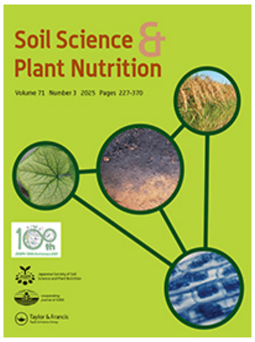

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RESEARCH ARTICLE

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Impact of effective soil depth on agronomic recommendations for sorghum and its economic viability in Africa

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ABSTRACT

Improving sorghum productivity, the second most important upland crop in Africa, is critical to meeting the continent's rapidly growing food demand. Previous research indicated that limited soil water, especially in soils with an effective soil depth (ESD) of ≤ 50 cm, restricts sorghum production under fertilized conditions. This finding suggests that optimal management practices, including fertilizer application rates, planting density, and variety selection, should vary by ESD. However, agronomic recommendations for sorghum in Africa have yet to incorporate ESD considerations. This study assessed the impact of ESD on optimal sorghum management practices and their economic stability amid fluctuating fertilizer prices. Two-year field experiments were conducted on soils with ESDs of 25, 50, and 100 cm in the Sudan Savanna, Africa's largest sorghum-producing region. These ESDs represent three dominant soil types in the region: two types of Plinthosols and Ferric Lixisol. Results showed that the optimal management practices varied by ESD: 37 kg N ha^{-1}, 3.1 hills m^{-2}, and Kapelga for 25 cm ESD; 74 kg N ha^{-1}, 8.3 hills m^{-2}, and Kapelga for 50 cm ESD; and 74 kg N ha^{-1}, 5.6 hills m^{-2}, and Sariaso14 for 100 cm ESD. These practices were economically robust for ESDs of 50 and 100 cm but not for 25 cm. A random forest regression model identified ESD as the most critical factor for sorghum yield, surpassing rainfall, nitrogen application rate, planting density, and variety. This study highlights the need for ESD-based agronomic recommendations to enhance food security and income stability for African farmers.

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Agronomic recommendation; effective soil depth; sorghum; sub-Saharan Africa; water shortage

1. Introduction

Improving agricultural productivity in sub-Saharan Africa (SSA) is vital to addressing the region's rapidly growing food demand. However, agricultural production growth has lagged behind population growth. Between 1982 and 2022, SSA's population grew 2.9 times (World Bank Group 2024a), whereas the yield per unit area of sorghum (*Sorghum bicolor*), SSA's second most important upland crop, increased only by 11% (FAO 2024). Bridging this gap is critical for achieving food security in SSA.

Low crop productivity in SSA is attributed to a lack of soil nutrients Liu et al. (2010); Sanchez (2002); Tittonell and Giller (2013) and the limited use of chemical fertilizers (Morris et al. 2007; Mueller et al. 2012). Tittonell and Giller (2013) concluded that nutrient availability, not water, is the primary constraint to crop production in SSA. Similarly, Twomlow et al. (2010) reported that nitrogen (N) deficiency, rather than soil moisture, limits crop yields even in semi-arid regions. However, Twomlow's findings are mainly based on southern Zimbabwe's Chromic Luvisols, which have a deep effective soil depth (ESD) (EU 2013). Therefore, these results may not be applicable to other SSA areas dominated by shallow soils, such as Plinthosols (PT) and Leptosols, which have low water holding capacity. Shallow soils are widespread in SSA; Eswaran et al. (1997) estimated that soils with ESD <25 cm and 25–50 cm account for 33% and 23% of Africa's land area, respectively. In a previous study (Ikazaki et al. 2024), we found that under fertilized conditions, soil water is a limiting factor on soils with ESD ≤50 cm, although it is not under unfertilized conditions. These findings suggest ESD significantly impacts fertilizer efficiency and should inform agronomic recommendations for sorghum in Africa.

Decades-old blanket fertilizer recommendations, often applied across diverse agro-ecological zones and soil types within entire countries, remain prevalent in many SSA nations (Kaizzi, Mohammed, and Nouri 2017; USAID and IFDC 2018). Despite their widespread use, these recommendations fail to

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identify optimal fertilizer application rates (Tonitto and Ricker-Gilbert 2016). Moreover, most do not account for price volatility in chemical fertilizers, placing local farmers at significant economic risk. For instance, global events like the COVID-19 pandemic and the Russia-Ukraine conflict caused fertilizer prices to surge 2.2 times between April 2020 and March 2022 (World Bank Group 2022). Adapting fertilization practices to local crops, soils, weather, and economic conditions is therefore crucial for improving crop yields and farmers' incomes, as emphasized in the Nairobi Declaration from the 2024 Africa Fertilizer and Soil Health Summit (African Union 2024).

The Optimizing Fertilizer Recommendations in Africa project aimed to set standards for fertilizer optimization. The project achieved this by calculating the net returns to fertilizer use (NRF) for different crops in semi-arid regions of West Africa (Dawi et al. 2017; Dicko et al. 2017; Nouri, Garba, and Wortmann 2017; Ouattara et al. 2017). However, the project neglected to consider ESD and fluctuations in fertilizer prices, resulting in critical gaps. Higher fertilizer rates on soils with greater ESD, such as Lixisols (LX), may boost sorghum yields due to better soil water conditions. Conversely, applying high rates on shallow soils like Plinthosols (PT) may fail to increase sorghum yields due to soil water deficits. Therefore, it is essential to reevaluate the optimal fertilizer application rate in soils with different ESD values. According to Ouattara et al. (2017) and Dicko et al. (2017), increasing the N fertilizer application rate to 90 kg N ha^{-1} for sorghum does not increase yield, even in the Guinea Savanna where annual rainfall exceeds 900 mm. Therefore, in the Sudan Savanna, which is Africa's largest sorghum-producing region with annual rainfall between 600 and 900 mm, the optimal N fertilizer application rate is expected to be less than 90 kg N ha^{-1}.

