Soil & Tillage Research 246 (2025) 106324

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Pearl millet yield reduction by soil erosion and its recovery potential through fertilizer application on an Arenosol in the Sahel

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ARTICLE INFO

Keywords:
Arid agriculture
Soil degradation
Soil restoration
Sub-Saharan Africa
Topsoil removal

ABSTRACT

Despite the heightened contribution of soil erosion to soil degradation in the Sahel, its impact, particularly topsoil loss, on crop productivity remains unclear. To address this issue, we investigated the effects of simulated erosion by removing topsoil on the grain yield of pearl millet in the Sahel. Three-year field experiments conducted on an Arenosol in Niger examined different levels of topsoil removal (0, 1.0, 2.5, 5.0, and 10 cm) and fertilization (unfertilized and fertilized) on the grain yield of pearl millet. Results showed that topsoil removal of 2.5 cm or more significantly reduced grain yield, with effects projected to become apparent in 5–6 years based on erosion rates previously reported. Under normal rainfall conditions in the first and third years, 2.5-cm topsoil removal under unfertilized conditions resulted in a yield reduction of 37 % cm^{-1}, surpassing the values reported in other humid to semi-arid regions of sub-Saharan Africa. Conversely, the grain yield remained unaffected following a 1-cm topsoil removal. Fertilizer application compensated for the grain yield loss in the plots of 2.5- and 5.0-cm topsoil removal but not effectively in the 10-cm removal plot. In conclusion, the loss of the thin Ap horizon markedly reduced plant-available water and nutrients in soils, leading to a decreased grain yield of pearl millet in the Sahel. Given the Ap horizon thinness and soil erosion prevalence in the Sahel, recognizing the topsoil loss in the early stages of soil erosion and implementing countermeasures are imperative to avoid a sharp decline in grain yield.

1. Introduction

Agricultural soil erosion ranks among the most destructive human-induced perturbations to soil sustainability (Amundson et al., 2015), as it adversely affects soil quality and productivity by reducing infiltration rates, water-holding capacity, nutrients, organic matter, soil biota, and soil depth (IPBES, 2019; Pimentel et al., 1995). Soil erosion rate in croplands (12.7 Mg ha^{-1} yr^{-1}) is substantially higher than that in native vegetation and the soil formation rate (Montgomery, 2007). Consequently, despite occupying a relatively small percentage of the world's land (11.2 %), croplands contribute disproportionately to total soil erosion (50.5 %) (Borrelli et al., 2017). Continuous depletion of nutrient resources and reduced water availability due to soil erosion can result in stunted plant growth, decreased overall productivity, and increased agricultural costs (Frye et al., 1982; Panagos et al., 2018). Preventing the loss of fertile topsoil caused by soil erosion represents an essential long-term strategy for achieving agricultural sustainability (Jones et al., 2013).

The erosion-induced loss of fertile surface soil results in decreased crop productivity and necessitates labor-intensive efforts to restore soil fertility. This challenge is particularly pronounced in sub-Saharan African (SSA) countries, where meeting the demand for staple food crops becomes increasingly difficult due to the growing population and the unaffordability of chemical fertilizers for local small-holder farmers (Sanchez, 2002; van Ittersum et al., 2016). Africa has the highest soil erosion rate (3.9 Mg ha^{-1} yr^{-1}) among South America (3.8 Mg ha^{-1} yr^{-1}), Asia (3.5 Mg ha^{-1} yr^{-1}), and other continents (Borrelli et al., 2017). Without fertilizer application, African agricultural soils exhibited

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https://doi.org/10.1016/j.still.2024.106324
Received 11 June 2024; Received in revised form 30 September 2024; Accepted 3 October 2024
Available online 16 October 2024

a negative overall phosphorus balance (−11.4 kg P ha^{-1} yr^{-1}) owing to high phosphorus losses resulting from severe soil erosion (Alewell et al., 2020). Erosion-induced yield losses of 2 %–40 %, with a mean loss of 9 % for the African continent and 6.6 % for SSA, have been reported (Lal, 1995, 2001). If higher soil erosion rates continue unabated, average annual crop yield declines of 16.5 % for the former and 14.5 % for the latter may be possible (Pimentel and Burgess, 2013). However, these estimations involve uncertainty mainly due to the high spatial variability in environmental conditions and soil erosion characteristics in SSA (Nishigaki et al., 2017).

Spatiotemporally erratic rainfall patterns combined with extremely sandy and less fertile soils markedly contribute to persistent food production insecurity in the Sahel (Agnew and Chappell, 1999). The region also suffers desertification and consequent depletion of soil fertility, primarily resulting from wind erosion (Ikazaki, 2015). Wind erosion causes soil and nutrient losses at rates of 4–5 mm yr^{-1} and 40–50 kg N ha^{-1} yr^{-1}, respectively, which is 2–3 times higher than the annual nitrogen uptake by pearl millet in this region (Ikazaki et al., 2012, 2011b). The impact of wind erosion on soil properties in the region could result from the loss of a loose sand layer, Ap horizon, which forms on the ground and is typically a few centimeters thick. This sandy Ap horizon overlays a crust layer, which has low water permeability, and prevents the deterioration of physical properties resulting from crust layer exposure. Hence, the loss of only several centimeters, including the sandy Ap horizon, could significantly decrease crop productivity. However, unlike regions with relatively high rainfall amounts in SSA (Lal, 1995; Mbagwu et al., 1984), the impact of soil loss on crop productivity in the Sahel remains unclear.

