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Effects of Shallow Tillage versus Fallow on Soil Physical Fertility in the Semi-Arid Context of Burkina Faso

Daouda Guébré[1*], Harouna Ouédraogo[2], Aminata Ganeme[2], Adama Ilboudo[2], Zédara Isaïs Boussim[3], Koulibi Fidèle Zongo[4], Salifou Traoré[2], Edmond Hien[2,5]

[1]Centre Universitaire de Ziniaré, Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso
[2]Unité de Formation et de Recherche en Sciences de la Vie et de la Terre, Université Joseph Ki-Zerbo, Ouagadougou, Burkina Faso
[3]Direction Régionale de l'Agriculture, de l'Élevage et des Ressources Halieutiques du Centre-Sud, Manga, Burkina Faso
[4]Centre Universitaire de Tenkodogo, Université Thomas Sankara, Ouagadougou, Burkina Faso
[5]Institut de Recherche pour le Développement (IRD), Ouagadougou, Burkina Faso
Email: *daoudaguebre12@gmail.com

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Abstract

In sub-Saharan Africa, soil fertility is declining due to inappropriate agricultural practices, which means that greater efforts are needed to increase crop production. Conservation strategies like fallowing are crucial for this, but population pressure and decreasing land are reducing fallow periods, hurting soil regeneration. This study examines the benefits of two agroecological management systems on soil physical fertility in a semi-arid context. The aim was to compare, on the one hand, plots that had been shallowly tilled and sown with sorghum with, on the other hand, fallow plots left to remain uncultivated. The experiment was conducted in the Sudano-Sahelian zone of Burkina Faso. The experimental design consisted of completely randomised blocks with a single factor, which is the soil management system representing the treatments. Each block contained two plots: one that was shallowly tilled (to a depth of 5 cm), and one that was left fallow for the same period (2013-2023). The results revealed contrasting soil organic matter dynamics between the different treatments and the two target years (2022 and 2023). The results show that Fallow led to a 25% increase in soil organic matter in 2022, compared to a 5% increase resulting from shallow tillage in 2023. Silt content also varied between +4 and −7%, respectively. In contrast, shallow tillage led to a decrease in soil moisture between 2022 and 2023 (−2% and −8%), a slight increase in infiltration (−3.89 and +0.33 mm s^{-1}) and bulk density (+0.20 and +0.23 g cm^{-3}), probably due to the effect of repeated tilling of soils. However, the results showed that the effects of shallow tillage on microaggregate formation are gradual, with contrasting benefits for the overall physical soil fertility. Nevertheless, this practice could offer an alternative solution to the problem of a scarcity of fallow land in the Sudano-Sahelian farming systems.

Keywords

Sahelian Agrosystems, Soil Organic Carbon, Fallow, Shallow Tillage, Soil Physical Parameters, Burkina Faso

1. Introduction

Land degradation has been a major concern for environmentalists in recent years [1] [2]. It is regarded as one of the most pressing challenges to be addressed by politicians and scientists [3], as it impacts the productivity of natural ecosystems, whether agricultural, pastoral or forestry. The interplay of climatic conditions and anthropogenic influences has been demonstrated to be a primary cause of soil erosion, resulting in the degradation of soil structure [4]. In the geographical context of the sub-Saharan region, natural soil degradation processes are accelerated by intensive farming practices and inappropriate agricultural practices (including deforestation, overexploitation, and low-input use) that are employed to support sustainable production [5]. It is estimated that more than one-third of soils are affected by soil degradation [6]. In this region, the most prevalent forms of degradation are erosion and loss of physical and organic soil fertility. Indeed, the scarcity of water resources, caused by decreases in inter-annual rainfall averages, is a significant contributing factor to this degradation and to lower crop yields. This situation is primarily attributed to agricultural activities and inadequate soil management [7] [8]. However, as demonstrated by Zongo [9] and Ilboudo [10], dynamic soil properties can change in response to appropriate land use and management.

It has been shown that improved agricultural practices contribute to soil conservation and slow down soil degradation [11]. Soil conservation is defined as a set of techniques generally defined as "all activities carried out locally, on degraded land or land subject to erosion, that maintain or increase the soil's productive capacity". These techniques include the prevention or reduction of soil erosion, compaction and salinity, and the maintenance or improvement of soil fertility [12]. In sub-Saharan agrosystems, a number of local conservation strategies have been developed along these lines. These include crop-fallow rotation and shallow tillage [13] [14].