More detailed agronomic recommendations for sorghum can be established by simultaneously considering fertilizer application rate, planting density, and variety. Previous studies (Painter and Leamer 1953; Rosolem et al. 1993; Welch, Burnett, and Eck 1966) have observed higher sorghum yields at planting densities greater than 10 hills m^{-2} under well-fertilized conditions. Furthermore, under conditions where soil nutrients and water are sufficient, varieties with higher potential yields are likely to be advantageous. However, without corresponding increases in producer prices to match fertilizer price spikes, fertilization may not generate economic benefits, even in soils with a deep ESD. Therefore, management practices deemed optimal from a yield perspective must be evaluated from an economic standpoint as well.

In this study, we examined the impact of ESD on the optimal combination of fertilizer application rate, planting density, and sorghum variety in the Sudan Savanna. First, we identified the optimal combination of N application rate, planting density, and variety for sorghum cultivation in each dominant soil type. Next, we examined the economic robustness of these optimal combinations under fluctuating fertilizer and producer prices from 2010 to 2022. Finally, we applied machine learning techniques to confirm whether ESD is a significant determinant of sorghum yield in the Sudan Savanna.

2. Materials and methods

2.1. Site description

A field experiment was conducted at the Saria station (12° 16′ N, 2°09′ W; 300 m above sea level) of the Institute of Environment and Agricultural Research (INERA), located on the Central Plateau of Burkina Faso, a key sorghum-producing region. Sorghum is mainly grown for self-consumption in this region. The Köppen system classifies the area's climate as BSh, characterized by an average annual rainfall of 800 mm and a mean temperature of 28°C. Rainfall follows a unimodal pattern, with the dry season spanning November to April and the rainy season from May to October. Annual potential evaporation averages between 1700 and 2000 mm (Ouattara et al. 2006). Three experimental fields featuring dominant soils of the Sudan Savanna (Ikazaki et al. 2018) were selected at the Saria station: Ferric Lixisol (LX-fr), Petric Plinthosols (PT-pt), and Pisoplinthic Petric Plinthosol (PT-pt.px) (Supplementary Fig. S1). These were the same fields used in studies by Iseki, Ikazaki, and Batieno (2021, 2023). The morphological, physical, and chemical properties of these soils were documented by Ikazaki et al. (2018; Tables 1 and 2). The ESD values for LX-fr, PT-pt, and PT-pt.px were recorded at 25 cm, 50 cm, and 100 cm, respectively. The soil classification in this study was based on the IUSS Working Group WRB (2015) rather than the 2022 version. This decision was made because the classification criteria for PT have changed, and using the latest system could cause inconsistencies with the results of previous studies.

2.2. Experimental settings

In 2015, we cultivated sorghum across the three fields without fertilization to minimize soil heterogeneity and standardize cropping history. Prior to cultivation, tall trees and shrubs were cleared. In 2016, 95 plots measuring 6.0 m × 4.0 m (length × width) were established in

Table 1. Physical properties of three dominant soils in the Sudan Savanna.

		Particle size distribution					Volumetric water content						
Layer (cm)	Coarse fragment ≥ 2 mm (% weight)	Coarse Sand 0.2–2 mm	Fine Sand 0.02–0.2 mm	Silt 0.002–0.02 mm	Clay < 0.002 mm	Bulk density ($Mg\ m^{-3}$)	pF 1.6	pF 2.0	pF 2.5	pF 3.0	pF 3.2	pF 3.8	pF 4.2
		(% weight of fine earth <2 mm)					(%)						
Ferric Lixisols (LX-fr)													
0–10	1.5	39.8	45.1	6.5	8.7	1.60	22.5	17.3	13.1	9.7	8.6	5.6	4.4
10–25	1.2	35.5	37.3	6.3	20.9	1.69	23.2	20.1	17.2	14.4	13.3	10.8	9.3
25–50	2.3	30.6	31.5	5.5	32.3	1.61	25.9	23.6	21.3	18.3	17.2	15.0	13.6
50–75	5.5	29.7	31.7	5.6	33.0	1.59	26.6	24.3	21.8	18.5	17.4	15.3	14.0
75–100	25.1	29.3	33.7	6.4	30.6	1.66	25.6	23.5	20.6	17.1	16.0	14.4	13.0
Petric Plinthosols (PT-px)													
0–10	27.8	43.1	41.9	4.9	10.1	1.65	20.7	15.0	10.1	8.2	7.5	4.4	4.0
10–25	39.9	40.2	36.5	4.9	18.4	1.63	20.2	15.9	12.1	10.3	9.7	7.0	6.3
25–50	58.0	35.1	31.4	5.6	27.9	1.72	18.7	16.5	14.5	13.1	12.6	10.9	10.0
Pisoplinthic Petric Plinthosols (PT-pt.px)													
0–10	54.1	49.9	40.5	5.2	4.4	1.78	16.3	13.6	11.1	8.9	8.1	5.9	4.9
10–25	58.4	50.2	39.3	5.0	5.4	1.86	16.0	14.4	12.2	9.7	8.9	6.6	5.4

The data is quoted from Ikazaki et al. (2018).
The soil classification in this study is based on the IUSS Working Group WRB (2015).

Table 2. Chemical properties of three dominant soils in the Sudan Savanna.