Restoring soil fertility using mineral and organic fertilizers is essential for closing the yield gap in degraded croplands in SSA (Nord et al., 2022; Tittonell and Giller, 2013; Zhou et al., 2015). Bielders et al. (2000) showed that broadcasted pearl millet stover mulching was effective to trap aeolian sediment transported by wind, which would contribute to ameliorate degraded lands. Treatment with organic amendments such as manure proved highly effective in restoring productivity by supplying macro- and micronutrients to eroded soils (Larney et al., 2000). In contrast, treatment with chemical fertilizer failed to restore yields to the level observed in noneroded soil (Wang et al., 2009). Mbagwu et al. (1984) observed the nonresponsiveness of maize yield to even higher fertilizer application rates in plots where 10 or 20 cm of topsoil had been removed in southeast Nigeria—an effect resulting from poor drainage conditions or other yield-limiting elements not supplied by fertilizer. Consequently, farmers can benefit from understanding the crop yield increase achieved through fertilizer application to counteract yield reductions at various levels of soil erosion. However, there have been few attempts to determine the effect of fertilizer application on crop yield recovery at different levels of soil erosion in field experiments in SSA.

The most recognized method for analyzing the impact of soil erosion on productivity involves evaluating crop yield variations among plots with varying degrees of erosion (Zhang et al., 2021). Major attempts to obtain data for this purpose include (1) removing or adding topsoil in experimental plots and (2) comparing crop yield along transects and plots with different erosion levels. Topsoil removal may exacerbate the negative effects of erosion on productivity, as it leads to the abrupt disappearance of topsoil without the natural preferential sorting of soil aggregates in erosion processes (Zhang et al., 2021). Higher values of yield reduction have been generally reported in previous studies using topsoil removal approach compared to other approaches (Bakker et al., 2004). Bakker et al. (2004) found an approximately 26.6 % yield reduction with topsoil removal (desurfacing) methods and a 10.9 % reduction with transect methods per 10 cm of soil loss. However, the confounding aspects of landscape position and inherent topsoil depth variability in Attempt 2 can be overcome using a topsoil removal experiment. Moreover, traditional cultivation practices in the Sahel involve minimal disturbance, typically utilizing push-hoes for only the top several centimeters of surface soil. This suggests that the disappearance of topsoil may, to some extent, mimic natural erosion processes. Therefore, the topsoil removal experiment is considered the easiest, most practical, and efficient quantitative method in research examining the effects of soil erosion on crop yields in the Sahel (Bakker et al., 2004; Gao et al., 2015; Zhang et al., 2021).

This study focuses on assessing the effect of topsoil removal on pearl millet productivity in the Sahel and quantifying the effectiveness of fertilizer application in restoring productivity in eroded soils. Of particular interest, we aimed to determine the depth of topsoil removal that causes significant yield loss in pearl millet and to understand to what depth of topsoil removal the yield loss can be recovered by fertilizer application.

2. Materials and methods

2.1. Field experiment

A three-year field trial was conducted at the International Crops Research Institute for the Semi-Arid Tropics West and Central Africa (IWCA) in Niger (13°14'16"N, 2°16'48"E, 230 m asl.) from 2009 to 2011. The climate is typical of the Sahel and is classified as BSh according to the Köppen climate classification system. The mean annual temperature was 29°C (based on the mean values from 1983 to 2008, with data missing for 2003, provided by IWCA). Rainfall is concentrated during the rainy season, from June to October. The mean rainfall during this period was 513 ± 113 mm (mean ± standard deviation based on data from 1983 to 2008, with data missing for 2003, provided by IWCA). According to the same data, the monthly rainfall in October was the lowest, averaging 15.6 mm, and mostly less than 10 mm. The total rainfall values in the cropping period from June to October were 493.6 and 476.1 mm in the first and third years, which were comparable to the mean value in this area. Meanwhile, the total rainfall in the second year was 661.2 mm, 29 % higher than the average value, due to the high rainfall amounts in September and October, which were 1.5 and 6.3 times higher than the average of each month (Fig. 1). Heavy rainfall events (>35 mm day^{-1}) were frequently observed after fertilizer application in the second year: three times (26, 33, and 40 days after sowing (DAS)) within a month after fertilizer application in the second year, while only once in the first (24 DAS) and third years (44 DAS).

The soil at the experimental site was classified as Dystric Sideralic Arenosol according to the WRB soil classification system (IUSS Working Group WRB, 2022). The temperature regime was isohyperthermic and moisture regime was ustic. The sand content exceeded 90 % throughout the soil profile up to a 180-cm depth (Supplemental Table 1 and Photo 1). The land history before the experiment is a 4-year fallow. A

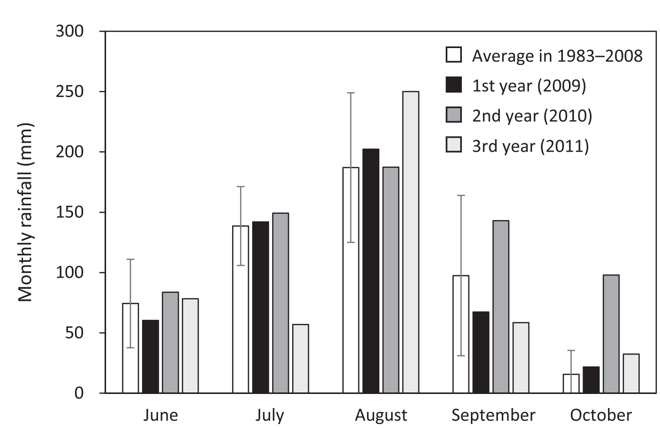

Fig. 1. Monthly rainfall at the experimental site during cropping seasons (June–October) in the three years and the average value in 1983–2008. Error bars represent the standard deviation of the values in 1983–2008.

randomized complete block split-plot design with three replicates was established in the 2009 season. Each block had two whole plots with and without fertilizer application and each whole plot had five subplots with different removal depths (0, 1.0, 2.5, 5.0, and 10 cm). In the fertilized plots, 200 kg ha^{-1} of NPK compound fertilizer (15 % N, 15 % P_2O_5, and 15 % K_2O) common in the study area was broadcasted 14 DAS following IWCA recommendations. The topsoils were excavated and removed manually from all the subplots using handheld rectangular shovels with 1-, 2.5-, and 5-cm thicknesses. The subplot measured 7 m by 7 m. The slope of the experimental site was 2 %, with the south side higher and the north side lower. To prevent soil and fertilizer from being carried outside the plots by erosive wind (east wind) and runoff water, and to prevent them from entering the adjacent plots, trenches (30 cm wide and 30 cm deep) were dug on the west and north sides of each plot, specifically on the leeward and lower sides. Soil accumulated in the trenches was removed as needed. The overview of the experimental site can be seen as Supplemental Photos 2 and 3. A landrace of pearl millet, Haini kirey (120 days to maturity), was used in this experiment owing to its widespread use by farmers in the region. The planting density of pearl millet was 1 m × 1 m and thus 10,000 plants per hector. About 20 pearl millet seeds were placed in pockets on June 14, 2009, June 20, 2010, and June 23, 2011, in the first to third years, respectively. Re-seeding was also performed as needed. Pearl millet was thinned to three plants per hill four weeks after sowing. Weeding was conducted twice by hand during the cropping season, and weed biomass was sampled to measure the weight at each plot.