Cyclic crop-fallow systems are widespread in the tropics due to their multiple advantages, in particular that of restoring certain soil fertility components after temporary cropping [15]. Indeed, fallow has been defined as the resting of arable land for a period determined by local conditions [16]. It represents an important component of the agricultural technical itinerary, given local farmers' limited access to mineral fertilizers [17]. Furthermore, Chotte [18] has confirmed the role of long-term fallow (>5 years) in regenerating numerous components of physical soil fertility. Indeed, the elimination of tillage helps to reaggregate soils, restoring their stability and capacity for infiltration and aeration [19] [20]. Research has shown that very large aggregates (those over 2 mm) grow in size, especially during times of extended fallow periods. Nevertheless, in view of the environmental situation, it has been shown that the traditional practices in this area have reached their maximum capacity very quickly [21]. Indeed, the practice of fallowing is increasingly compromised by the high demand for arable land following strong demographic pressure, which no longer allows for long-duration fallows. Furthermore, studies by Luo [22] and Powlson [23] have reported limited benefits of no-till systems on carbon storage, and consequently on the aggregation process in the soil. Thus, it is evident that further investigation is required in order to achieve a more profound comprehension of the long-term repercussions that tillage systems and crop rotations exert on soil carbon (C) and nitrogen (N) dynamics [24].

On the other hand, the practice of shallow tillage, which is intended to loosen the soil and/or destroy weeds, remains a pivotal factor in achieving optimal agricultural productivity. Several studies have already shown the benefits of shallow tillage on soil fertility [25]-[27]. Evidently, the consequences of shallow tillage manifest in the characteristics of soil, including its structure, moisture regime, granulometry, and susceptibility to erosion. However, it appears that shallow tillage has multiple and complex impacts on soil physical properties. Consequently, several studies have concluded that tillage is not an absolute necessity, and that its effectiveness is questionable [26] [28] [29]. Further research is therefore required to improve our understanding of the long-term effects that tillage systems and crop-fallow rotations have on key soil parameters.

Nevertheless, there is a paucity of comparative studies on the responses of soil physical quality to fallow and shallow tillage practices in the semi-arid context of our agrosystems. Few studies have previously been observed with regard to the effects of the addition of compost with reduced tillage on soil porosity [30] or on the effects of minimum tillage (scarification) in rotation with a legume (Mucuna) on cotton yields [31]. It is therefore imperative to develop a comprehensive understanding of the variability in responses to soil hydro-structural stabilisation practices, particularly in the context of limited organic resources inherent to our agrosystems. This understanding is crucial, especially in the context of long-term fallow and shallow tillage without external inputs. In this respect, Guebre [32] argued for the necessity of further studies to understand the aggregate dynamics and soil quality induced in Sahelian agrosystems involving tillage.

This study examined the extent to which shallow tillage of plots cultivated with sorghum improves the physical soil fertility compared with fallowing uncultivated plots. More specifically, we aimed to compare the effects of these two practices on soil organic matter (SOM) dynamics and soil physical properties, such as temperature and moisture, particle size distribution, aggregate fractions, infiltration, and bulk density. The hypothesis was that the loss of organic matter and degradation of key soil physical parameters due to the fallow deficit could be mitigated by successive shallow tillage of the soils.

2. Material and Methods

2.1. Study Site

The study was conducted at the Gampèla experimental site (lat: 12.4167 N and long: 1.3479 W) located in the Sudano-Sahelian zone of Burkina Faso in the West African region. The climate is tropical, hot and dry, with annual rainfall ranging from 700 to 800 mm [33]. Average annual temperatures range from 22˚C in the coldest period to 38˚C in the hottest. The soils belong to the Endogleyic Acrisol group according to the World Reference Base classification [34]. The texture is sandy-loamy in the surface horizon (10 cm) and clayey in the lower horizons. These soils are low in organic matter (less than 1% carbon) with an average CEC ranging from 7 to 12 cmol kg^{-1}. The average contents of the major chemical elements are low and shown as follows: total nitrogen (0.05 g kg^{-1}), available phosphorus (1.3 ppm) and total potassium (1257 ppm).

2.2. Experimental Design and Trial Conduct

The experimental design consists of completely randomised blocks with a single factor, which is the soil management system representing the treatments. Each treatment is repeated four times across four blocks. The design was implemented within an experimental site covering a total of 2 ha. This design formed part of a long-term trial and included several other treatments (nine in total) on methods for restoring degraded soils. However, for the purposes of this study, the focus was on two treatments from the overall design. The first treatment involved plots subjected to shallow tillage and cultivated with sorghum (*Sorghum bicolor* (L.) Moench var. kapelga). The second concerned plots left fallow and uncultivated during the same period (2013-2023). This choice was made to understand how the physical fertility of the soil responds to successive shallow tillage, with a view to finding alternatives to the scarcity of fallow land in this area.