							Exchangeable bases					CEC		EBS[‡]	Bray-1 P
Layer (cm)	pH (H_2O, 1:5)	pH (KCl, 1:5)	EC ($mS\ m^{-1}$)	OC ($g\ kg^{-1}$)	TN	C/N†	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	per fine earth	per clay	(%)	($mgP\ kg^{-1}$)
							($cmol_c\ kg^{-1}$)								
Ferric Lixisols (LX-fr)															
0–10	4.9	4.0	4.3	2.2	0.3	8.8	0.5	0.2	0.1	0.0	0.1	1.7	20.1	85.6	3.7
10–25	5.3	4.3	4.2	2.4	0.3	8.3	1.4	0.6	0.0	0.0	0.0	2.9	15.2	95.6	1.2
25–50	5.2	4.3	2.9	2.4	0.3	7.9	1.7	0.8	0.1	0.0	0.0	4.7	14.4	98.6	0.4
50–75	5.3	4.3	2.5	2.2	0.3	7.6	1.6	0.8	0.1	0.0	0.1	4.5	13.5	97.8	0.5
75–100	5.5	4.3	2.4	1.5	0.2	6.6	1.4	0.8	0.1	0.0	0.1	2.7	8.9	96.8	0.6
Petric Plinthosols (PT-px)															
0–10	5.3	4.2	2.8	3.1	0.3	10.5	0.7	0.2	0.0	0.0	0.1	1.2	13.3	90.8	2.9
10–25	5.8	4.6	3.3	3.2	0.3	10.3	1.4	0.3	0.0	0.0	0.0	1.6	8.8	98.8	1.5
25–50	6.2	5.0	3.4	2.9	0.3	9.1	2.1	0.5	0.0	0.0	0.0	3.6	12.1	100.0	0.7
Pisoplinthic Petric Plinthosols (PT-pt.px)															
0–10	5.5	4.5	2.8	2.5	0.2	10.3	0.5	0.1	0.0	0.0	0.1	0.8	18.7	88.6	2.1
10–25	5.3	4.3	2.6	1.9	0.2	10.1	0.3	0.1	0.0	0.0	0.1	0.7	12.8	77.1	1.6

EC: electrical conductivity; OC: organic carbon content; TN: total nitrogen content; CEC: cation exchange capacity; EBS: effective base saturation.
†Ratio of OC to TN; [‡] Ratio of exchangeable (Ca + Mg + K + Na) to exchangeable (Ca + Mg + K + Na + Al) defined in IUSS Working Group WRB (2015).
The data is quoted from Ikazaki et al. (2018).
The soil classification in this study is based on the IUSS Working Group WRB (2015).

each field. We implemented 19 treatments (Table 3) in a split-split design, each with five replicates, to account for three factors: N application rate, planting density, and sorghum variety. According to Burkina Faso's long-standing recommendations (IRAT, 1978), the recommended N application rate is 37 kg ha^{-1}, along with 23 kg ha^{-1} of phosphorus pentoxide (P_2O_5) and 14 kg ha^{-1} of potassium oxide (K_2O). This study tested three N levels: 37, 74, and 111 kg N ha^{-1}, focusing solely on N as it is the primary limiting factor for sorghum yield in this region (Tonitto and Ricker-Gilbert 2016). Unlike phosphorus, Hons et al. (1986) and Stichler, Mcfarland, and Coffman (1997) also identified N as critical to sorghum yield.

Planting densities were set at 3.1 hills m^{-2} (80 cm ×40 cm), 5.6 hills m^{-2} (60 cm ×30 cm), and 8.3 hills m^{-2} (60 cm ×20 cm) between rows and hills. As stated earlier, previous studies have observed higher sorghum yields at planting densities greater than 10 hills m^{-2} under well-fertilized conditions (Painter and Leamer 1953; Rosolem et al. 1993; Welch, Burnett, and Eck 1966). However, the dominant soils in this region are highly sandy and have low nutrient content (Ikazaki et al. 2018). Therefore, based on observations from farmers' fields where large amounts of manure were applied and sorghum yields were very high, the planting density was set to less than 10 hills m^{-2} in this study. An 80 cm row spacing aligns with ox plows, while 60 cm reflects donkey plows, which are more prevalent locally. We used two improved sorghum varieties, Kapelga (KP; Kondombo-Barro, Vom Brocke, and Trouche 2007) and Sariaso14 (S14; Trouche, Chantereau, and Kondombo-Barro 2005), both non-hybrid varieties developed by INERA. As KP and S14

Table 3. Treatments other than soil types.

Treatment number[†]	Variety	Density (hills m^{-2})	Nitrogen application rate (kg N ha^{-1})
1 (Control)	Kapelga	3.1	0
2 (BR)	Kapelga	3.1	37
3	Kapelga	3.1	74
4	Kapelga	3.1	111
5	Kapelga	5.6	37
6	Kapelga	5.6	74
7	Kapelga	5.6	111
8	Kapelga	8.3	37
9	Kapelga	8.3	74
10	Kapelga	8.3	111
11	Sariaso14	3.1	37
12	Sariaso14	3.1	74
13	Sariaso14	3.1	111
14	Sariaso14	5.6	37
15	Sariaso14	5.6	74
16	Sariaso14	5.6	111
17	Sariaso14	8.3	37
18	Sariaso14	8.3	74
19	Sariaso14	8.3	111

[†]BR, blanket recommendation in Burkina Faso with Kapelga.

are varieties suitable for regions with annual rainfall of 500–850 mm and 700–900 mm respectively, KP is expected to have lower water requirements than S14. On the other hand, the potential grain yield of S14 (4.7 Mg ha^{-1}; Trouche, Chantereau, and Kondombo-Barro 2005) is higher than that of KP (2.8 Mg ha^{-1}; Kondombo-Barro, Vom Brocke, and Trouche 2007), making S14 more likely to exhibit a stronger response to fertilization. The pure white color and taste of KP grains are considered more appealing to local farmers compared to those of S14 grains.