2.2. Soil sampling and analysis

To assess the vertical variation in the initial soil fertility of the surface layer at the experimental site, soil samples were collected before topsoil removal at depths of 0–1.0, 1.0–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0, 5.0–7.0, 7.0–9.0, 9.0–11.0, 11.0–13.0, 13.0–15.0, 15.0–17.5, and 17.5–20.0 cm at 5 points in the experimental site and then mixed to make composite samples. The soil samples were then air-dried, passed through a 2-mm sieve, and used for subsequent analysis. Soil pH and electric conductivity (EC) were determined in deionized water at a soil-to-solution ratio of 1:5. The total carbon content (TC) and total nitrogen content (TN) were quantified using the dry combustion method with an NC analyzer (VarioMAX CN; Elemental Analysensystem GmbH, Hanau, Germany). Exchangeable cations (Ca, Mg, K, and Na) and cation exchangeable capacity (CEC) were measured using the ammonium acetate method following van Reeuwijk (2002). Exchangeable Al was extracted by 1 M KCl and determined as in van Reeuwijk (2002). Nutrient loss due to topsoil removal was calculated based on the depth of topsoil removal, the bulk density and nutrient concentration of the topsoil. The bulk density values used were previously measured as 1.58 Mg m^{-3} (0–3 cm depth) and 1.65 Mg m^{-3} (3–10 cm depth) (Supplemental Table 1).

To obtain the soil water retention curve, soil samples were taken at 10, 30, 50, and 80 cm depth using the 100 mL metal core. Then, the volumetric water contents at tensions of 9.8, 31, 98, and 1500 kPa (permanent wilting point) were measured with a pressure plate apparatus as described in Dane and Hopmans (2002).

2.3. Plant sampling and analysis

To monitor pearl millet growth, the dates of heading and flowering were recorded. After drying the panicles in the field for two weeks, in early November, yield components (survival rate, stem number per survived hill, panicle number per stem, grain weight per panicle) and grain yield were determined using all plants in each plot after removing one border row on each side of the plot (25 plants from 25 m^2 per plot) (Supplemental Photo 4). The collected plant samples were oven-dried at 70℃ for 48 h and weighed. The weight of the weed biomass was also recorded after drying at 70℃ for 48 h.

2.4. Environmental monitoring

Rainfall amount was measured with a tipping bucket rain gauge (TE525; Campbell Scientific, Inc., UT, USA) at the experiment site and recorded using a data logger (CR1000; Campbell Scientific, Inc., UT, USA) at 30-min intervals throughout the experimental period. The volumetric water content (VWC) of soils at a depth of 0–10 cm was continuously measured using time domain reflectometer probes (CS616; Campbell Scientific, Inc., UT, USA) with one replication in a subplot of 0, 1, 2.5, and 5 cm topsoil removal in a representative main plot. The profile moisture content was also monitored using soil moisture probes (Easy-AG 1358; Sentek, SA, Australia) at depths of 10, 30, 50, and 80 cm in the same plots as above. Data on soil moisture were recorded using a data logger (CR1000) at 30-min intervals from June to October 2009. The data in the plot with 10-cm topsoil removal was missing because we failed to measure it.

The amount of soil water at the lower tension than the permanent wilting point (1500 kPa) in the soil profile (0–100 cm depth) was calculated with the bulk density, VWC at the permanent wilting point, VWC at that time, and thickness of each layer. The VWCs at depths of 10, 30, 50, and 80 cm were used to calculate the soil water content of layers of 0–20, 20–40, 40–60, and 60–100 cm, respectively. Supplemental Table 1 contains the bulk density of each layer.

2.5. Statistical analyses

Statistical analyses were performed using JMP14 software (SAS Institute Inc., Cary, NC, USA). A Pearson correlation analysis was performed to assess the relationship among the soil properties in the top 20-cm depth. Grain yield and stem number per survived hill of pearl millet and weed biomass were logarithmically transformed for normality. Then, analysis of variance (ANOVA) was conducted to determine the individual effects of topsoil removal depth, fertilizer application, and experimental year on the measured variables. The mean values of these transformed variables and other original variables, except survival rate, in different treatment plots were then compared with the plot with 0-cm topsoil removal under unfertilized conditions (hereafter control) using the Dunnett's test. The survival rate did not follow a normal distribution even after logarithmical transformation. Therefore, the mean values of its original data in different treatment plots were compared with the control using the Steel test. In all cases, statistical significance was determined at the $p < 0.05$ level.

3. Results

3.1. Initial soil properties of the surface layer and nutrient losses by topsoil removal

Soil pH, EC, TN, TC, and exchangeable Ca decreased with increasing soil depth, whereas the C:N ratio and exchangeable Al increased with increasing soil depth (Table 1). Exchangeable Mg, exchangeable Na, and CEC exhibited unclear trends in relation to soil depth. Thus, the surface soils of the plots after topsoil removal had lower pH, EC, TN, TC, and exchangeable Ca and higher C:N ratio and exchangeable Al than those of the original soil (i.e., the plot of 0-cm removal). Soil pH negatively correlated with exchangeable Al ($r = -0.97$, $p < 0.001$, $n = 12$) but positively correlated with exchangeable Ca ($r = 0.94$, $p < 0.001$, $n = 12$).