For plots subjected to shallow tillage, the number of tillings per season depended on the plant cover. The plots were not fertilised and were tilled manually to a shallow depth (5 cm) from 2013 to 2023. The aim of this operation was to bury weeds and their seeds in order to limit their unwanted emergence. Two sorghum plants were strategically retained within each plot, resulting in a planting density of approximately 33,600 plants per hectare. Each sub-plot measured 5 m × 5 m (25 m^2). The blocks were spaced an average of 2 m apart, and the sub-plots 1 m apart.

2.3. Preparation and Collection of Samples

Five elementary soil samples (at a depth of 0 - 10 cm) were taken in the target years of 2022 and 2023 (*i.e.*, the ninth and tenth years of the experiment). Samples were taken in staggered rows on each undisturbed plot (or square in fallow land) before sowing (for cultivated plots), using an auger with a diameter of 3 cm. A total of 40 soil samples (5 samples × 8 plots) were taken from all the plots covered by the study. Composite samples were then prepared for each plot or square concerned by mixing the individual samples, resulting in 8 composite soil samples (1 composite sample per plot × 8 plots). These composite samples were then air-dried and sieved to 2 mm for laboratory parameter evaluation.

2.4. Field and Laboratory Parameters Measured

All plots (0 - 10 cm) were measured for the same parameters in the field and laboratory over the two target years (2022 and 2023). Average values were calculated for each parameter and each treatment. Thus, for each plot under consideration, an average value for each measured parameter was calculated and used as the average value per sub-plot for the statistical analyses. Topsoil temperature (˚C) and volumetric humidity (%) were measured in the field using a probe moisture meter (IMKO Model HD2, Germany). Three repetitive measurements were taken diagonally across each plot over a period of one month at three-day intervals. Soil permeability was assessed during dry periods on all plots using the BEST method (Beerkan Estimation of Soil Transfer Parameters) [35]. Soil bulk density was determined using the cylinder method (as the soil was non-gravelly), in accordance with the AFNOR [36]. Soil texture (three-fraction granulometry) was determined using the hydrometric method in a dispersing solution containing 40 g of sodium hexametaphosphate and 10 g of sodium carbonate. Aggregate size separation was performed using the wet sieving method adapted from Elliott [37]. Manual sieving using a series of two sieves (mesh 250 and 63 μm) produced three aggregate classes: i) >250 μm (macro-aggregates); ii) 63 - 250 μm (micro-aggregates); and iii) <63 μm (silts and clays). The Walkey and Black method, modified by Graham [38], was used to assess soil organic matter.

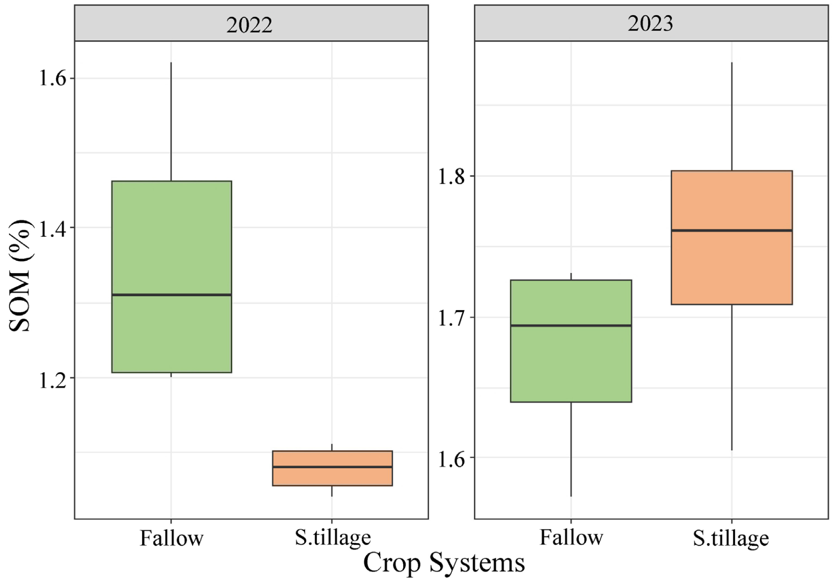
2.5. Statistical Analysis

The mean and standard deviation were calculated for each management system (shallow tillage and fallow). The composite plot samples from the four blocks consisting of the replicates (n = 4) and the mean values of the repeated field measurements were all taken into account simultaneously in the statistical models. The hypotheses of equality of means between treatments were tested using generalised linear models (GLM). Subsequently, tests to compare the means were carried out using Tukey's contrasts with a significance level of 5% [39]. The relationships between the measured parameters were assessed through principal component analyses. Spearman's correlation coefficient was used as an auxiliary metric to evaluate the efficacy of these relationships. All statistical analyses were performed using R (4.4.2) statistical software.