Soil was prepared using an ox plow two weeks before sowing. Plots were surrounded by 8-cm-high earth mounds to prevent runoff contamination. Both varieties were hand-planted on June 27–28, 2016, and 29 June 2017. Two weeks after sowing (WAS), plants in each hill were thinned to three. Fertilized plots received 100 kg ha^{-1} of 14–23–14 NPK compound fertilizer 2 WAS, with additional urea (46% N) adjusting N levels. Urea was applied in two doses: half at 4 WAS and the rest at 6 WAS as a topdressing. We manually controlled weeds two to three times per season. Sorghum was harvested on October 27–31, 2016 and on November 7–9, 2017.

2.3. Measurements

2.3.1. Weather

Meteorological data were recorded at 10-min intervals with an automatic weather station. The equipment included a temperature and relative humidity sensor (HygroVUE5; Campbell Scientific, Logan, UT), a rain gauge (TE525MM-L; Campbell Scientific), an albedometer (SRA01; Hukseflux, Delft, Netherlands), a wind sensor (034B-L; Campbell Scientific), and a barometer (PTB110; Vaisala, Helsinki, Finland).

2.3.2. Soil

Continuous monitoring of volumetric water content (VWC) began on 25 July 2016, using 30-cm-long time-domain reflectometry (TDR) probes (CS616; Campbell Scientific, UT) installed in a control plot within each field. The probes were placed within the ESD for all soil types: at depths of 0–10, 10–25, 25–50, and 50–75 cm in LX-fr; 0–10, 10–25, and 25–50 cm in PT-pt; and 0–10 and 10–25 cm in PT-pt.px. To account for temperature effects on the TDR probes, soil temperature was recorded at each depth using thermistor probes (108; Campbell Scientific, UT), following the manufacturer's protocol. VWC measurements were calibrated using the gravimetric method as per the manufacturer's protocol. Every two weeks, soil samples were collected from each layer in all fields, and the gravimetric VWC was determined after drying the samples in an oven at 105°C for over 24 h.

Soil water retention for each layer was estimated as a weighted average of retention values as shown in Table 1. The permanent wilting point was defined as a pF value of 4.2, and the total available soil water at pF values below 4.2 was calculated by summing the values for each layer within the ESD for each soil type.

2.3.3. Sorghum

Plots near abandoned termite mounds or a tall tree cleared in 2015, which exhibited exceptionally high sorghum growth, were excluded prior to fertilizer application. The exclusion was necessary because these plots' increased sorghum yield could obscure the effects of study variables (rainfall amount, N application rate, planting density, and variety). We harvested and analyzed all sorghum plants, excluding those at the edges of each plot, to determine their yield and its components. The harvested area was 12.5, 13.0, and 13.4 m^2 for planting densities of 3.1, 5.6, and 8.3 hills m^{-2}, respectively. We separated the panicles into rachises and grains and measured the mass of the stover and rachis after oven-drying at 70°C for 48 h. We measured the grain moisture content, which was approximately 11%, using a portable moisture tester (MT-16; Agratronix, OH). Yield components analyzed included the number of stems per hectare, number of panicles per stem, number of grains per panicle, and 100-grain dry weight (g) (good grain only).

2.3.4. Economic evaluation

The NRF (Franc Communaute Financiere Africaine [FCFA] ha^{-1}) was calculated as follows: $NRF = \Delta Y \times PP - Cf - Cs$

where ΔY represents the increased yield (kg ha^{-1}) compared to the control plot without fertilization, PP is the producer price of sorghum (FCFA kg^{-1}), Cf is the cost of fertilizer use (FCFA ha^{-1}), and Cs is the cost of seeds (FCFA ha^{-1}). Since the producer price of sorghum in Burkina Faso was unavailable for 2014–2019 and 2023, a regression equation was derived to estimate the producer price based on market prices using historical producer prices from 2007–2013 (FAO (2014), 2024) and 2020–2022 (FAO 2024) as well as market prices for the same period (World Bank Group 2024b) ($R^2 = 0.96$, $p < 0.001$, $n = 10$). This equation was used to estimate producer prices for the missing years (2014–2019 and 2023). Similarly, since the cost of fertilizer use was only available for 2017 (Ouattara et al. 2017; a 50-kg bag of urea and NPK compound fertilizer cost 13,500 FCFA), we estimated it using fertilizer market prices reported by the World Bank Group (2024c), assuming that the cost of fertilizer use was linked to the fertilizer market prices. When calculating NRF, the producer price for the subsequent year of cultivation was used, as farmers generally harvest sorghum in November and sell it the following year. The seed cost was calculated assuming 15 seeds per hill, a 100-grain weight of 2.1 g, and a price of 500 FCFA kg^{-1} for both KP and S14 seeds.

To assess the robustness of the optimal combination of the N application rate, planting density, and sorghum variety for each soil type, the NRF was recalculated for each optimal combination using historical fertilizer prices (2010–2022) and producer prices of sorghum (2011–2023) in Burkina Faso. Additionally, the benefit-cost ratio (BCR) was calculated using the following formula to evaluate the potential for the widespread use of these optimal combinations:

$$BCR = (\Delta Y \times PP)/(Cf + Cs)$$

According to Ronner et al. (2016), a $BCR > 2$ is required for promoting new technologies to local farmers.

2.4. Statistical analysis

The statistical analysis was conducted using SPSS ver. 21 (IBM, Armonk, NY). We analyzed the effects of rainfall amount, N application rate, planting density, and variety on sorghum yield and NRF using a generalized linear model (GLM). The amount of rainfall, N application rate, planting density, and variety were all treated as fixed factors in this model. Replication (block effect), on the other hand, was treated as a random factor due to the study using a split-split design (refer to Montgomery 2013 for more details). Similarly, the GLM was employed to assess the effects of rainfall, N application rate, and planting density on each yield component for KP. A post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted for comparisons among groups.