The nutrient loss due to topsoil removal generally increased linearly with soil depth (Table 2). However, in the case of exchangeable Ca, the loss rate was higher for shallower layers (0–1.0 cm and 0–2.5 cm depths) than for deeper layers (0–5.0 cm and 0–10 cm depths) due to the higher concentration in the shallower layer. Conversely, for exchangeable Al, the loss rate was higher for deeper layers as the concentration was lower in the surface layer.

Table 1
Soil chemical properties of the 0–20 cm layer.

Depth (cm)	pH	Electric conductivity (mS m^{-1})	Total N (%)	Total C	C:N ratio	Available P[a] (mg kg^{-1})	Exchangeable Ca (cmol$_c$ kg^{-1})	Exchangeable Mg	Exchangeable Na	Exchangeable Al	Cation exchange capacity
0–1.0	5.86	2.04	0.03	0.28	9.66	8.5	0.33	0.23	0.15	0.03	0.42
1.0–2.0	5.75	1.93	0.03	0.31	9.87	8.5	0.38	0.26	0.16	0.08	0.94
2.0–3.0	5.55	1.59	0.03	0.27	10.1	8.5	0.23	0.18	0.15	0.20	0.85
3.0–4.0	5.40	1.51	0.03	0.26	10.0	8.8	0.25	0.30	0.23	0.28	0.88
4.0–5.0	5.42	1.49	0.02	0.22	9.74	8.8	0.17	0.24	0.21	0.33	0.87
5.0–7.0	5.26	1.47	0.02	0.22	9.91	8.8	0.13	0.31	0.28	0.37	0.86
7.0–9.0	5.18	1.76	0.02	0.22	10.3	8.8	0.11	0.19	0.17	0.41	0.86
9.0–11.0	5.31	1.54	0.02	0.19	10.1	8.8	0.08	0.15	0.14	0.48	1.00
11.0–13.0	5.18	1.25	0.02	0.18	10.5	8.8	0.06	0.15	0.14	0.45	0.82
13.0–15.0	5.18	1.17	0.02	0.17	10.2	8.8	0.08	0.20	0.18	0.51	0.96
15.0–17.5	5.12	1.19	0.02	0.16	10.9	8.8	0.07	0.19	0.17	0.54	0.89
17.5–20.0	5.10	1.10	0.02	0.17	11.1	8.8	0.06	0.24	0.22	0.57	1.00

[a] The values of available P content (Bray I method) were referred from Table 2 in the supplemental materials.

Table 2
Nutrient loss by topsoil removal.

Depth (cm)	Total N (g m^{-2})	Total C (g m^{-2})	Available P (g m^{-2})	Exchangeable Ca (g m^{-2})	Exchangeable Mg (g m^{-2})	Exchangeable Na (g m^{-2})	Exchangeable Al (g m^{-2})
0–1.0	4.57	44.13	0.13	1.05	0.44	0.54	0.12
0–2.5	11.58	113.79	0.20	2.59	1.11	1.39	0.88
0–5.0	21.78	214.89	0.36	4.33	2.36	3.33	3.97
0–10.0	39.06	389.69	0.72	6.19	4.65	7.20	13.07

3.2. Grain yield

Grain yield was significantly affected by topsoil removal depth, fertilizer application, and experimental year ($p < 0.01$). Due to the high rainfall amount in the second year, the grain yield was significantly higher in the second year than the first and third years (Fig. 2). The average grain yield of the first and third years with normal rainfall decreased significantly in the plots with 2.5-cm or more topsoil removal under unfertilized conditions compared with the control (Fig. 2). The topsoil removal of 2.5, 5, and 10 cm depths under unfertilized conditions resulted in 92 %, 97 %, and 99 % grain yield reductions, respectively. However, this reduction was clear ($p = 0.080$) only in the plot

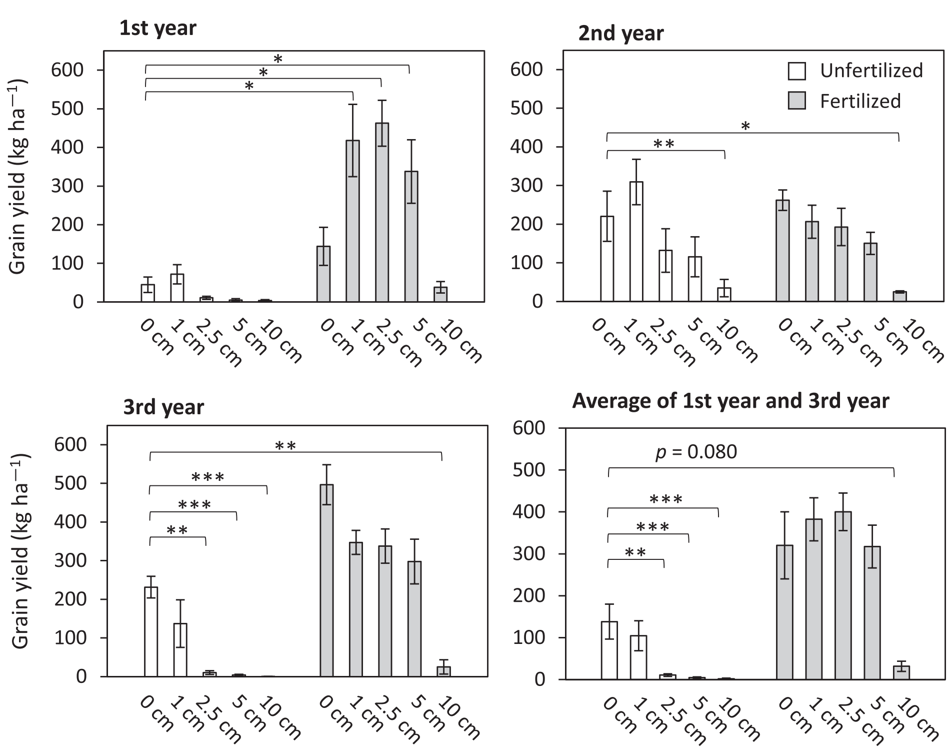

Fig. 2. Effects of different depths of topsoil removal and fertilizer treatments on pearl millet grain yield in the three years. Asterisks indicate significant differences from the plot of 0-cm topsoil removal under unfertilized conditions using the Dunnett's test after logarithmic transformation for normality. Error bars represent the standard error of the replications. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