3. Results

3.1. Effects of Fallow and Shallow Tillage on Soil Organic Matter

The impact of the two cropping systems on soil organic matter levels over the two measurement periods is illustrated in Figure 1. Compared to shallow tillage, fallowing significantly increased soil organic matter content in 2022 (F = 7.689; p = 0.032), but not in 2023. The results revealed contrasting soil organic carbon dynamics under the two practices. A pair-wise comparison shows that fallow practice resulted in a 25% increase in SOM in 2022, whereas shallow tillage led to a 5% increase in 2023. However, the latter increase was not significant (F = 1.373; p = 0.286).



S. tillage: Shallow tillage.

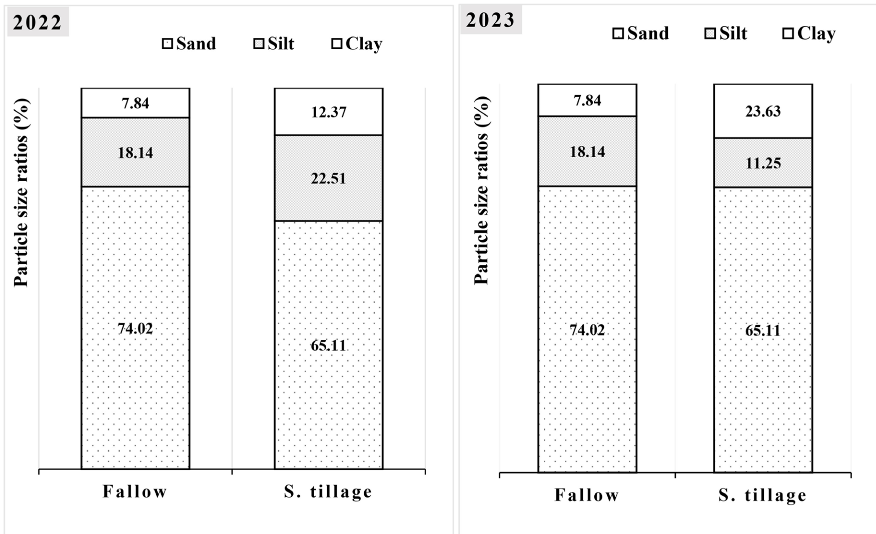
Figure 1. Variation in soil organic matter (SOM) according to cropping systems and two years.

3.2. Effects of Fallow and Shallow Tillage on Soil Texture

In 2022, the ninth consecutive year of fallow and shallow tillage, we observed an average decrease of 8% in the proportion of sand plots with shallow tillage (Figure 2). This result is consistent with those observed in the subsequent year (2023). However, the dynamics of silt proportions exhibited notable variations between 2022 and 2023. Compared to fallow, the proportion of silt in plots with shallow tillage increased by 4% in 2022, but fell to −7% in 2023. However, clay proportions exhibited an increase that was similar in both years (+4% on average on tilled plots). Statistical analysis revealed a significant difference between fallow and shallow tillage for sand (F = 27.41; p = 0.001), silt (F = 9.029; p = 0.023) and clay (F = 29.93; p = 0.001) proportions in 2022. Furthermore, a similar trend was observed in 2023 for sand (F = 27.41; p = 0.001), silt (F = 66.73; p = 0.000), and clay (F = 58.22; p = 0.000).

