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Rice productivity and soil hydrodynamic properties under lowland *Elaeis guineensis* and *Borassus aethiopum*: An asset rice agroforestry system

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ABSTRACT

Lowlands are facing significant destruction of their natural habitats breaking the interrelationships between soil hydro-physical and installed crops yield parameters. This study investigates the response of rice grain and biomass yields, and soil hydrodynamic properties to *Elaeis guineensis* and *Borassus aethiopum* rice cropping systems in lowlands of the commune of Parakou, Northern Benin. We considered four lowlands with 18 trees, viz. nine *Elaeis guineensis* and nine *Borassus aethiopum*. The results show that trees crown area, DBH and distance from waterbed were 24.2% higher, and 38.6 and 27.6% lower under *Borassus aethiopum* compared to *Elaeis guineensis*, respectively. Soil Ks was lower under *Borassus aethiopum* than *Elaeis guineensis*; while soil water content, capillary water holding capacity and capillary porosity were higher. Rice grain and biomass yields were 113.1 and 110.8% higher under *Borassus aethiopum* compared to *Elaeis guineensis*. However, no difference in grain and biomass yields occurred between outside and under crowns. Positive correlations were obtained between rice grain yield and harvest index, and between rice biomass yield and trees distance from waterbed. Nonetheless, rice grain yield and trees DBH were negatively correlated. Soil depth and crown indirectly influenced rice biomass yield through a direct effect on root biomass, and the two species also indirectly influenced rice biomass and grain yield through direct positive effect on crown area. The findings show that the presence of *Elaeis guineensis* and *Borassus aethiopum* trees in rice cropping agroforestry systems can help for their protection and improve the ecosystems and yield of rice cropping agroforestry systems.

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INTRODUCTION

Rice is a major crop that contributes to food security globally and in sub-Saharan Africa (SSA) in particular, where it serves both for human consumption and an important component of animal feed (Salvador and Casco, 2025; Uwuigbe *et al.*, 2022; Ugochukwu and Chukudinife, 2022).

Rice has been cultivated in different ecosystems of SSA: drylands and lowlands including wetlands, swamps, inland valleys and flood plains (Firmin *et al.*, 2025; Bado *et al.*, 2018; Tanaka *et al.*, 2013). Lowlands are areas subject, to some degree, of annual flooding where shallow groundwater tables under slow-flowing rivers allows the development of rice crops and off-season gardening (Firmin *et al.*, 2025; Panda and Barik, 2021; Erenstein *et al.*, 2006). Soils in lowlands often have low permeability and total porosity due to prolonged saturation and fine-textured sedimentation, which influence water movement and root aeration (Goulart *et al.*, 2021).

Rice production in Benin has increased through the expansion of cultivation area rather than increasing rice yields (Wabi *et al.*, 2022), leaving the rice cropping systems with issues such as drop in yield and soil hydro-physical.

Several tree species have been combined with rice cropping systems across the African continent, including *Sesbania rostrata*, *Aeschynomene afraspera*, *Acacia auriculiformis*, *Gliricidia sepium* and *Gmelia arborea* (Rodenburg *et al.*, 2022). In Benin, *Borassus aethiopum* is used for medicine, handcraft, food, construction, firewood, and ceremonies and ritual (Salako *et al.*, 2018).

Although ranked as an important palm in West African countries, *Borassus aethiopum* also faces significant threats through an overexploitation and destruction of its natural habitats (Michon *et al.*, 2018). Trees are known to improve soil water flow and water retention through preferential flow and non-preferential flow known as matrix flow (Cruz-

Alonso *et al.*, 2022; Jiang *et al.*, 2020). Moreover, they provide soil aeration which is necessary for crops growth (Zhang *et al.*, 2024). Previous studies used both modeling and experimental approaches to develop oil palm-rice agroforestry system (Perez *et al.*, 2024). However, till today less is known on the influence of *Borassus aethiopum* and *Elaeis guineensis* on the soil hydrodynamic properties, and on the relationship between rice productivity and these variables in natural croplands such as lowlands. This study sets out to fill this gap and expand our knowledge to integrate both trees and crops in rice production systems for sustainable production.

Benin has more than 205,000 ha of lowland area, but only 10% are actually used for agricultural purpose (CBF/DGR, 2000). Especially, the commune of Parakou in the northern Benin has about 677 ha of lowland areas, where only 20% are managed and 7% are used mainly for rice production. While various research results show an increasing exploitation of lowland areas, other results at the same time highlight an unprecedented destruction of their vegetation cover which makes them very vulnerable to degradation factors. Besides, the used techniques and practices for improving rice productivity in lowlands, viz. fertilizers inputs and water management practices, highly affect both rice yield and farmland ecosystem, especially through the destruction of available trees (Baronian *et al.*, 2024; He *et al.*, 2022). For instance, the average yield for rice crop in Africans' farms ranges between 0.5 and 2 t ha⁻¹ for upland rice and 1 and 2 t ha⁻¹ for rainfed lowland rice (Balasubramanian *et al.*, 2007). However, despite the high yield of lowland rice, till 7.5 t/ha in Adja-Ouèrè (Benin) (Gbenou, 2020), a large yield gap has been reported between potential yields of irrigated lowland rice and farm yields. It is therefore obvious that rice cropping systems is representative for a good understanding of the relationship between rice yield on the one hand, and on the other hand the physical and hydrodynamic behavior of lowland areas of the commune of Parakou.