The relative importance of factors, i.e., ESD, rainfall, N application rate, planting density, and variety, in predicting sorghum yield was assessed using the Random Forest Regressor from the sklearn.ensemble module in Python (version 3.10.12). In this analysis, due to technical reasons, ESD could not be obtained for each plot, and therefore representative values (100 cm for LX-fr, 50 cm for PT-pt, and 25 cm for PT-pt.px) were used based on Ikazaki et al. (2018). The hyperparameter n_estimators (number of trees in the forest) was adjusted to 10,000, while other hyperparameters retained their default values. Feature importance was calculated five times using fivefold cross-validation, and the means of each factor were compared using the Tukey HSD test. Significance for all tests was defined as $p < 0.05$.

3. Results

3.1. Weather and soil water

The annual rainfall was 879 mm in 2016 and 723 mm in 2017. The total rainfall, mean daily minimum/maximum temperatures, and mean solar radiation during the growing period (June 20 to October 20) were 632 mm, 22.4°C/32.3°C, and 21.8 MJ m^{-2} day^{-1}, respectively, in 2016, and 523 mm, 22.2°C/33.0°C, and 22.6 MJ m^{-2} day^{-1}, respectively, in 2017.

Considering that the mean rainfall during the same period over the past 38 years (1978–2015) is 663 mm ± 110 mm (mean ± standard deviation), rainfall was near average in 2016 but below average in 2017. Total soil water available for sorghum within the ESD aligned with differences in ESD: LX-fr > PT-pt > PT-pt.px (Figure 1). Reflecting the rainfall amount, it was higher in 2016 than in 2017 from booting to half-blooming stages (60–80 days after sowing, DAS) across all soil types.

3.2. Effects of rainfall, fertilization, planting density, and variety on sorghum production and economic return

Reduced rainfall significantly decreased sorghum yield and NRF across all soil types (Table 4, Supplementary Table S1). Sorghum yield saturation was observed at 74 kg N ha^{-1} in soils with deep or moderate ESDs (LX-fr and PT-pt), a value higher than the decades-old blanket recommendation of 37 kg N ha^{-1} (IRAT 1978). However, in soils with a shallow ESD (PT-pt.px), saturation occurred at 37 kg N ha^{-1}. Similarly, NRF was highest at 74 kg N ha^{-1} in LX-fr and PT-pt. Synergistic effects of rainfall and fertilization (R x F) were evident in LX-fr and PT-pt. As expected, a higher planting density than the blanket recommendation of 3.1 hills m^{-2} (IRAT 1978) increased yield and NRF in LX-fr (5.6 hills m^{-2}) and PT-pt (8.3 hills m^{-2}), but not in PT-pt.px. Unexpectedly, S14 did not generally outperform KP, though its yield was higher under normal rainfall conditions in LX-fr (Supplementary Tables S2 and S3). In contrast, S14's yield and NRF were significantly lower than KP's in PT-pt.px.

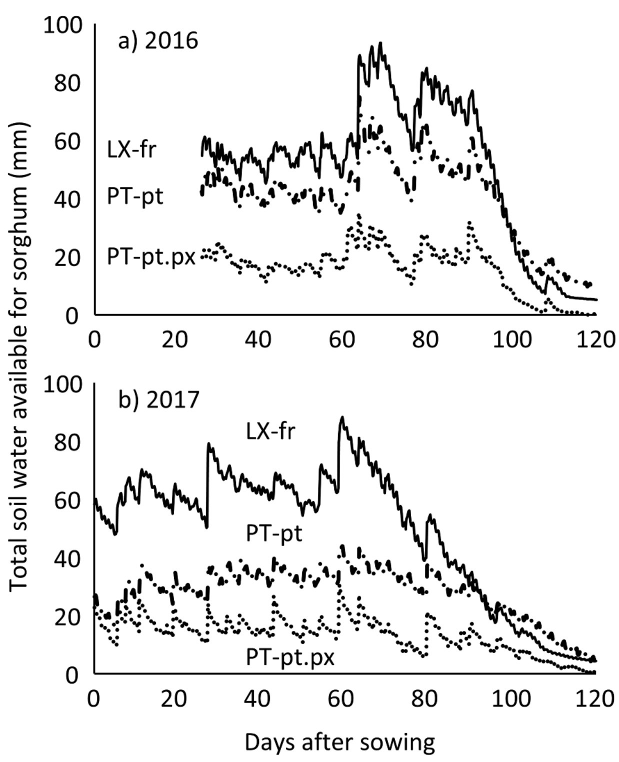

Figure 1. Total soil water available for sorghum within the effective soil depth. Ferric Lixisols (LX-fr), Petric Plinthosols (PT-pt), and Pisoplinthic Petric Plinthosols (PT-pt.px) had effective soil depths of 100 cm (deep), 50 cm (moderate), and 25 cm (shallow), respectively. The solid, dashed, and dotted lines represent the water levels in LX-fr, PT-pt, and PT-pt.px, respectively. Data were collected from the control plot for each soil type. The permanent wilting point was defined as a pF value of 4.2, and the total available soil water at pF values below 4.2 was calculated by summing the values for each layer within the ESD for each soil type.

3.3. Effects of rainfall, fertilization, and planting density on yield components of Kapelga

Yield components were assessed for Kapelga but not for S14, as the latter did not grow well in PT-pt.px in 2017. Reduced rainfall significantly decreased the number of stems but not other yield components in LX-fr with a deep ESD (Table 5). In contrast, it negatively impacted several yield components in PT-pt and PT-pt.px with moderate or shallow ESDs. Fertilization effects were observed only in the number of grains per panicle in LX-fr and PT-pt. Higher planting densities than the decades-old blanket recommendation significantly increased the number of stems but reduced the number of panicles per stem in PT-pt.px while decreasing the number of grains per panicle across all soil types. Similarly, Stickler and Wearden (1965) reported that increasing density reduces the number of grains per panicle. In summary, higher planting densities significantly increased the number of grains per hectare in PT-pt, showed a near-significant increase in LX-fr ($p = 0.057$), but had no effect in PT-pt.px (data not shown).