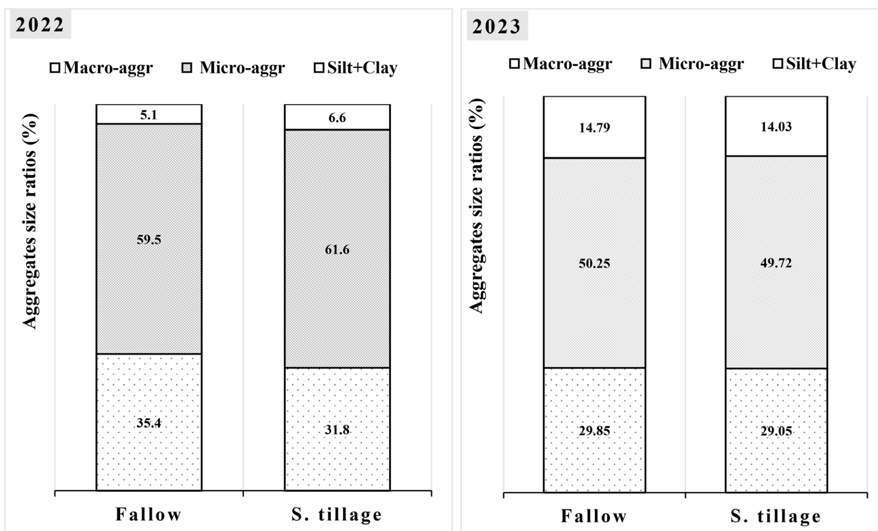
3.3. Effects of Fallow and Shallow Tillage on Soil Aggregate Distribution

In comparison with fallow land, shallow tillage resulted in a significant decrease in soil macro-aggregate proportions in 2022 (Figure 3). The decline was determined to be −3.6% (F= 58.85; p = 0.000). Conversely, the proportion of micro-aggregates increased from 59.5% to 61.6% in the same period. This increase was found to be significant (F= 26.21; p = 0.002). Similarly, the proportion of smaller aggregates (silts + clay) exhibited an increase from 5.1% to 6.6%. A significant difference was revealed by this development (F = 71.07; p = 0.000). In 2023, no significant difference was recorded for all three aggregate types and for the two practices considered (Figure 3). However, a downward trend was recorded on plots with shallow tillage compared with fallow. The respective losses incurred by the macro, micro and small aggregates were −0.8%, −0.5% and −0.7%, respectively.



S. tillage: Shallow tillage.

Figure 2. Variation in the distribution of soil particles according to cropping systems and two years.



S. tillage: Shallow tillage.

Figure 3. Variation in soil aggregate fractions according to cropping systems and two years.

3.4. Effects of Different Cropping Systems on Soil Moisture, Temperature, Bulk Density and Infiltration

Table 1 illustrates the impact of the two systems on key soil porosity indicators. In 2022, the implementation of shallow tillage resulted in a substantial decline in soil moisture and infiltration values, with a decrease of −2% ($F = 13.51$; $p = 0.01$) and −3.9 mm.s^{-1} ($F = 135.8$; $p = 0.000$), respectively. Conversely, bulk density values exhibited a significant increase in tilled plots, with an average increase of 0.2 g.cm^{-3} ($F = 34.82$; $p = 0.001$). However, there was a relatively similar variation in topsoil temperature between fallow and shallow tillage. There was no significant difference in temperature variation between the two systems over two consecutive years. Furthermore, variations similar to those observed in 2022 were noted in 2023. The analysis showed that tilled plots resulted in a significant reduction in soil moisture levels, with a decrease of 8% ($F = 82.98$; $p = 0.000$). However, the observed infiltration rate varied between shallow tillage (1.66 mm/s) and fallow (1.33 mm/s). This increase under shallow tillage was significant ($F = 6$; $p = 0.049$). Similarly, there was a substantial increase in soil bulk density of 0.23 g/cm^3 ($F = 46.98$; $p = 0.000$).

Table 1. Variations in moisture, temperature, bulk density and soil infiltration in cropping systems.

Years (Y)	2022		2023		Effects		
Crop Systems (S)	Fallow	S. tillage	Fallow	S. tillage	Y	S	S x Y
Moisture (%)	15.88 ± 0.88^a	13.92 ± 0.60^b	57.42 ± 0.43^a	48.93 ± 1.81^b	s*	s*	s*
Temperature (˚C)	27.00 ± 0.72^a	27.75 ± 0.73^a	29.71 ± 0.55^a	30.55 ± 1.58^a	s*	ns	ns
Bulk density (g.cm^{-3})	1.39 ± 0.06^b	1.59 ± 0.03^a	1.75 ± 0.12^b	1.98 ± 0.01^a	s*	s*	s*
Infiltration (mm s^{-1})	6.62 ± 1.79^a	2.73 ± 0.15^b	1.33 ± 0.29^a	1.66 ± 0.00^b	s*	s*	s*