This study assesses the response of rice grain and biomass yields and soil hydrodynamic properties to *Elaeis guineensis* and *Borassus aethiopum* rice cropping systems in lowland. It first examines *Elaeis guineensis* and *Borassus aethiopum* trees crown areas between the two species, and their root biomasses in two soil depth. Then, it examines the influence of soil depth and tree crown on the soil water content. Finally, this research analyses the interrelationships among rice yields, the trees' characteristics, and the lowland soil hydrodynamic properties. Data on soil hydrodynamic properties and rice production were collected on four plots, under and outside crown of the two species. The findings provide knowledge on the interdependence between *Elaeis guineensis* and *Borassus aethiopum* trees and

rice productivity for their integration in rice cropping agroforestry systems. The use of these species in rice cropping agroforestry systems can also help for their protection and improve the ecosystems of rice cropping agroforestry systems, especially soil protection functions, water flow regulation and rice yield improvement of lowland areas. They will also help ensure good control of soil degradation factors and sustainable rice production in lowland areas.

MATERIALS AND METHODS

Experimental sites

The study was conducted in the commune of Parakou, Borgou, Benin Republic. Parakou is located between 9°21' North latitude and 2°37' East longitude, with an average altitude of 350 m (Fig. 1).

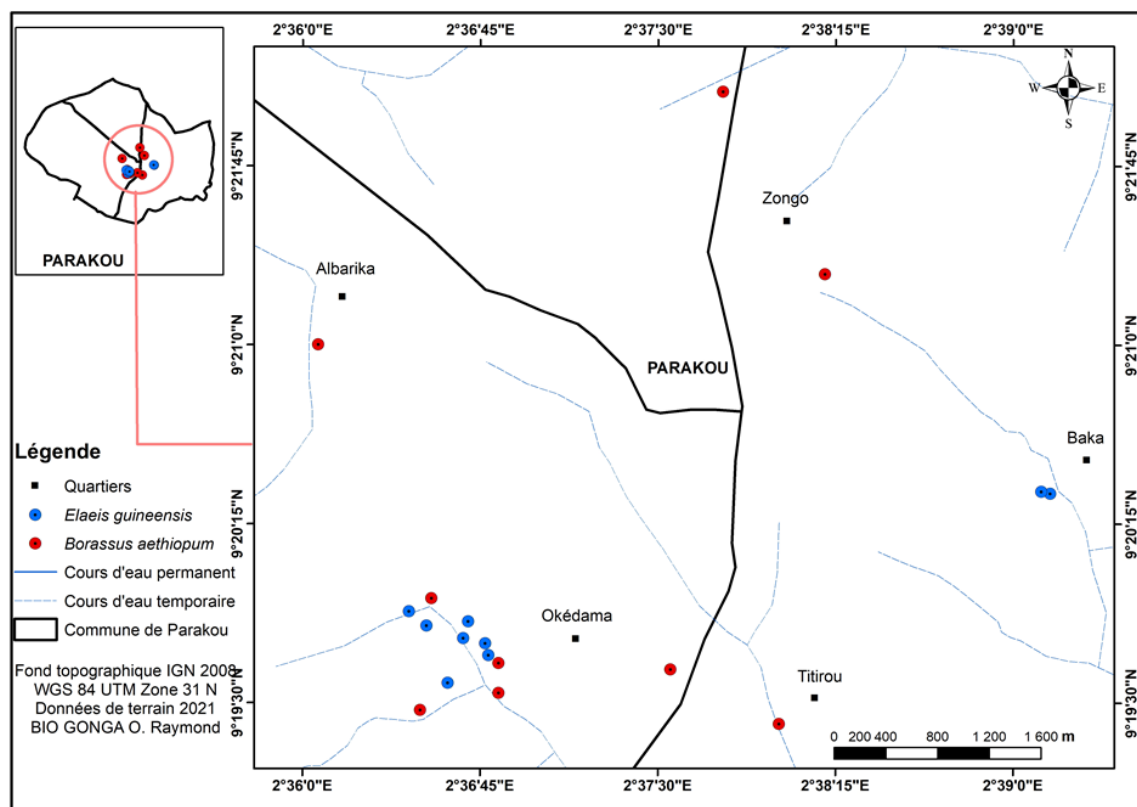


Fig. 1. Location of *Elaeis guineensis* and *Borassus aethiopum* trees on the experimental sites of the lowlands in Parakou

It covers an area of 441 km², and has three districts with 58 neighborhoods. The climate of Parakou is humid tropical characterized by two seasons: a rainy season and a dry season. The average annual rainfall is about 1200 mm and the average annual

temperature is 26.8°C. Parakou has about 677 ha of lowland areas of which only 20% are managed and 7% are under agricultural practices. Almost 84% of the used lowlands are used for rainy rice cropping and 16% for banana production.

The experimental sites are located in the rice cropping lowlands of Okédama, Titirou, Albarika, Zongo and Baka neighborhoods. These neighborhoods are spread across the three districts of Parakou. Two tree species, namely the palm tree (*Elaeis guineensis*) and the palmyra palm (*Borassus aethiopum*), are predominant in the lowlands and involved in this study.