3.4. Robustness of optimal combinations for each soil type

Figure 2 illustrates the changes in NRF for the optimal combinations determined for each soil type in Section 4.1, alongside NRF values for BCR = 2. While the average NRF values (solid lines) for all soil types were positive, the average value minus the standard error (SE) was negative in over half of the years (7 out of 13) for PT-pt.px. Between 2010 and 2022, average NRF values exceeding BCR = 2 were observed 11 times in LX-fr, 5 times in PT-pt., and 3 times in PT-pt.px.

Table 4. Effects of rainfall, fertilization, density and variety on grain yield and net return to fertilizer use for each dominant soil type.

	Grain yield (kg ha^{-1})			Net return to fertilizer use (10^3 FCFA ha^{-1})		
	LX-fr	PT-pt	PT-pt.px	LX-fr	PT-pt	PT-pt.px
Rainfall (R)						
Low (2017)	1160 a	560 a	528 a	53 a	−19 a	−10 a
Average (2016)	1829 b	1110 b	1029 b	159 b	59 b	48 b
Fertilization (F; kg N ha^{-1})						
37	1098 a	619 a	691 a	55 a	3 a	25 a
74	1660 b	1049 c	857 a	136 b	60 b	33 a
111	1724 b	820 b	782 a	126 b	−4 a	−3 a
Density (D; hills m^{-2})						
3.1	1332 a	696 a	784 a	80 a	−2 a	24 a
5.6	1661 b	828 ab	762 a	136 b	19 ab	17 a
8.3	1490 ab	975 b	774 a	101 ab	43 b	14 a
Variety (V)						
Kapelga	1453 a	870 a	853 b	100 a	28 a	34 b
Sariaso14	1535 a	800 a	691 a	112 a	12 a	2 a
R	**	***	***	*	***	***
F	**	***	ns	*	***	ns
D	*	*	ns	*	*	ns
V	ns	ns	**	ns	ns	**
R × F	**	*	ns	**	*	ns
R × D	ns	*	ns	ns	ns	ns
R × V	**	ns	*	**	ns	*
F × D	ns	ns	ns	ns	ns	ns
F × V	ns	ns	ns	ns	ns	ns
D × V	ns	ns	ns	ns	ns	ns
R × F × D	ns	ns	ns	ns	ns	ns
R × F × V	ns	*	*	ns	*	*
R × D × V	ns	ns	ns	ns	ns	ns
F × D × V	ns	ns	ns	ns	ns	ns
R × F × D × V	ns	ns	ns	ns	ns	ns

LX-fr, Ferric Lixisols; PT-pt, Petric Plinthosols; PT-pt.px, Pisoplinthic Petric Plinthosols. The effective soil depth is 100 cm (deep), 50 cm (moderate), and 25 cm (shallow) for LX-fr, PT-pt, and PT-pt.px, respectively.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns, not significant ($p > 0.05$).
Mean values with different letters are significantly different between treatments ($p < 0.05$).
Comparison between treatments #2–19 (Table 3) over two years.

Table 5. Effects of rainfall, fertilization, and density on yield components of Kapelga for each dominant soil type.

	Number of stems (10^3 ha^{-1})			Number of panicles (stem^{-1})			Number of grains (panicle^{-1})			100 grain weight (g)		
	LX-fr	PT-pt	PT-pt.px	LX-fr	PT-pt	PT-pt.px	LX-fr	PT-pt	PT-pt.px	LX-fr	PT-pt	PT-pt.px
Rainfall (R)												
Low (2017)	137 a	144 a	150 a	0.81 a	0.68 a	0.70 a	636 a	389 a	370 a	1.92 a	1.84 a	1.76 a
Average (2016)	156 b	145 a	162 b	0.85 a	0.80 b	0.86 b	689 a	505 b	431 a	2.03 a	1.99 b	2.00 b
Fertilization (F; kg N ha^{-1})												
37	148 a	151 a	159 a	0.78 a	0.72 a	0.79 a	568 a	336 a	376 a	1.93 a	1.93 a	1.86 a
74	150 a	143 a	155 a	0.86 a	0.78 a	0.78 a	677 b	535 c	428 a	1.99 a	1.94 a	1.92 a
111	141 a	140 a	153 a	0.85 a	0.74 a	0.76 a	742 b	469 b	393 a	2.01 a	1.88 a	1.85 a
Density (D; hills m^{-2})												
3.1	86 a	81 a	89 a	0.86 a	0.77 a	0.86 b	877 c	595 c	537 b	1.99 a	1.98 a	1.89 a
5.6	146 b	142 b	154 b	0.83 a	0.73 a	0.79 b	658 b	416 b	363 a	1.98 a	1.88 a	1.93 a
8.3	207 c	210 c	222 c	0.80 a	0.74 a	0.69 a	453 a	333 a	303 a	1.96 a	1.89 a	1.81 a
R	*	ns	**	ns	*	**	ns	**	ns	ns	*	**
F	ns	ns	ns	ns	ns	ns	**	***	ns	ns	ns	ns
D	***	***	***	ns	ns	**	***	***	***	ns	ns	ns
R×F	ns	*	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
R×D	*	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
F×D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
R×F×D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

LX-fr, Ferric Lixisols; PT-pt, Petric Plinthosols; PT-pt.px, Pisoplinthic Petric Plinthosols.
The effective soil depth is 100 cm (deep), 50 cm (moderate), and 25 cm (shallow) for LX-fr, PT-pt, and PT-pt.px, respectively.
*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns, not significant ($p > 0.05$).
Mean values with different letters are significantly different between treatments ($p < 0.05$).
Comparison between treatments #2–10 (Table 3) over two years.