with 10-cm topsoil removal under fertilized conditions, exhibiting an 77 % reduction compared with the control. The topsoil removal of 1 cm did not result in a significant decrease in the average grain yield in normal rainfall years compared with the control under either unfertilized or fertilized conditions. In the first year, the grain yield reduction compared with the control was not significant in any plots with topsoil removal under unfertilized conditions, while it became significant in the unfertilized plots with 10-cm removal in the second year and 2.5-cm or more removal in the third year. In the second year, fertilizer treatment did not significantly affect grain yield. In the third year, the effect of fertilizer treatment on increasing grain yield was significant in the plots with 2.5-cm or more topsoil removal.

3.3. Yield components and growth stage of pearl millet

The days to heading of pearl millet were significantly shortened by 8.8–13.3 days in the fertilized plots with different topsoil removal depths, except for 10 cm (Fig. 3a). Although not significant, the survival rate tended to decrease with the topsoil removal depth increasing under unfertilized conditions (Fig. 3b). Conversely, the survival rate in the plots with topsoil removal under fertilized conditions was comparable to or even higher than that in the control. Although fertilizer application significantly recovered the decrease in stem number per hill in the plots with 5- and 10-cm removal, panicle number per stem in the plot with 10-cm removal, and grain weight per panicle in the plots with 2.5- and 5-cm removal (Fig. 3c–e), it failed to restore the decrease in grain weight per panicle in the plot with 10-cm topsoil removal (Fig. 3e).

3.4. Weed biomass

The effects of topsoil removal depth ($p < 0.001$), fertilizer application ($p < 0.05$), and experimental year ($p < 0.001$) on weed biomass were significant. The weed biomass was significantly reduced in the plots with 2.5-cm or more topsoil removal regardless of fertilizer treatment throughout the three years (Fig. 4). Under unfertilized conditions, the total weed biomass in the three years was reduced by 86 %, 93 %, and 98 % in the plots with 2.5-, 5-, and 10-cm topsoil removal, respectively.

3.5. Soil moisture content

The VWC of the surface layer (0–10-cm depth) largely fluctuated during the cropping period of the first year following the cycles of rainfall events and dry spells in all the treatment plots (Fig. 5). The VWC

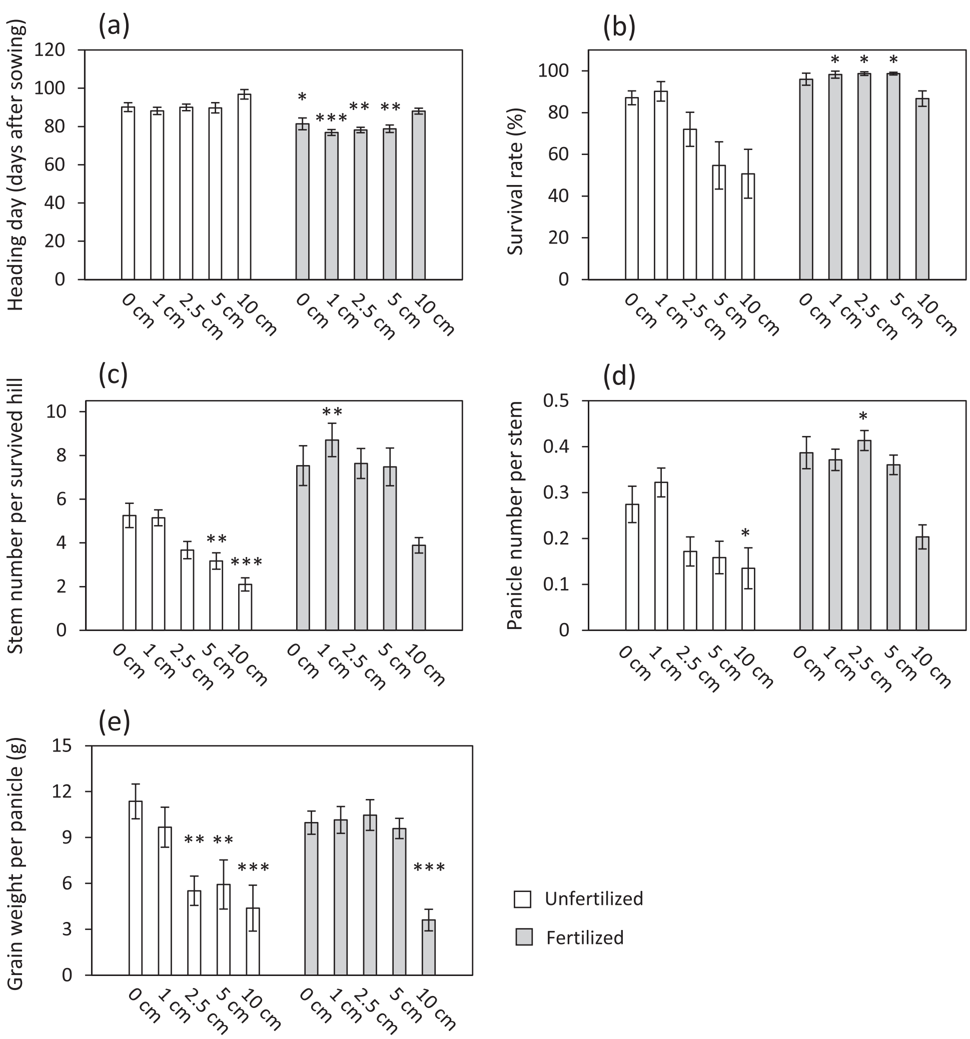

Fig. 3. Effects of different depths of topsoil removal and fertilizer treatments on heading day (a), survival rate (b), stem number per survived hill (c), panicle number per stem (d), and grain weight per panicle (e) of pearl millet over a three-year period. Asterisks indicate significant differences from the plot of 0-cm topsoil removal under unfertilized conditions. The Dunnett's test was conducted for the original data of heading day, panicle number per stem, and grain weight per panicle and for the logarithmic transformed data of stem number per survived hill. The Steel's test was conducted for the original data of survival rate. Error bars represent the standard error of the replications. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