Study design

Nine individual trees were randomly chosen for each species of *Elaeis guineensis* and *Borassus aethiopum* in the studied lowlands. Then, four sampling plots were installed close to each selected tree: two plots at one meter to have the plot under the crown of the tree, and two others at six meters from the trunk to have the plot outside the crown of the tree. In total, 18 trees of both species hosted 72 sampling plots (9×2×4). In each plot, root biomass and soil samples for hydrodynamic data were collected at two different depths including shallow layer (0-10 cm) and deep layer (40-50 cm).

IR 841 rice variety was then sown in July in the lowland areas under flat plowed conditions. Sowing was carried out in pockets dug with a hoe, following rows and spacing of 20 cm x 20 cm.

An average number of 8 rice grains per pocket was used at an average depth of 4 cm. None of the producers used chemical fertilizers. However, each producer's crops underwent at least two rounds of phytosanitary treatment during the crop's development cycle. The short-cycle IR 841 variety matured slightly earlier, and harvest began in October. The harvested rice plants were air-dried for at least 72 hours before being weighed and threshed.

Data collection and data analysis

Soil hydrodynamic properties

Soil hydrodynamic properties were determined following the methodological approach of Jiang *et al.* (2019). In short, four soil samples were collected around each selected tree using Copecky tubes (200 cm³ cylinder): two diametrically parallel to the

waterbed, and two diametrically perpendicular to the waterbed. The weight of each empty cylinder (Whcr) was taken before the sample collection using a 0.1 g precision balance. Then, soil samples were collected with the cylinders (Wcrws) and weighed (Wcrws) for the determination of soil properties viz. soil bulk density, total porosity, gravimetric water content, capillary retention capacity, soil capillary porosity, field capacity, Soil saturation capacity.

The bulk density (g cm⁻³) was calculated as the ratio of weight of soil and the volume of the cylinder (200 cm³) using the following formula (Eq. 1):

$$\text{Bulk density} = \frac{\text{Soil weight (g)}}{\text{Volume of cylinder (cm}^3\text{)}} \quad (\text{Eq. 1})$$

The total porosity is defined as the ratio of void volume to total soil volume. Briefly, for its determination the soil cylinders were placed in a tank containing potable water for the saturation experiment in the laboratory (Jiang *et al.*, 2019). The water level in the tank was close to the surface of the cylinders, without water entering the samples above the cylinders to avoid trapping of air bubbles in the cylinders upon saturation. The weigh of the cylinders at saturation is measured after 24 hours of saturation experiment. The saturated soil core cylinders were placed on a prepared sand layer drain soil water by gravity, then weighed after two hours and after five days of drainage experiment. Finally, the cylinders containing soil samples were placed in an oven at 105°C for 24 hours and weighed to obtain the soil phase weight. Total porosity was calculated as the ratio of the soil water (g) after saturation (difference of saturated soil core cylinders weight and soil phase weight) to the volume of the cylinder (cm³).

Gravimetric water content is the amount of water present in the soil after sample collection relative to its dry mass, generally expressed as a percentage (g of water per 100 g of soil) (Mondal *et al.*, 2024). The gravimetric water content, capillary retention capacity, capillary porosity, field capacity, and saturation capacity were calculated Per Zakari *et al.* (2025).

Root biomass

For the root biomass, the previously oven dried four soil samples were lumped and air dried. Then, the roots contained in each sample were extracted, counted and weighed using a 0.1 g precision balance. Only eye identified roots were processed.

Soil hydraulic conductivity

Four soil water infiltration tests were carried out at 1 m and 6 m from each trunk and parallel to the waterbed to determine the soil hydraulic conductivity. A total of 15 L of water was put into a single-ring cylinder till 10 cm height (14 cm in diameter and 28 cm in height) inserted at a depth of 5 cm into the soil, to collect water infiltration data (Xiao-Jin *et al.*, 2021). The height of the water in the cylinder was measured at a frequency of one minute for the first 10 minutes of the infiltration test, 2 minutes from the 10th to the 30th minutes, 5 minutes from the 30th to the 80th minutes (Mbilou *et al.*, 2016). The water height measurement was extended up to 120 or 130 minutes if the difference in infiltration rate (capacity) between the last two measurements is higher than 90%. The cylinder is refilled by adding water each time the water height in the cylinder drops to 5 cm, to bring it back to 10 cm height.

Rice grain and biomass yields

Four yield squares (1 m²) were used for the estimation of rice yield and biomass namely: two parallel to the minor bed at 1 m and 6 m and two perpendicular to the minor bed at 1 m and 6 m from each tree. Then, straw biomass and rice grain were collected in each square for the calculation of rice grain and biomass yield. The weighing is carried out first after drying in the open air and then after drying in an oven at 70 degrees Celsius. The harvest index is estimated as the ratio between the marketable yield of cultivated rice and the quantity of total biomass produced, expressed as a proportion of dry matter.

Rain data

Daily rainfall data were collected to monitor the behavior of rainfall events based on dates. Total

porosity was calculated assuming no air was trapped in soil pores and then validated using dry bulk density and a particle density of 2.65 g/ cm³.

Statistical analysis

The collected raw data was first carefully recorded into an Excel spreadsheet, and comprehensive statistical tests were subsequently performed using R software, version 4.4.2 (R Foundation for Statistical Computing, 2024).