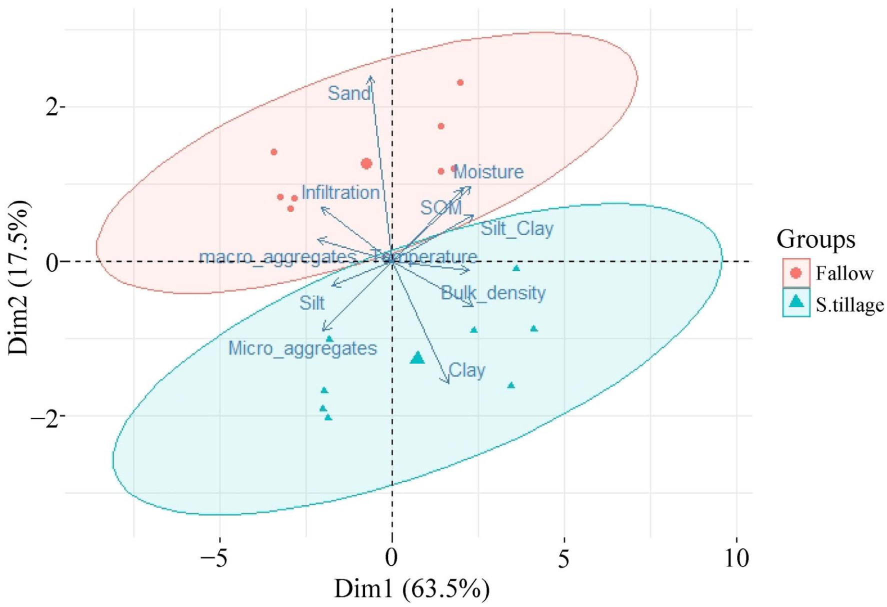
Effects **ns:** no significant ($p > 0.05$), **s*:** significant ($p < 0.05$). Means within a soil variable followed by the same letter are not significantly different ($p > 0.05$).

In addition, all the parameters under consideration were found to be significantly influenced by measurement time (years) and cropping systems, as well as by the effects of their interaction, with the exception of soil temperature ($p > 0.05$). The results show that increasing practice time significantly improved moisture levels ($p = 0.000$), temperature ($p = 0.002$), bulk density ($p = 0.000$) and soil infiltration ($p = 0.000$). The overall effect of cropping systems was also significant ($p = 0.024$; $p = 0.001$; $p = 0.000$, respectively for humidity, bulk density and soil infiltration). Moreover, Significant interactions involving measurement times and cropping systems were found for humidity (AIC = 53.085; $p = 0.000$), density (AIC = −33.891; $p = 0.009$), and soil infiltration (AIC = 93.392; $p = 0.000$).

3.5. Effects of Different Cropping Systems on the Relationships between Physical Properties and Soil Organic Matter

As shown in **Figure 4**, principal component analysis was used to investigate the relationship between physical parameters and soil organic matter over the two-year period in focus. The analysis identified two distinct groups based on the specific cropping system adopted. The fallow group consists of the following variables: sand, infiltration, macro-aggregates, organic matter, moisture, and small aggregates formed by silt and clay. The shallow tillage group consists of temperature, bulk density, clay content and micro-aggregates. The cumulative contributions reached 81% (Dim1 explained 63.5% and Dim2 explained 17.5%).

The results of Spearman's test showed a strong and important link between soil organic matter (SOM) and moisture (r= 0.7) as well as between SOM and small aggregates (silt + clay) (r= 0.9) (**Figure 5**). Interestingly, a negative relationship has been established between SOM and micro-aggregates ($r = -0.8$). A positive and significant relationship was also observed between infiltration and macro-aggregates ($r = 0.8$), as well as between silt and micro-aggregates ($r = 0.5$). Additionally, strong negative relationships were recorded between sand and clay ($r = -0.9$), between bulk density and infiltration ($r = -0.8$), and between bulk density and macro-aggregates ($r = -0.7$).



