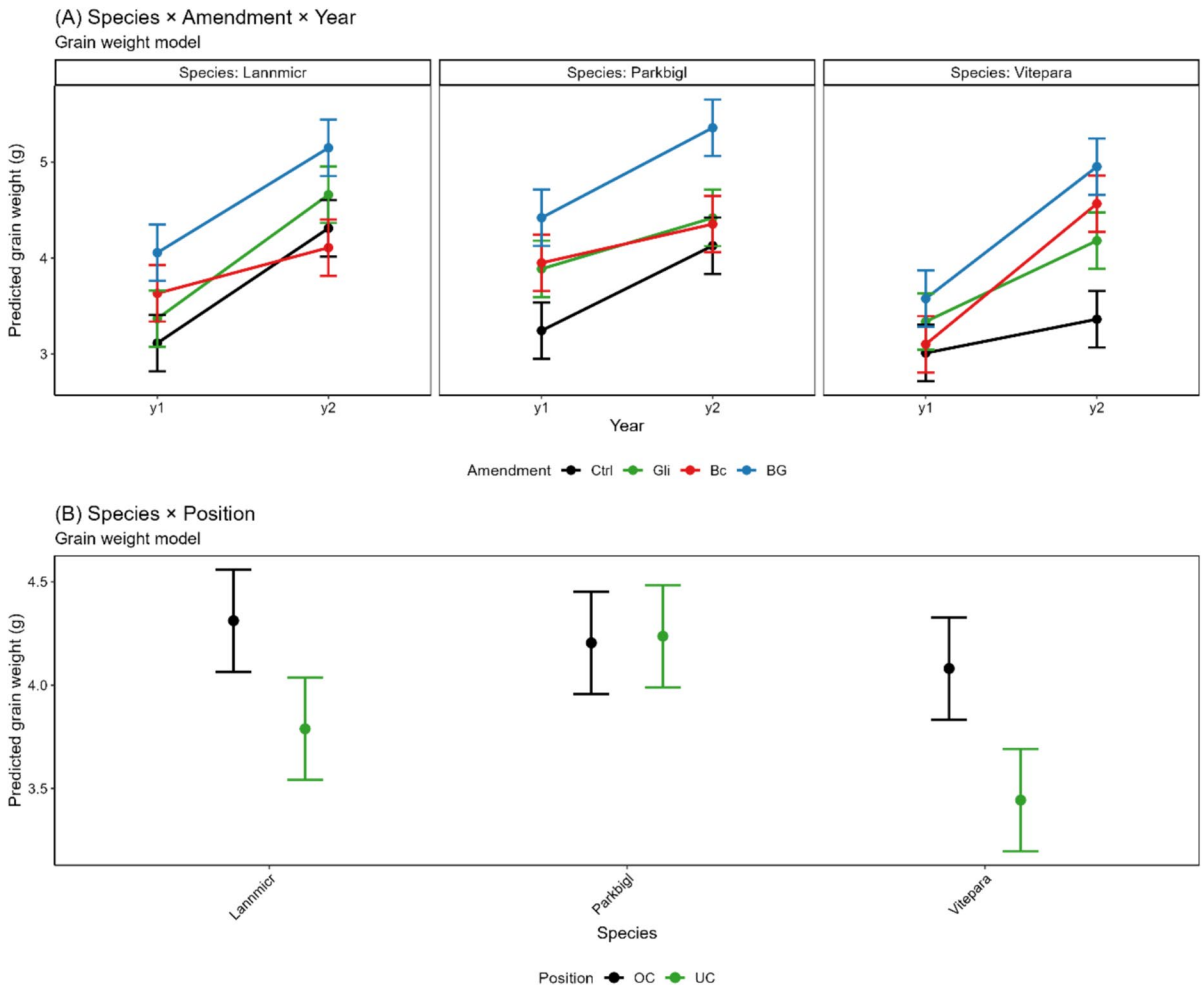


Fig. 6 Effect of amendment, position and year on *Sorghum bicolor* grain weight

thermal and water regime at ground level. In addition to above-ground interactions, below-ground competition also plays a critical role in tree–crop interactions. Tree and crop roots compete for access to soil nutrients (Bai et al. 2023), and several studies have shown that tree proximity can reduce crop yields by 22.9% to 47.3%, depending on the agroclimatic zone (Biru 2021). However, this competitive effect may be mitigated in systems involving deep-rooted tree species, which can exploit deeper soil layers and thus reduce direct competition with crops characterized by shallow root systems (Sahu et al. 2025). In this context, the present results suggest that the moderate shading associated with *Parkia biglobosa* is less restrictive for sorghum growth than the denser canopies of *Lannea macrocarpa* and *Vitellaria paradoxa*. Moreover, *Parkia biglobosa* appears to exert lower competition for water and soil nutrients, likely due to differences in rooting depth, canopy architecture, and resource-use efficiency. These functional traits may explain its more favorable coexistence with associated crops in agroforestry parkland systems.

The results of Gnangle et al. (2012) are in the same vein, showing that cotton plants under the *Vitellaria paradoxa* crown showed an average height reduction of 6.58% compared with those outside the crown. They also noted a drop in fresh biomass and capsular production, reflecting a cumulative negative effect of shading on growth and productivity.

These various studies converge towards the idea that, although certain trees such as *Vitellaria paradoxa* can improve soil fertility in the long term

through the litter they produce, their dense crowns act as a limiting factor for crops due to excessive shading. This constraint is particularly marked in traditional agroforestry systems, where tree density and location are not always optimized for crop needs.

The present study underscores the importance the importance of strategic agroforestry management, integrating not only the benefits of trees on soil quality, but also their impact on the light available for crops. Strategic spacing, controlled pruning or the choice of less shady tree species such as *Parkia biglobosa* can help mitigate negative effects while maintaining the ecosystem services offered by trees.

Effect of amendment, position and year on *Sorghum bicolor* yield