Shapiro-Wilk normality test was used to assess the normality of the different response variables including rice grain and biomass yields, and non-normal data were transformed. Analysis of variances (ANOVA) and t-test were used to evaluate the effect of factors on response variables (tree characteristics, soil hydrodynamic properties and yield components), and to compare the response variables between factor levels concerning species (*Elaeis guineensis* and *Borassus aethiopum*), soil depth (0-10 cm and 40-40) and crown (under and outside). Correlation analyses were computed for the quantitative variables, and followed by a principal component analysis (PCA) to obtain the dependent relationships among the variables. Finally, Structural equation model (SEM) analysis was computed to evaluate the dependency between exogenous and endogenous variables. PCA was performed using factoextra package (Kassambara and Mundt, 2017), SEM using Lavaan 0.6-19 package (Rosseel, 2012) for R.

RESULTS

Rainfall during the experiment

The cumulative rainfall during the experiment was 731 mm, and was distributed in 46 rain events (Fig. 2). Two rainfall peaks were recorded in July and August, with rainfall amount of 60 and 83 mm, respectively. A total of 14 dry spell events (no rain during three consecutive days or more) were recorded during the experiment, with the highest spells of 14 and 12 days that occurred in October and July, respectively (Fig. 2).

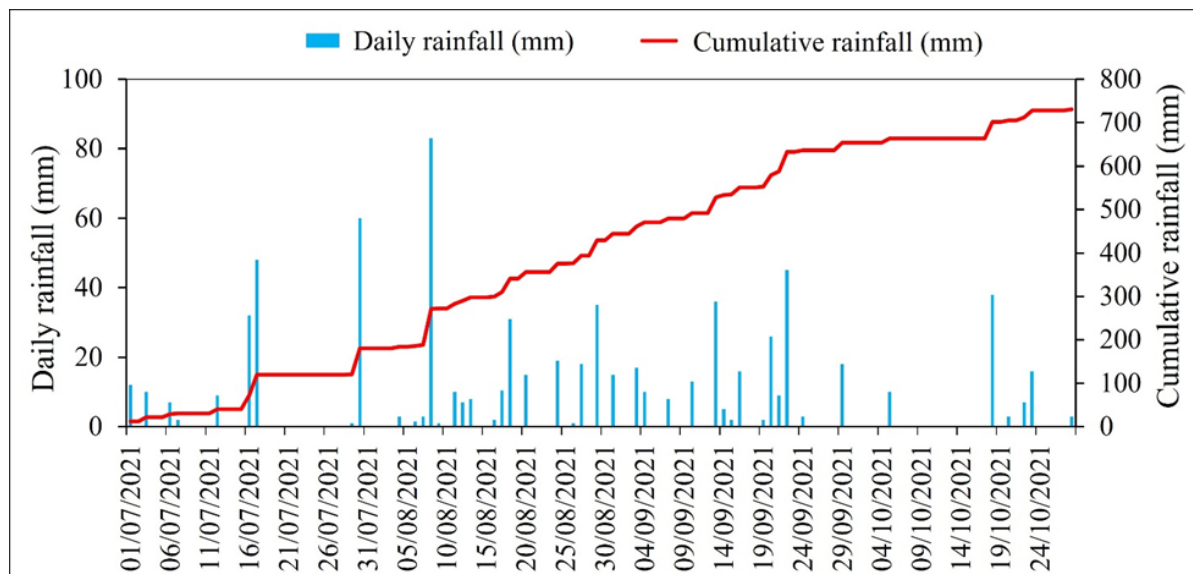


Fig. 2. Change in precipitation amount (daily and cumulative) and rain events during the experiment

Table 1. Trees crown area and DBH of the two species, and characteristics of their roots as function of crown and soil depth

Factors			Trees characteristics and soil root parameters					
Species	Crown	Soil depth	Crown area (m ²)	DBH (m)	Distance (m)	Root biomass (g)	Root volume (cm ³)	Root ratio (%)
Borassus	Under	Shallow	35.712±13.228	1.417±0.351	10.147±6.445	0.242±0.410	0.163±0.312	0.081±0.156
		Deep	35.737±13.611	1.354±0.225	9.128±4.803	1.017±1.373	0.498±0.875	0.249±0.438
	Outside	Shallow	35.737±13.611	1.354±0.225	9.128±4.803	0.783±0.960	0.328±0.710	0.164±0.355
		Deep	35.737±13.611	1.354±0.225	9.128±4.803	5.467±4.360	7.176±10.74	3.588±5.370
Elaeis	Under	Shallow	28.497±08.065	2.126±0.230	12.288±6.785	0.159±0.250	0.329±0.820	0.164±0.410
		Deep	28.873±07.985	2.150±0.244	13.189±7.611	2.194±0.987	1.593±1.124	0.797±0.562
	Outside	Shallow	28.873±07.985	2.150±0.244	13.189±7.611	0.461±0.694	0.428±0.795	0.214±0.398
		Deep	28.873±07.985	2.150±0.244	13.189±7.611	5.294±1.664	6.906±3.816	3.453±1.908
p-values								
Species			<0.001***	<0.001***	0.001**	0.620	0.690	0.690
Crown			-	-	0.968	<0.001***	<0.001***	<0.001***
Soil depth			-	-	0.968	<0.001***	<0.001***	<0.001***
Species*Crown			-	-	0.655	0.191	0.601	0.601
Species*Soil depth			-	-	0.655	0.245	0.838	0.838
Crown*Soil depth			-	-	0.973	<0.001***	<0.001***	<0.001***
Species*Crown*Soil depth			-	-	0.655	0.360	0.635	0.635

Distance (m) is the distance between tree position and waterbed; DBH is the diameter of the trees at breast height. Root ratio is the volume ratio occupied by the roots in the collected soil core.