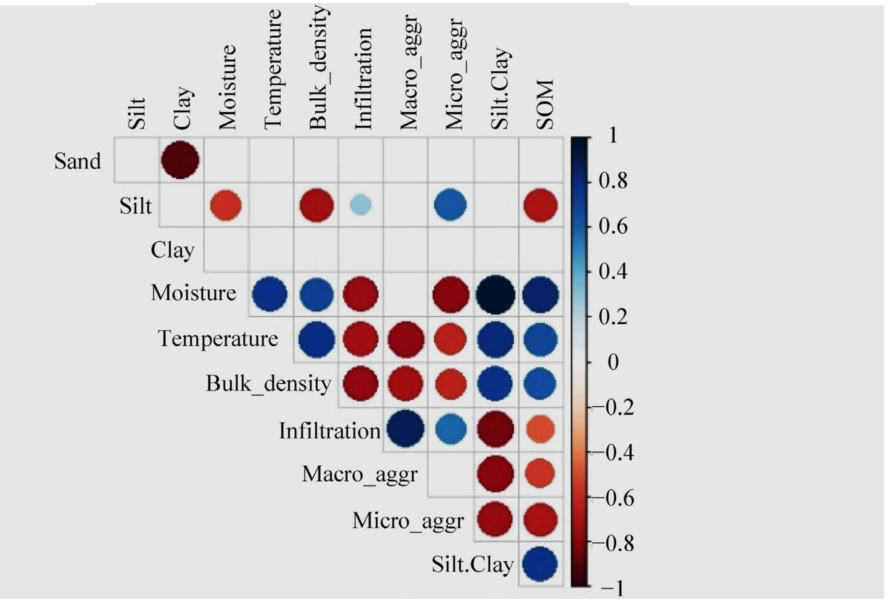
SOM: Soil Organic Matter; Macro_aggr: macro-aggregates; Micro_aggr: micro-aggregates; Silt.Clay: Small-sized aggregates (silt + clay); S_tillage: Shallow tillage.

Figure 4. Principal component analysis (PCA) of soil parameters, categorised by cropping system.

4. Discussion

4.1. Fallow Land Increases the Soil's Organic Matter Content

The presence of high SOM content under fallow as opposed to shallow tillage is



SOM: Soil Organic Matter; Macro_aggr: macro-aggregates; Micro_aggr: micro-aggregates; Silt.Clay: small-sized aggregates (silt + clay); S. tillage: Shallow tillage.

Figure 5. Global Spearman correlations between soil parameters measured on the two cropping systems.

attributable to the effect of plant debris decomposition under fallow. Like soil cover, fallow is well known for its positive effect on soil carbon content in semi-arid environments [26] [40] [41]. In fact, dos Santos Souza, de Paula Rezende [42] estimate that full application of conservation agriculture principles such as fallowing increases soil organic carbon stocks. These results suggest that soil fauna mobilise soil organic matter well under fallow conditions, in contrast to shallow tillage without organic inputs. The significant function of soil fauna in the mobilisation of soil organic matter has been previously examined by numerous studies [43]-[45]. Indeed, the regular tilling of soils can result in the loss of soil structure, thereby facilitating the upwelling and dispersion of small-sized organic fractions. These fractions become more mobile and consequently exposed to the splash effects of heavy rainfall, which is a common occurrence in this region [33] [46]. Consequently, the absence of any restitution, in conjunction with the persistent tillage under plots with shallow tillage, resulted in a decline in soil organic matter levels in 2022, in contrast to soils under fallow. In this respect, Bonzi [26] has shown that organic matter levels decrease by an average of 2% per year in this area following tillage.

However, the relative decline in SOM content in 2023 in fallow plots clearly reflects a contrast in the dynamics of soil organic carbon (SOC) in hot and dry tropical environments. In this regard, Chenu [47] showed that the capacity of soils to accumulate organic carbon over time, the amount of organic carbon that a soil can accumulate and the number of years during which this accumulation can persist are difficult to predict. Indeed, SOM content appears to vary from one year to the next depending on inputs, although there is a downward trend. Additionally, Bonzi [26] estimates that high doses of organic fertiliser (approximately 40 t. ha^{-1} yr^{-1}) would be required to increase soil organic matter content. Furthermore, Berthelin [48] claims that raising soil organic carbon content over two or three decades could necessitate the use of significant quantities of organic residues. Thus, our results highlighted the difficulty of predicting the behaviour of organic carbon in the topsoil horizons of a semi-arid environment. In this order of ideas, many studies have shown that no-till cropping systems have no impact on soil organic carbon (SOC) and are no better than conventional tillage systems [24] [49]-[51]. However, the studies of Li [52] and Liu [53] suggest that the different pathways through which carbon enters the soil are mainly attributable to priming effects. In contrary, Sanou [8] argues that this is related to the sources of inputs and the availability of other nutrients (N and P) in the soil; whereas Masobeng [54] attributes it to the effects of changing agricultural practices, particularly the conversion of grasslands to croplands. Therefore, we hypothesised that, within these agrosystems, soil organic carbon storage is a gradual process that remains linked to cropping practices. Nevertheless, one of the main conclusions of this study is that light tillage has the potential to increase and stabilise soil organic carbon. In this regard, studies conducted in other contexts have shown that a reduction in tillage can lead to a rapid accumulation of carbon during the first four years, even if this additional storage could subsequently be cancelled out [49] [55].