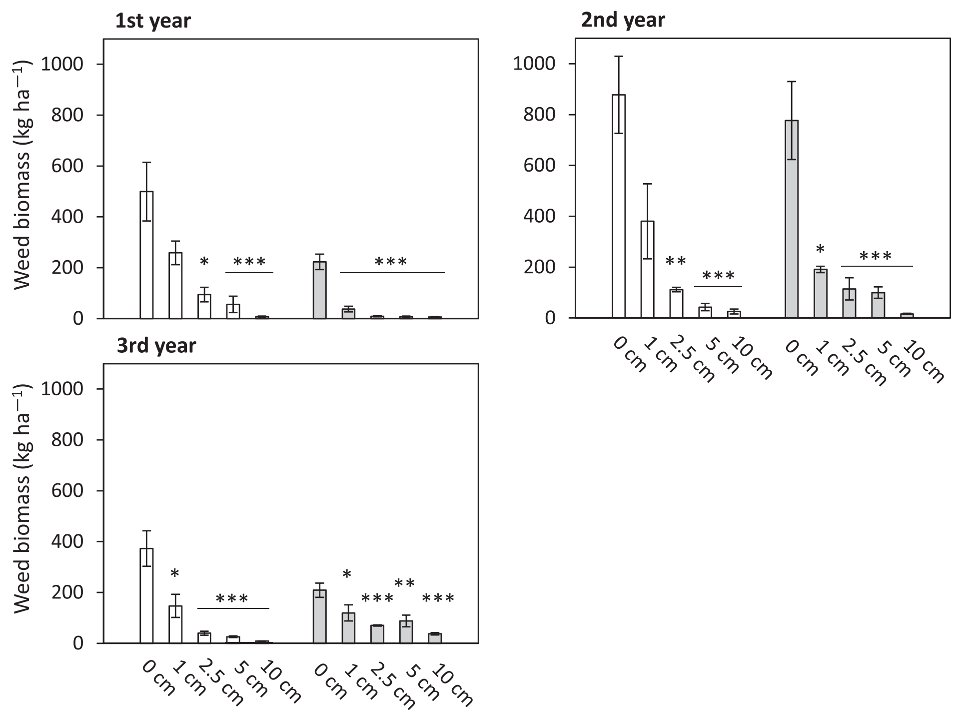

Fig. 4. Effects of different depths of topsoil removal and fertilizer treatments on weed biomass in the three years. Asterisks indicate significant differences from the plot of 0-cm topsoil removal under unfertilized conditions using the Dunnett's test after logarithmic transformation for normality. Error bars represent the standard error of the replications. *** $p < 0.001$, ** $p < 0.01$, and *** $p < 0.001$.

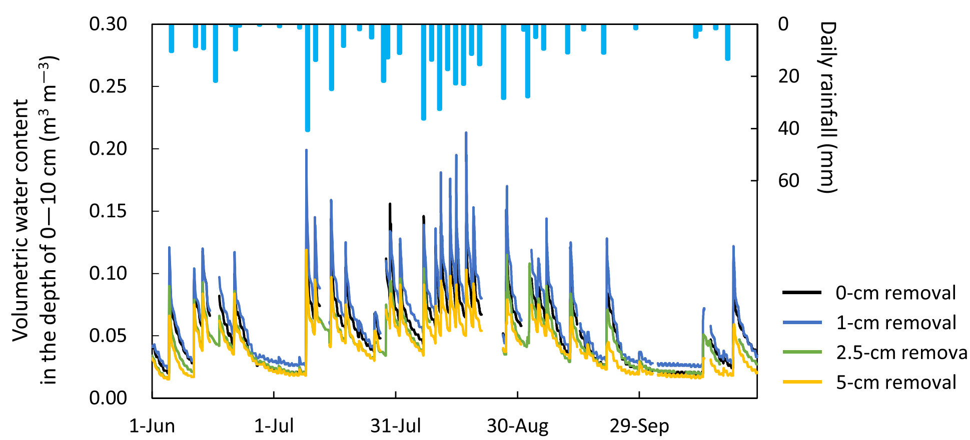

Fig. 5. Hourly fluctuations in volumetric water content of the 0–10-cm layers in the plots with different depths of topsoil removal and daily rainfall during a cropping season (June–October) of the first year of the experiment (2009).

of the surface layer in the plots with 0- and 1-cm removal more responded to rainfall events with higher peaks of VWC than the plots with 2.5- and 5-cm removal. The average VWC of the surface layer during the cropping period of the first year was 0.05, 0.06, 0.04, and 0.04 $m^3 m^{-3}$ in the plots with 0-, 1-, 2.5-, and 5-cm removal, respectively.

The amount of soil water at the lower tension than the permanent wilting point (1500 kPa)—the amount of water available for pearl millet—within the depth of 0–100 cm was generally low in the early (June) and the late (October) of the cropping season in all the plots in the first year. It increased in the middle of the cropping season and showed its peak around mid-August, corresponding to the rainfall pattern (Fig. 6). The amount of soil water available for pearl millet within a depth of 0–100 cm was generally highest in the plot of 1-cm removal, followed by 0-, 2.5-, and 5-cm removal. The average during the cropping period of the first year was 12.1, 20.0, 6.8, and 4.4 mm in the plots with 0-, 1-, 2.5-, and 5-cm removal, respectively.