Characteristics of the lowland trees and soil roots

The trees crown area, DBH and distance from waterbed were 24.2% higher, and 38.6 and 27.6% lower under *Borassus aethiopum* compared to *Elaeis guineensis*, respectively (Table 1). The root biomass, root volume and root ratio were 69.9, 83.3 and 82.6% lower under the crown than outside the crown, respectively (Table 1). Similarly, the root biomass, root volume and root ratio were 88.2, 92.6 and 92.3%

lower in deep soils (40-50cm) than in shallow soil (0-10cm), respectively (Table 1). Regarding the interaction Crown*Soil depth, the root volume in shallow soils was 54.3% higher outside the crown than under the crown; but 573.1% higher in deep soils.

The root biomass and root ratio followed the same trend of the root volume in regard to the interaction Crown*Soil depth.

Table 2. Effect of species, crown and soil depth on soil hydrodynamic properties

Factors		Soil properties								
Species	Crown	Soil depth	Ks (cm/min)	SWC (%)	BD (g.cm-3)	TP (%)	Cwhc (%)	CP (%)	FC (%)	Swhc (%)
Borassus	Outside	0-10 cm	0.011±0.007	24.903±06.225	1.552±0.173	41.442±6.514	24.708±05.918	0.037±0.005	24.356±05.906	26.549±06.103
		40-50 cm	0.010±0.007	17.743±06.534	1.725±0.197	34.906±7.438	18.467±06.268	0.031±0.008	17.343±06.235	19.755±06.014
	Under	0-10 cm	0.020±0.031	32.919±07.707	1.314±0.139	50.397±5.227	32.584±06.601	0.042±0.005	32.141±06.548	35.156±07.114
		40-50 cm	0.020±0.031	21.663±08.579	1.533±0.205	42.160±7.734	22.300±07.946	0.033±0.007	21.114±07.729	24.073±07.943
Elaeis	Outside	0-10 cm	0.125±0.219	21.425±08.618	1.575±0.166	40.558±6.256	22.967±06.855	0.035±0.006	21.937±06.501	26.034±07.284
		40-50 cm	0.119±0.214	16.046±10.980	1.723±0.163	34.970±6.151	17.748±10.295	0.030±0.013	14.792±02.919	20.174±10.494
	Under	0-10 cm	0.106±0.187	27.691±13.149	1.396±0.225	47.319±8.507	28.961±10.640	0.038±0.007	27.892±10.268	32.628±11.090
		40-50 cm	0.106±0.187	13.553±05.539	1.597±0.163	39.754±6.161	17.621±03.028	0.028±0.003	20.290±13.026	20.987±05.418
p-values										
Species			<0.001***	0.002**	0.168	0.168	0.034*	0.014*	0.059	0.281
Crown			0.906	0.008**	<0.001***	<0.001***	<0.001***	0.113	<0.001***	<0.001***
Soil depth			0.948	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Species*Crown			0.603	0.163	0.307	0.307	0.248	0.273	0.985	0.298
Species*Soil depth			0.955	0.850	0.722	0.722	0.994	0.958	0.534	0.944
Crown*Soil depth			0.948	0.030*	0.421	0.421	0.046*	0.122	0.393	0.059
Species*Crown*Soil depth			0.955	0.425	0.952	0.952	0.680	0.646	0.502	0.778

Ks: hydraulic conductivity; SWC: Gravimetric water content; BD: Bulk density; TP: Total porosity; Cwhc: Capillary water holding capacity; CP: Capillary porosity; FC: Field capacity; Swhc: Saturated water holding capacity.

Response of soil hydro-physical properties to lowland soil and *Elaeis guineensis* and *Borassus aethiopum* trees

Elaeis guineensis and *Borassus aethiopum* trees significantly affected most of the soil hydro-physical properties. The soil Ks was 86.6% lower under *Borassus aethiopum* than *Elaeis guineensis*; while soil water content, capillary water holding capacity and capillary porosity were 23.5, 12.3 and 9.2% higher (Table 2). The soil water content, total porosity, capillary water holding capacity, field capacity and soil water holding capacity were 16.4, 15.5, 17.3, 22.7 and 18.0% lower outside the crown than under the crown; while bulk density was 12.6% higher (Table 2). The soil water content, total porosity, capillary water holding capacity, capillary porosity, Field capacity and soil water holding capacity were 55.0, 18.4, 43.5, 24.6, 44.6 and 41.6% higher in deep soils than shallow soils; but bulk density was 11.3% lower. The interaction Crown*Soil depth showed that soil water content in shallow soils was 23.6% lower outside the crown than under the crown; and no significant difference of soil water content in deep soils was found outside the crown and under the crown.