Experimental results indicate that the dry weight above-ground dry biomass yield of *Sorghum* is significantly influenced by the type of amendment applied, the year of cultivation and the tree species, particularly outside the shade zone. This variability can be explained by the combined effects of shade and soil fertility. Comparative analysis between the two cropping seasons shows that, for the same amendment, *Sorghum* dry weight above-ground dry biomass yield is significantly higher in the second year. This improvement can be attributed to the greater stability of edaphic conditions over time and to the cumulative effect of the amendments on soil fertility. Of the amendments tested, the one combining Biochar and *Gliricidia sepium* proved the most effective, recording the highest dry weights. This result suggests a synergy between the capacity of biochar to improve water and nutrient retention, and the enriching organic inputs provided by *Gliricidia*, favorable to the vegetative development of *Sorghum*. Djousse Kanouo, (2017) found that the application of biochar led to a significant improvement in corn grain yield, with an increase of 54% in the first production season and 51% in the second, compared to control plots without biochar. Similarly, the results obtained by Mounirou, (2022) indicate that the application of biochar led to a significant increase in chlorophyll concentration and total onion yield compared to control plots without amendments. The results obtained by Husk and Major, (2012) indicated that the application of biochar led to a significant increase in total onion yield compared to unamended control plots. Conversely, the control plots (without amendment) had the lowest yields, confirming the importance of organic inputs to compensate for the natural poverty of leached tropical soils. Studies conducted by Kouyate et al. (2021) on the contribution of *Gliricidia sepium* prunings to corn mulch showed a significant increase ($P < 0.05$) in corn grain yield compared to the cultivation system without *Gliricidia sepium* during the two years of experimentation. Ouedraogo et al. (2023) observed a significant improvement in corn and *Sorghum* grain yield with the addition of G*liricidia* biomass. Studies conducted by Kouadio et al. (2011) showed that *Gliricidia,* when associated with crops or used as improved fallow land from the third year onwards, contributed to a significant improvement in coffee and cassava yields, the restoration and maintenance of soil fertility, and a reduction in weed growth.