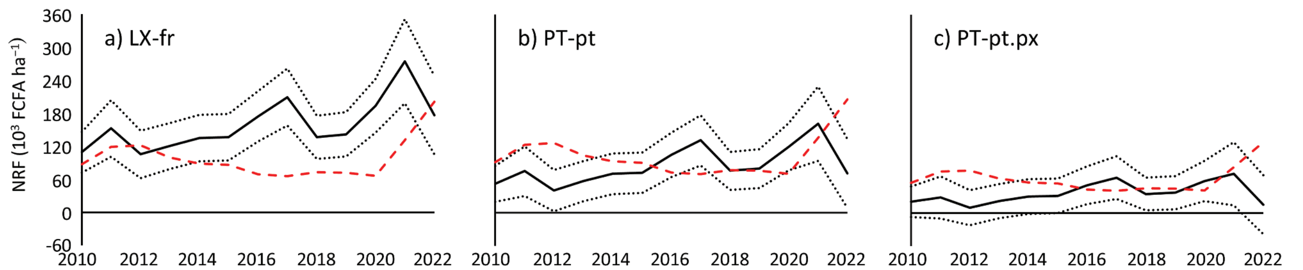

Figure 2. Estimated net return to fertilizer use from 2010 to 2022 under the optimal management practices for each soil type. Ferric Lixisols (LX-fr), Petric Plinthosols (PT-pt), and Pisoplinthic Petric Plinthosols (PT-pt.px) are shown. The dotted lines indicate the range of the standard error of the NRF, and the red dashed lines indicate a benefit cost ratio of 2 for each year. The optimal combination of nitrogen (N) application rate, planting density, and variety is 74 kg N ha^{-1} 5.6 hills m^{-2}, and Sariaso14 for LX-fr; 74 kg N ha^{-1}, 8.3 hills m^{-2}, and Kapelga for PT-pt; and 37 kg N ha^{-1}, 3.1 hills m^{-2}, and Kapelga for PT-pt.px.

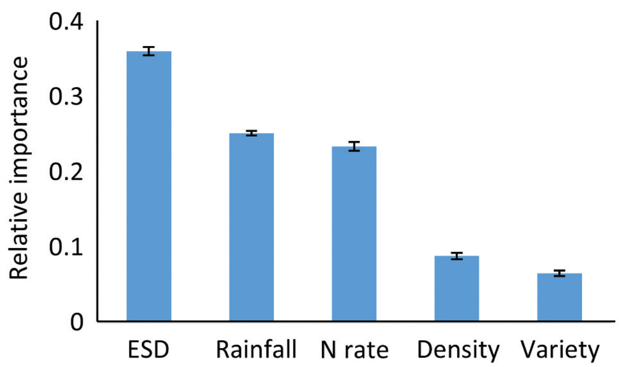

Figure 3. Relative importance of each factor in predicting sorghum yield. ESD and N are effective soil depth and nitrogen, respectively. Error bars represent standard errors of the mean.

3.5. *Relative importance of factors in predicting sorghum yield*

Figure 3 presents the feature importance for each factor. ESD ranked as the most important, followed by rainfall and N application rate, while planting density and variety exhibited low importance.

4. Discussion

4.1. *Optimal management of sorghum cultivation in the Sudan Savanna*

The effects of fertilization, planting density, and variety separately contributed to sorghum yield and NRF, as indicated by the lack of interaction between these factors (Table 4). Therefore, the optimal N application rate, planting density, and variety for each soil type were determined independently to maximize sorghum yield and NRF values. Based on Table 4, the optimal combinations of N application rate and planting density were 74 kg N ha^{-1} with 5.6 hills m^{-2} for LX-fr, 74 kg N ha^{-1} with 8.3 hills m^{-2} for PT-pt, and 37 kg N ha^{-1} with 3.1 hills m^{-2} for PT-pt.px. As the chemical properties of these soils were similar (Table 2), the ESD, which determines the amount of available soil moisture, would have had the greatest impact on the optimal combinations. Higher N rates and planting densities than the historically recommended blanket values improved both sorghum yield and economic returns in LX-fr and PT-pt with deep or moderate ESDs. Similarly, MacCarthy, Sommer, and Vlek (2009) reported that sorghum yield in a PT bush field in northern Ghana increased with N application rates up to approximately 80 kg N ha^{-1} when planted at a density of 6.2 hills m^{-2}. The difference in the optimal N application rate between LX-fr and PT-pt (74 kg N ha^{-1}) and PT-pt.px (37 kg N ha^{-1}) can be attributed to the lower soil water content in PT-pt.px (Figure 1), resulting from its lower water holding capacity (i.e., coarser texture and shallower ESD) compared to LX-fr and PT-pt. In contrast, the higher soil water content in LX-fr likely amplified the synergistic effects of rainfall and fertilization, leading to increased sorghum yield and NRF. Additionally, the higher yield observed in 2016 compared to 2017 can be attributed to more favorable soil water availability during the booting to half-blooming stages (60 to 80 DAS) in 2016. Water deficits during this critical period are known to significantly reduce grain yield (Inuyama, Musick, and Dusek 1976; Lewis, Hiler, and Jordan 1974; Salter and Goode 1967).