Response of rice yield to lowland soil and *Elaeis guineensis* and *Borassus aethiopum* trees

The grain and biomass yield were only influenced by the species. Indeed, grain and biomass yield were 113.1 and 110.8% higher under *Borassus aethiopum* compared to

Elaeis guineensis. The harvest index varied from 0.40 to 0.43, however, it did not significantly vary between Species and Crown. Moreover, no significant difference in grain and biomass yield was found between the outside crown and under crown of each species (Fig. 3).

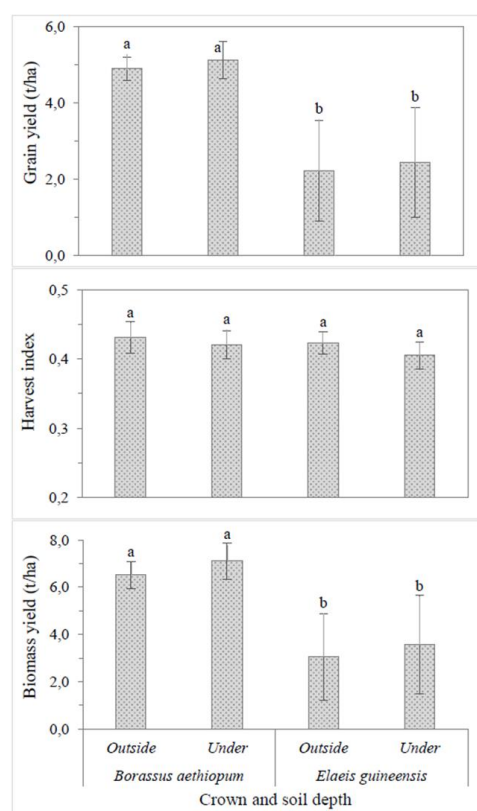


Fig. 3. Rice grain yield, harvest index and biomass yield under and outer crown of *Borassus aethiopum* and *Elaeis guineensis*.

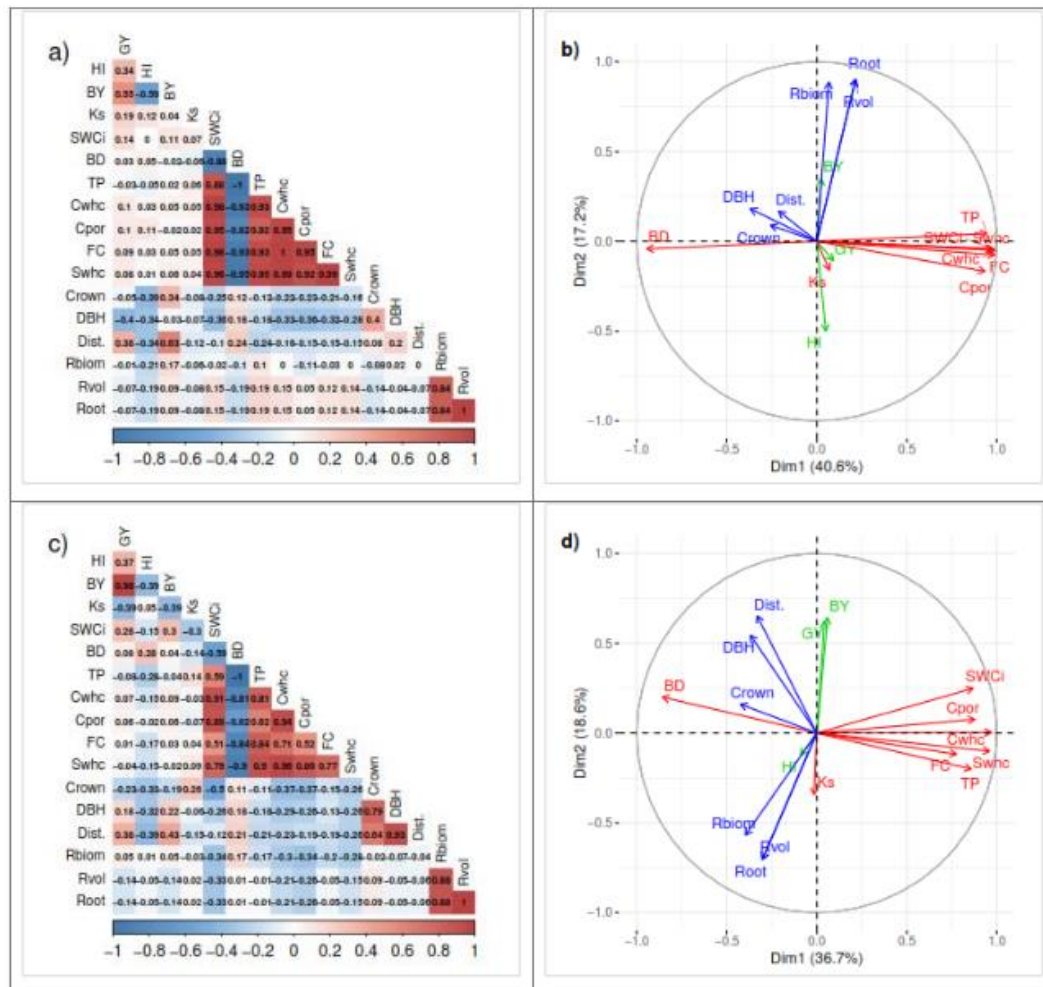


Fig. 4. Correlation and principal component analysis between soil properties, trees characteristics and soil root biomass of *Borassus aethiopum* (a and b) and *Elaeis guineensis* (c and d)

Rvol: root volume; Rblom: root biomass; Dist: Distance from tree to water bed; DBH: diameter at breast height; Crown: crown area; Swhc: Soil water holding capacity; FC: field capacity; Cpor: capillary porosity; Cwhc: capillary water holding capacity; TP: total porosity; BD: bulk density; SWCi: soil water content; Ks: soil hydraulic conductivity; BY: biomass yield; HI: harvest index; GY: grain yield.