Furthermore, a spatial analysis of yield shows that *Sorghum* grown outside the shade has a significantly higher dry weight above-ground dry biomass yield than that measured under the shade, particularly under the *Lannea microcarpa* and *Vitellaria paradoxa* species. This difference can be explained by the greater shading effect under these species, which reduces photosynthesis, slows vegetative growth and limits biomass accumulation. So, despite any microclimatic advantages under tree cover (reduced evapotranspiration or organic matter contribution), excessive shading is detrimental to *Sorghum* production, particularly under *Vitellaria paradoxa*, known for its dense foliage. These results corroborate those of Abdou et al. (2014) who found an improvement in average grain yield, 1000-seed weight, and panicle weight in the area under but not close to the trunk of Acacia senegal (L.) Willd. Azeem et al, (2019) also found an increase in biomass yield (BY) of white beans and wheat in both years with and without chemical fertilizer. There was an increase in organic matter, total N and assimilable P for good agricultural practice compared with farmer practice. However, the practice did not affect total K and soil pH (Nacro et al. 2011). It is probably this improvement in organic matter levels of N, P that must have improved *Sorghum* growth and consequently *Sorghum* dry and grain peas. The effect of shading had no impact on off-farm yields for any species. This may be due to the fact that *Sorghum* crops benefit from the same climatic and edaphic conditions outside the nursery.

Under the canopy, *Sorghum* grown under *Parkia biglobosa* had a significantly higher grain weight grain yield than that observed under the other tree species, reflecting a more favorable interaction between this species and *Sorghum* cultivation. On the other hand, the lowest yields were recorded under *Vitellaria paradoxa*, followed by *Lannea microcarpa*, whose dense shading seems to strongly alter the availability of light required for photosynthesis. These results indicate that shading generated by *Vitellaria paradoxa* and *Lannea microcarpa* has a pronounced negative effect on grain productivity in *Sorghum*, probably due to their thick foliage, their less permissive canopy architecture to light penetration, or even potential allelopathic interactions. These observations underline the importance of considering the ecophysiological characteristics of tree species in the design of agroforestry systems, in order to limit competitive effects and maximize synergies between trees and food crops. Contrary to our results, Bayala et al, (2003) showed that the application of *Parkia biglobosa* mulch reduced S*orghum* grain yield by 33% and total biomass by 21%. In contrast, *Vitellaria paradoxa* mulch significantly improved crop performance, increasing grain yield by 120% and total biomass by 43%. Saidou et al, (2013) showed that grain and straw yields under the canopy were reduced by 46.6% and 32.8% respectively, compared with those outside the canopy. In Benin, Gnangle et al. (2012) found that the average capsular production of cotton decreased by 13.06% under the crown of shea, while its average fresh biomass fell by 36.06% under the same conditions. A study carried out on agroforestry parks by Saidou et al, (2013) showed that the presence of shea trees had a significantly positive influence on soil moisture and temperature in increasing proportion to crown diameter, but generated significantly low yields under shea trees compared with those outside. Other studies on leguminous plants have shown that leguminous plants belonging to the Fabaceae and Mimosaceae families are capable of restoring soil fertility due to their high capacity to produce plant biomass which, when buried in the soil, produces organic matter (Akedrin et al. 2020). Woody species such as *Vitellaria paradoxa, Anogeissus leiocarpa, Combretum micranthum, Lannea microcarpa, Diospyros mespiliformis* have been recognized, for example, as improving the agronomic performance of annual crops thanks to their long-term litter (Bambara et al. 2019). Various in situ measurements have shown that *Sorghum* yields in plots receiving *Vitellaria* leaf litter for the first time were lower than those in control plots, whereas after three consecutive years of Vitellaria leaf litter, the plots were more productive (Bambara et al. 2019). A study carried out on *Cordyla pinnata* showed that, on the one hand, it draws nutrients from soil horizons, brings them to the surface in the form of litter (leaves, branches, bark, fruit) and behaves as an important source of nutrients and, on the other hand, is compatible with the cultivation of *Sorghum* and groundnuts (Ndiaye et al. 2012). Organic matter plays both an essential role in maintaining structural stability (maintaining macroporosity) and as a support for biological activity in the soil, while influencing, depending on its nature, the capacity to store water reserves (Akedrin et al. 2020; Kate et al. 2016). According to Doumbia et al. (2020), average grain yields of cotton, maize and *Sorghum* associated with *G. sepium* had significantly improved from 2016 to 2018. Also, there was a 5% increase in soil organic carbon and total nitrogen content in soils located in the alleys of the *G. sepium* plantation. *G. sepium* in association with crops has the potential to improve their yields and soil (Doumbia et al. 2020). Low adoption of improved soil conservation, integrated water management and harvesting systems, and the use of less productive and adaptive cultivars, results in extreme degradation of cropland and lower crop productivity (Koglo et al. 2018). This situation is generally at the root of growers' search for new, more productive plots. To satisfy their hunger, they destroy forests to gain access to new, more fertile land with higher yields.