The optimal sorghum variety for both Plinthosols (PT-pt, PT-pt.px) would be KP. Notably, S14 performed poorly in PT-pt.px with a shallow ESD in 2017. Although the rainfall in 2017 was low (723 mm), it was still within the range of 700–900 mm that is considered suitable for S14 cultivation. Therefore, the poor growth of S14 was probably due to the low available soil moisture caused by the low ESD in PT-pt.px, rather than the low rainfall. When releasing a new variety in this area in the future, it will be necessary to indicate not only the rainfall standards suitable for that variety, but also the ESD standards at the same time. By contrast, in LX-fr, which features a deep ESD, the yield of S14 surpassed that of KP in

2016 under average rainfall conditions (Supplementary Tables S2 and S3). Although S14 did not show a significant overall advantage over KP (Table 4), we concluded that S14 is optimal for LX-fr because the probability of an average or high rainfall year is higher than a year with low rainfall. In summary, ESD significantly influenced the optimal variety, and on soils with an ESD of approximately 100 cm, the high-yield variety S14 May be more suitable.

4.2. Factors influencing the Kapelga grain yield under fertilized conditions

Reduced rainfall primarily affected the number of stems in LX-fr while significantly influencing multiple yield components in Pt-pt and PT-pt.px (Table 5). This distinction is consistent with Figure 1, which indicates that the total available water for sorghum in fertilized LX-fr plots was likely higher than in PT-pt and PT-pt.px plots. Notably, the reduction in 100-grain weight observed in PT-pt and PT-pt.px (Table 5) suggests that these soils did not have enough water from the heading to the soft dough stages (about 65–98 DAS in this study), as corroborated by Eck and Musick (1979) and Stichler, Mcfarland, and Coffman (1997).

Higher N application rates, exceeding the outdated decades-old recommendation, significantly increased the number of grains per panicle in LX-fr and PT-pt (Table 5). This enhancement directly contributed to higher yields, as the number of grains per panicle is widely recognized as a primary determinant of sorghum yield (FAO (2012); Ouédraogo, Mando, and Zombré 2001, Wright, Smith, and McWilliam 1983, Zaongo et al. 1997). Although increasing planting density reduced the number of grains per panicle, it simultaneously increased the number of grains per hectare in LX-fr and PT-pt. This compensatory effect likely contributed to the observed yield increases in these soils. The predominance of the number of grains over seed weight in determining yield has been emphasized in earlier studies (Craufurd and Peacock 1993; Heinrich, Francis, and Eastin 1983; Saeed, Francis, and Clegg 1986). This may be attributed to the sorghum yield in this region being sink-determined, meaning the number of grains is relatively small compared to the availability of net photosynthetic assimilates (van Oosterom et al. 2010).

4.3. Robustness of optimal sorghum management practices

The optimal management practices identified in Section 4.1 are highly robust against fluctuations in fertilizer and producer prices for LX-fr and PT-pt with deep or moderate ESDs. This robustness is demonstrated by the consistently positive average NRF values minus its SE over 13 years (2010–2022; Figure 2). Even during the extreme fertilizer price increases in 2021 and 2022, NRF minus its SE remained positive due to a rapid rise in sorghum producer prices (Supplementary Fig. S2). However, for PT-pt.px with a shallow ESD, the average NRF values minus SE were negative in more than half of the 13 years. Consequently, when disseminating the optimal management practice for PT-pt.px, although essentially similar to current blanket recommendations, it is crucial to communicate the associated risks to local farmers.

The average NRF values in LX-fr mostly exceeded BCR of 2, which is the threshold for farmers to adopt new technologies according to Ronner et al. (2016). Thus, introducing the optimal management practice for this soil type should be prioritized. Conversely, while most farmers could achieve an NRF > 0 with optimal management in PT-pt, the average NRF values fell below BCR = 2 with a probability exceeding 60%. This suggests that adoption rates among local farmers may be limited. Nevertheless, studies in Burkina Faso have reported that farmers are less risk averse regarding fertilizer application (Le Cotty et al. 2021, Nauges, Bougherara, and Koussoubé 2021), implying that the actual BCR threshold for adoption may be lower than 2. Future research should clarify this threshold to better guide agronomic recommendations.

In PT-pt.px, the average NRF values were generally below BCR = 2, and NRF could even be negative, making it challenging to promote the proposed optimal management practice for this soil type. This is likely to apply to many Leptosols, characterized by ESDs <25 cm, which are widely distributed in the semi-arid regions of Africa. However, this does not imply that sorghum cultivation with chemical fertilizers is impractical in these soils. Studies such as Bationo et al. (2004) have shown that combining chemical fertilizers with compost can enhance their effectiveness. Thus, future research should explore the impact of integrated fertilizer-compost applications on NRF in PT-pt.px and similar Leptosols with shallow ESDs.

This study is the first to demonstrate that ESD is the most critical factor influencing sorghum yield in the Sudan Savanna, surpassing other factors like rainfall, variety, and management practices. The ESD also significantly affects optimal management practices, emphasizing its central role in sorghum cultivation in Africa. Encouragingly, soil types classified by the IUSS Working Group WRB (2015) correlate well with ESD in the Sudan Savanna (Ikazaki et al. 2018), enabling ESD prediction based on soil type. However, current soil maps, such as those from the EU et al. (2013), are only available at large scales. Additionally, while Africa SoilGrids provides a 1000 m resolution map of root zone depth (Leenaars et al. 2018), it shows a significant deviation from measured ESD values in the 192 km^2 Doulou watershed, including the Saria station (unpublished data: $n = 62$; mean error of 47.2 cm with a standard deviation of 20.1 cm, and nonsignificant correlation coefficient). Developing a simple method for producing small-scale soil maps tailored to local farmers' needs is therefore urgently required. Such maps could enable precise estimation of soil types and ESD for individual fields. With these tools, extension agencies could efficiently promote ESD-based optimal management practices, improving fertilizer use efficiency and minimizing economic risks for farmers.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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