Relationship between rice yield and soil hydrodynamic properties under *Elaeis guineensis* and *Borassus aethiopum*

The soil hydrodynamic properties under *Borassus aethiopum* were strongly correlated with each other, except Ks which showed weak correlation with other soil properties (Fig. 4a). Bulk density was negatively correlated with initial soil water content, total porosity, capillary water holding capacity, capillary porosity, field capacity, and soil water holding capacity; with correlation coefficient (r) ranging from -0.82 to -0.95. Oppositely, the initial soil water content was positively correlated with total porosity, capillary water holding

capacity, capillary porosity, field capacity and soil water holding capacity (r : 0.88 to 0.98). Obvious correlation occurred between *Borassus aethiopum* trees characteristics and rice yield parameters. Indeed, positive correlations were obtained between rice grain yield and harvest index, and between rice biomass yield and trees distance from waterbed, with correlation coefficient ranging between 0.38 and 0.55. On the contrary, negative correlation occurred between rice grain yield and DBH ($r = -0.4$).

The principal component analysis results show that the first two principal components explained

40.6% and 17.2% of the total variance (Fig. 4b). As expected, strong association happened among root biomass, root volume and root ratio; among tree crown, DBH and distance from waterbed; and among rice grain yield, biomass yield and harvest ratio. Similarly, soil properties including initial soil water content, total porosity, field capacity, capillary porosity, capillary water holding capacity, and soil water holding capacity clustered together, while Ks and bulk density were negatively associated with the other cluster.

The correlation between rice yield and soil hydrodynamics properties under *Elaeis guineensis* followed the same trend as for *Borassus aethiopum*, with some exceptions (Fig. 4c). Under *Elaeis guineensis*, rice grain yield was more strongly correlated to rice biomass yield ($r = 0.98$). Similarly, the crown was more strongly correlated to DBH ($r = 0.79$) and distance from waterbed ($r = 0.64$). Unlike *Borassus aethiopum*, a negative correlation was observed between rice grain yield and Ks ($r = -0.39$), while positive correlation was found between rice grain yield and DBH ($r = 0.18$). Generally, the Principal component analysis results show that the relationship among rice yield parameters and soil hydrodynamics properties were similar under *Elaeis guineensis* and *Borassus aethiopum*, except for the association between rice grain yield and biomass yield which was higher under *Elaeis guineensis* (Fig. 4d).

Finally, the structural equation model reveals that soil depth and crown indirectly influenced rice biomass yield through a direct effect on root biomass ($\lambda = -1.04$ and 0.77 , respectively) and soil water content ($\lambda = 1.11$ and 0.54 , respectively) (Fig. 5). Furthermore, the species also indirectly influenced rice biomass and grain yield through direct positive effect on crown area ($\lambda = 0.72$). Root biomass, soil water content and crown area positively affected rice biomass yield ($\lambda = 0.21$, 0.25 and 0.36 , respectively); while crown area was negatively influenced rice grain yield ($\lambda = -0.24$). Changes in biomass yield were positively associated with grain yield ($\lambda = 0.66$).

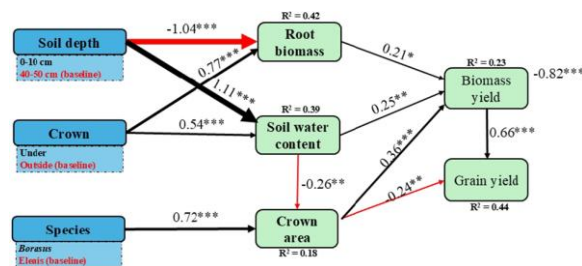


Fig. 5. Structural equation model showing the underlying mechanism of rice grain and biomass yields in lowlands under *Borassus aethiopum* and *Elaeis guineensis*

The thickness of the path equates to the strength of the path coefficient. Black and red arrows indicate positive and negative paths respectively. Green color boxes are response variables; blue color boxes represent the factor, and below each factor is shown its level and the baseline of comparison. The proportion of variation explained by the model (R^2) are shown next to each endogenous variable. Stars associated to values are the level of significance of the p -value (***: $p < 0.001$; **: $p < 0.01$; and *: $p < 0.05$). Chi square = 13.27, p -value = 0.427, degree of freedom (DF) = 13, RMSEA = 0.014, Comparative Fit Index (CFI) = 0.999.

Overall, the model explained 42, 39 and 18% of the variation in root biomass, soil water content and crown area, respectively; and 23 and 44% of variation in biomass and grain yield, respectively (Fig. 5).