Conclusion and implications for sustainable agroforestry-based soil fertility management

This study demonstrates that *Sorghum bicolor* growth and yield are strongly influenced by soil amendment type, agroforestry tree species, crown position, and interannual variability. Across all tree environments, the combined application of *Gliricidia sepium* biomass and biochar consistently produced superior plant height, leaf development, and above-ground dry biomass compared with single amendments and the unamended control.

The enhanced performance observed under the combined treatment highlights the complementary roles of nitrogen-rich *Gliricidia sepium* biomass in supporting crop nutrition and biochar as a carbon-based soil amendment that improves nutrient-use efficiency and water availability in the root zone. While these mechanisms are well documented in previous studies, their direct effects on soil chemical and physical properties could not be verified in the present work due to the absence of pre-sowing and post-harvest soil analyses. Such analyses were not conducted because of limited financial and technical resources. Future studies will explicitly include comprehensive soil assessments to quantify changes in soil nutrient status, organic carbon, and water-holding capacity, thereby strengthening the interpretation of crop responses.

Unamended soils consistently showed the poorest growth and yield performance across species, positions, and years, indicating severe nutrient limitation under the prevailing conditions. Although soil fertility restoration could not be directly measured, the weak performance of the control treatments underscores the urgent need for effective soil fertility management strategies in degraded agroecosystems.

Shading effects differed markedly among tree species. Dense canopies of *Vitellaria paradoxa* and *Lannea microcarpa* significantly constrained sorghum growth, whereas *Parkia biglobosa* exerted a comparatively lower negative effect, confirming its greater compatibility with cereal production in parkland agroforestry systems. This finding emphasizes the importance of tree species selection and canopy management in optimizing crop performance.

The observed improvement in sorghum growth and yield from the first to the second year suggests a potential residual or cumulative effect of organic biomass and biochar applications on crop performance. However, in the absence of soil analytical data, this trend cannot be conclusively attributed to sustained soil fertility enhancement and should be interpreted with caution.

Overall, the results indicate that the strategic integration of leguminous biomass and biochar, combined with appropriate agroforestry design, can substantially improve sorghum productivity under resource-limited farming conditions in sub-Saharan Africa. Future research integrating long-term soil monitoring will be essential to fully assess the sustainability and soil-restorative potential of these practices.

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Author contribution Amos Baninwain Nambima: Conceived and designed the study, coordinated the experimental setup, and contributed to the writing and organization of all sections of the manuscript.—Narcisse Yehouenou: Performed data processing, statistical analyses, and contributed to the interpretation of results.—Abdoul Sodick Alassiri: Ensured the monitoring of the experimental design and was responsible for field data collection.—Thierry Dèhouégnon Houehanou and Gérard Nounagnon Gouwakinnou: Provided continuous supervision throughout all stages of the research, from the preparation of the experimental design to field oversight, and critically revised the manuscript to enhance its scientific quality.

Data availability The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflicts of interest The authors declare no conflict of interest.

Ethical approval This study did not involve human participants or animals. Field experiments were conducted with the consent of local landowners and in accordance with local agricultural practices and regulations.

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