4. Discussion

The topsoil removal of 2.5-cm or more depth resulted in a significantly decreased pearl millet grain yield in the Sahel. Ikazaki (2015) highlighted the role of the thin Ap horizon (about 3 cm, called the loose sand layer) of the original soil in conserving crop productivity in the Sahel region. Soil water availability markedly decreased after removing 2.5-cm or more depth of topsoil, corroborating the finding of Bakker et al. (2004) that plant-available water typically decreases with increasing removal depth. Conversely, the pearl millet grain yield remained unaffected following topsoil removal at a 1-cm depth, despite nutrient loss. This is likely attributed to the relatively low weed biomass and resulting favorable soil moisture conditions in both the surface layer and soil profile in the plot with 1-cm topsoil removal. Additionally, as the root density of pearl millet is mostly concentrated in the 0–15-cm depth (Faye et al., 2019), it suggests that the effect of minimal nutrient

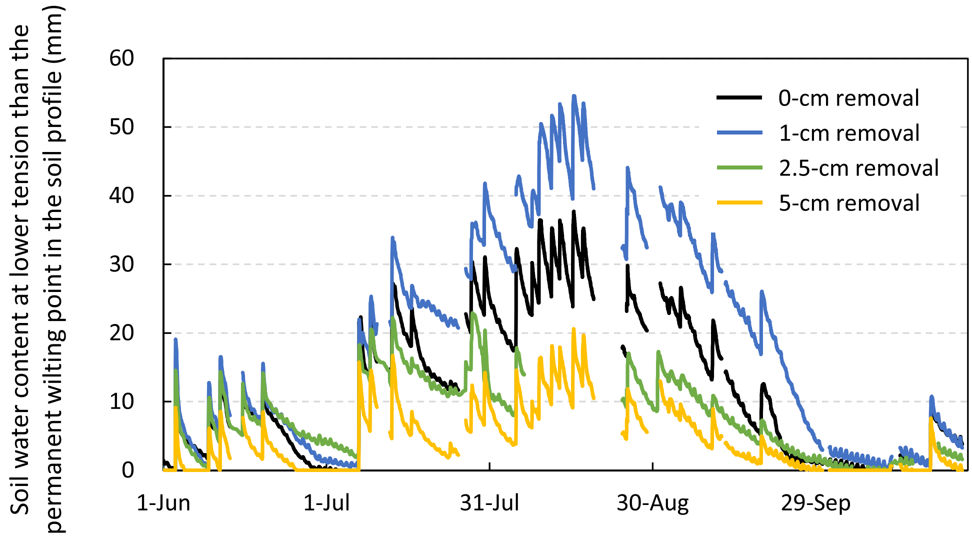

Fig. 6. Hourly fluctuations in soil water content at lower tension than the permanent wilting point in the soil profile (0–100 cm depth) in the plots with different depths of topsoil removal during a cropping season (June–October) of the first year of the experiment (2009).

loss resulting from 1-cm topsoil removal was counteracted by the positive effects mentioned earlier for pearl millet. The estimated yield reduction per depth was 37 % cm^{-1} for the plot of 2.5-cm removal under no fertilization in the normal rainfall years, which exceeded the previously reported values of 20 % cm^{-1} for Ultisols and 10 % cm^{-1} for Alfisols cultivated with various crops in humid to semi-arid conditions in SSA (Lal, 1995). Zhang et al. (2021) also reported that crop yields decreased with decreasing the remaining depth of the A horizon, although they mostly reviewed studies with more than a 5-cm depth of remaining A horizon (69 % of total samples). Therefore, the Ap horizon depletion markedly decreased pearl millet yield in the Sahel region. Given the high soil erosion rate in this region, ranging from 4 to 5 mm $year^{-1}$ (Bielders et al., 2000; Ikazaki et al., 2011b), the yield reduction will become severe within 5–6 years (2.5-cm topsoil removal) under unfertilized conditions. Considering the current situation in the Sahel region, where the widespread adoption of soil conservation measures is insufficient and the use of chemical fertilizers is limited (Nord et al., 2022), our data suggests that the decline in crop yields due to soil erosion is an urgent challenge in this area.

Fertilizer application resulted in the recovery of the grain yield loss of pearl millet caused by topsoil removal at 2.5- and 5.0-cm depths in the normal rainfall years. The positive effect of fertilizer application on pearl millet growth resulted from the high survival rate of plants and, to a lesser extent, the high numbers of stem per hill and panicle per stem, and grain weight per panicle. Fertilizer application also resulted in a remarkable shortening of the days to heading by 8.8–13.3 days. Mahalakshmi and Bidinger (1985) reported that a decreased pearl millet grain yield resulted from the coincidence of severe water stress with flowering and early grain filling. Thus, the shortened growing period by fertilizer application may contribute to drought escape, as the flowering stage of pearl millet coincides with late-September when rainfall and plant-available soil water content are low in this region. Our results corroborate those of Lal (1995) which showed that fertilizer input at the recommended rate mitigated the yield loss compared with low fertilizer input or no external input in SSA. The observation that the reduction in soil available water in the plots at 2.5- and 5.0-cm depths did not affect the recovery of pearl millet grain yield under fertilizer application suggests that nutrient deficiency had a greater effect on grain yield reduction in these plots than water availability. However, in the 10-cm topsoil removal plots, fertilizer application failed to restore grain yield effectively to the level observed in noneroded plots, probably resulting from the depletion of micronutrient (Awio et al., 2021) and available water (Bakker et al., 2004; Frye et al., 1982). The pH level, even at the plot with 10-cm removal, was not likely a factor of nonresponse to fertilizer application because pearl millet is tolerant to Al toxicity and low pH (Ahlrichs et al., 1991; Kretzschmar et al., 1991). Michels and Bielders (2005) highlighted the significance of organic matter and lime application, such as manure and calcium carbonate, to increase pH and P availability on an erosion-affected soil in the Sahel. Larney et al. (2000) also suggested that removing moisture stress as a yield- and fertilizer response-limiting factor through irrigation did not offset topsoil loss, even with adequate N and P fertilization. Therefore, in severely eroded fields, conventional fertilizer management may be insufficient for crop yield recovery and should be combined with organic fertilizers to improve soil physical properties and replenish essential nutrients (Larney et al., 2000). Given the high soil erosion rate in the Sahel, the fields may become less sensitive to fertilizer application within 20–25 years (10-cm topsoil removal) without any countermeasure against soil erosion. Zhang et al. (2021) proposed that increasing production inputs to compensate for nutrient losses arising from erosion may be reasonable for increasing crop yield but does not support the sustainability of agricultural practices. Land management should be implemented to control soil erosion and simultaneously improve soil fertility and crop yields, such as the Fallow Band System developed in the Sahel (Ikazaki et al., 2024, 2011a) and other techniques using organic materials (Bielders et al., 2000; Nord et al., 2022).