DISCUSSION

Response of soil hydro-physical properties to lowland soil and *Elaeis guineensis* and *Borassus aethiopum* trees

The presence of *Elaeis guineensis* and *Borassus aethiopum* significantly influenced multiple soil hydro-physical properties. The saturated hydraulic conductivity was lower under *Borassus aethiopum*, whereas soil water content, capillary water holding capacity, and capillary porosity were comparatively higher, indicating greater water retention despite slower infiltration rates.

Soil analyses revealed that water content, total porosity, capillary water holding capacity, field capacity, and overall water holding capacity were consistently lower outside tree crowns compared to beneath them, while

bulk density was elevated in crown-excluded zones. These findings align with the observations of Pezzopane *et al.* (2015), who reported enhanced water uptake near trees. The higher bulk density observed beyond the crown area may be attributed to reduced root activity, which restricts soil aeration and contributes to increased natural compaction.

The interaction between trees crowns and soil depth further revealed that shallow soils retained more moisture under crowns than outside, with no significant variation at deeper layers. Prasad *et al.* (2010) attributed decreased water content up to 40 cm depth near tree rows to active root absorption. Similarly, Dilla *et al.* (2019) documented soil moisture levels ranging from 10–20%, which decreased both with depth and distance from trees within the top 20 cm, corroborated by (Boffa *et al.*, 2000). Enhanced soil fertility was also observed near tree crowns, with increased levels of organic carbon and potassium compared to central block areas. Rhoades (1995) confirmed high moisture up to 15 cm depth under *Faidherbia albida* canopies, though differences diminished at 15–30 cm.

Response of rice yield to lowland soil and *Elaeis guineensis* and *Borassus aethiopum* trees

The results of this study reveal that rice grain and biomass yields were higher under *Borassus aethiopum* compared to *Elaeis guineensis*. This could be explained by the fact that each species competes differently with rice, and that *Elaeis guineensis* is more competitive than *Borassus*.

This result is consistent with previous findings, which reported that crop growth in plots containing *Grevillea* trees was almost always better than in plots with *Gliricidia* trees (Odhambo *et al.*, 2001). It seems likely that one could conclude that *Gliricidia* was more competitive than *Grevillea*. This opinion is further supported by the arguments of AJM De Costa and Chandrapala (2000), Schroth and Zech (1995) and Rao *et al.* (1993), who stated that unless pruned, *Gliricidia* can compete with crops when grown together. Similarly, Tadesse *et al.* (2021) reported that yields of teff, finger

millet, and maize under *A. abyssinica* were significantly lower than those obtained under other treatments, highlighting increased competition for light, water, and nutrients (Jose *et al.*, 2000).

Our results also show that no significant difference in rice grain and biomass yields was observed under the trees crowns and outside the crowns, for each species. These findings contrast with those reported in scientific literature, where several authors have noted a reduction in yield under the influence of trees, often attributed to competition for light, water, or nutrients (Sharma *et al.*, 1996; Hocking *et al.*, 1996). The observed variability could stem from the diversity of woody species involved, whose density and root architecture influence resource competition dynamics in different ways. However, Puri *et al.* (1994) reported that *Acacia nilotica* (L.) tree reduced crop yield under its canopy, and this reduction varies with distance from tree trunk. Maize height under *G. robusta* and *Eucalyptus* spp. was significantly reduced due to the effect of the tree canopy (Nyaga *et al.*, 2019). Also, the reduction in yield under the trees may be caused by the shade and hence, lower photosynthetic rates (Bremner, 1972).

Relationship between rice yield and soil hydrodynamic properties under *Elaeis guineensis* and *Borassus aethiopum*

The soil hydrodynamic properties under *Borassus aethiopum* were strongly correlated with each other, except Ks which showed weak correlation with other soil properties. As expected, a strong negative correlation was observed between BD and porosity, which underscores the inverse relationship where an increase in soil compaction leads to a reduction in pore space. This relationship plays a critical role in influencing root penetration, water movement, and microbial activity in forest soils (Hartmann *et al.*, 2014). Soil water holding capacity displayed a moderate positive correlation with porosity and a corresponding negative correlation with BD. These relationships suggest that soils with greater porosity can retain more water for crop production (Ghorbani *et al.*, 2023; Katigari *et al.*, 2022; Obalum *et al.*, 2011).

CONCLUSION

The presence of *Elaeis guineensis* and *Borassus aethiopum* significantly affected soil hydro-physical properties in rice the studied agroforestry system. The soil hydrodynamic properties under *Borassus aethiopum* were strongly correlated with each other, except the saturated hydraulic conductivity which exhibited weak correlation with other soil properties. Shallow soils retained more moisture under crowns than outside, and no difference of soil water content occurred in the deeper layers, suggesting a continuous renewal of the deeper soil layer water content. Rice grain and biomass yields were higher under *Borassus aethiopum* compared to *Elaeis guineensis*, highlighting specific influence of trees characteristics on rice crop or a particular competition of rice crop and trees in agroforestry systems. However, despite the observed difference in grain and biomass yields between tree species, no significant differences were found under and outside the tree crowns. It is necessary to explore on the one hand the influence of tree morphology and physiology on soil physical and hydrological properties, as well as crop growth and yield parameters for specific trees, and on the other hand the interrelationship between these variables. The findings show that rice cropping agroforestry systems can help with trees protection and improve rice yield. They will also help ensure good control of soil degradation factors and sustainable rice production in lowlands.

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