Fertilizer application had no significant effect on pearl millet grain yield or weed biomass in the second year. This could be attributed to the heavy rainfall events concentrated soon after fertilizer application in the second year, which probably caused nutrient losses by runoff and leaching and resulted in low nutrient recovery by pearl millet. Although broadcasting is a labor-saving practice, it increases the opportunity for direct detachment and/or dissolution of nutrients in runoff compared with fertilizer incorporation (Withers et al., 2000). The leaching of nitrate and phosphate ions and subsequent low nutrient use efficiency have also been reported in sandy soils in other regions in SSA (Nyamangara et al., 2003; Sugihara et al., 2012). Therefore, besides the impact of erosion-induced soil loss, the loss of applied fertilizer is another concern; increasing nutrient use efficiency is a great challenge for small-holder farmers in SSA, where most of them cannot afford chemical fertilizers (Tsujimoto et al., 2019). Fertilizer microdosing would be a potential technique to improve fertilizer use efficiency in the Sahel. Ibrahim et al. (2016) reported comparable pearl millet grain yield by fertilizer microdosing treatment to that with broadcasting in Niger, while the fertilizer application rate was substantially reduced by 88 %, 69 %, and 100 % for N, P, and K, respectively. The high nutrient use efficiency resulted from the enhanced lateral root growth of peal millet by fertilizer microdosing (Ibrahim et al., 2015, 2016). Split application of fertilizers has also been suggested to increase nutrient utilization efficiency and grain yield in the Sahel (Fatondji and Ibrahim, 2018; Ibrahim and Fatondji, 2020).

The grain yield reduction observed in the plots with 2.5-cm and 5-cm topsoil removal became significant after consecutive cultivation under unfertilized conditions. The decrease in grain yield over the years probably resulted from the depletion of soil organic matter and available nutrients and the increasing competition with weeds. The time lag between soil loss and the consequences of reduced crop production may lead to an underestimated impact of initial soil erosion. However, prompt actions are needed to prevent soil erosion before yield reduction becomes evident. Importantly, deeper topsoil removal results in higher recovery costs for crop production (Pimentel et al., 1995). To avoid further erosion-induced reduction of crop productivity, farmers need to realize this induced topsoil loss at the initial stage, particularly Ap horizon depletion, and apply countermeasures to reduce soil erosion and conserve soil fertility in the Sahel.

The markedly reduced weed biomass observed in the topsoil removal of 2.5 cm or more under unfertilized conditions could result from the disappearance of the seed bank of weeds by topsoil removal. Zhang et al. (2001) reported that 75.8 % of total seeds within the layer of 0–10 cm depth was present in the top 2 cm in a field after five-year abandonment. As a result, the pearl millet grain yield in the plots with 2.5-cm to 5-cm removal were likely overrated, particularly under fertilized conditions, due to less competition between pearl millet and weeds. The competition between main crops and weeds is a primary factor contributing to crop yield reduction in many croplands across SSA, largely due to the limited use of herbicides among local farmers (Rodenburg et al., 2019). However, previous topsoil removal experiments overlooked the difference in weed biomass at different removal depths (Bakker et al., 2004; Zhang et al., 2021). A significant reduction in weed biomass can positively influence crop yield in experiments involving deeper topsoil removal, as it helps alleviate competition between crops and weeds. A caution is needed when the utilization efficiencies of water and nutrients are discussed in the topsoil removal experiments (Lal, 2015).

5. Conclusion

Our results demonstrated that topsoil removal of 2.5 cm or more significantly decreased pearl millet grain yield by over 92 % in an Arenosol in the Sahel under normal rainfall condition. This decline per removal depth was more pronounced compared to previous reports from other regions in SSA. However, the grain yield remained unaffected in the topsoil removal of 1-cm. These results emphasize that the loss of a thin Ap horizon markedly contributes to reduce plant-available water and nutrient contents in soils, resulting in a decline in pearl millet yield in the Sahel. The recommended fertilizer management compensated for the grain yield loss in the plots of less than 5-cm topsoil removal but not effectively in the 10-cm removal plot. Overall, the loss of Ap horizon can degrade soil fertility, threaten pearl millet production stability, and increase grain yield recovery costs in the region. Sahelian farmers should recognize topsoil loss in the early stages of soil erosion and implement appropriate countermeasures within their labor and economic capabilities to prevent a decline in crop yield caused by the loss of the Ap horizon.

CRediT authorship contribution statement

Shinya Funakawa: Writing – review & editing, Supervision. **Dougbedji Fatondji:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Kenta Ikazaki:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tomohiro Nishigaki:** Writing – original draft, Visualization, Validation, Software, Formal analysis. **Ueru Tanaka:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Hitoshi Shinjo:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

Acknowledgments

This study was performed under the JIRCAS-ICRISAT collaborative project, “Improvement of Fertility of Sandy Soils in the Semi-Arid Zone of West Africa through Organic Matter Management.” Portions of this study were financially supported by the JSPS KAKENHI Grant Number JP20405005 and JP22405020. We thank Mr. Moussa Alkaldi, the late Mr. Tahirou Saley, Mr. Hamidou Boubacar, and Mr. Ibrahim Hassan for their invaluable help during the field trial.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2024.106324.

Data availability

Data will be made available on request.

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