4.2. Shallow Tillage Reduces the Proportion of Sand and Increases That of Clay at the Soil Surface

The results showed a clear inverse relationship between the clay and sand content of tilled and fallow plots. Indeed, repeated tillage of plots would have promoted the destruction of large aggregates, thereby increasing the proportion of fine particles on the soil surface. Furthermore, the shallow depth of the soil could explain the increased presence of clayey horizons that are brought to the surface during tilling. These results confirm those of Garcia-Franco [56] and Ouattara [1], who reported significant increases in clay in the surface layer after reduced tillage. Additionally, tillage actions can lead to soil compaction. This can destroy soil structure, especially true when the same area is repeatedly trampled. Thus, our results show that while light tillage to prepare the seedbed remains necessary, it could be responsible for the loss of soil structural stability in the long term [19] [29]. However, the variations in silt quantities between the two cropping systems and during the two consecutive years demonstrate the instability of the system within this agro-climatic context. Indeed, specific agricultural practices, in conjunction with macrofauna, have the capacity to modify the relative proportion of silt or clay, thereby influencing soil granulometry over time [45]. It has been established that macrofauna have the capacity to induce soil bioerosion through two distinct mechanisms: displacement and ingestion of particulate organic matter [57]. However, there is an absence of evidence to suggest that particle selection occurs during the bioturbation process when macrofauna (termites) utilise only the surface horizon

[45] [57]. In addition, Bottinelli [58] hypothesised that termites, in particular, enhance the clay content of their structures by utilising deep soils, particularly when the structures are designed to be durable and stable over an extended period.

In view of the results obtained, we suggested that changes in soil texture may also be due to the displacement of soil particles on the surface, depending on the characteristics of the species of macrofauna. For instance, the contrasting proportions of silt to sand and clay could be attributed to a selection of fine rather than coarse particles in relation to the feeding behaviour of the species. Indeed, termites have been observed to construct ephemeral structures from a mixture of soil particles and saliva, thereby providing a protective enclosure around potential food sources [59]. Despite these structures exhibiting sensitivity to precipitation [60], several studies have emphasised the importance of particle selection in coatings formed by translocating soil to protect foraging [43] [61]-[63].

Therefore, it is hypothesised that shallow tillage would gradually eliminate inactive surface coarse elements, thereby increasing the useful volume of the soil. Consequently, the practice of shallow tillage would have resulted in the loosening of the soil, thereby stimulating a revival of macrofaunal activity. This, in turn, exerts an influence on the particle size distribution of the soil. However, further studies are required to determine the specific contributions of soil-dwelling species and the multiple pathways through which silt enters the system, in order to enhance our understanding of its dynamics.

4.3. Fallow Land Promotes the Formation of Macro-Aggregates, While Shallow Tillage Increases the Amount of Fine Particles

The present study showed that fallowing increases the formation of macro-aggregates, whereas shallow tillage promotes the formation of aggregates associated with fine particles (such as silt and clay). The results indicate that permanent tillage has a comparable impact on macro-aggregates to the splash effects of heavy rainfall. The instability of large aggregates is clearly caused by the lack of sufficient organic debris in the soil. The present results are in alignment with those of Chotte [18], who indicated that fallow land plays a pivotal role in the process of soil reaggregation and the restoration of soil stability. Conversely, tillage and exposure to rainfall have been observed to quickly destroy aggregates larger than 2 mm, as their stability depends on highly exposed organic matter that oxidises quickly.

Furthermore, the formation of microaggregates in tilled plots may indicate a relatively rapid decomposition of organic debris (the herbaceous biomass that farmers leave in place after tillage), coupled with the release of biogenic products and other binding agents, such as polysaccharides and root exudates from cultivated plants. It is well established that soil mineral phases (iron and aluminium oxides, which are abundant in these soils) can function as binding agents in the formation and stability of soil aggregates [64] [65]. In addition, these phases have been shown to protect the soil organic carbon (SOC) through chemical interaction [66] [67]. Consequently, the rapid decomposition of organic matter is hypothesised to have promoted a solidphase reaction between the organic compounds and the clay and silt particles. This process would result in the formation of small, stable aggregates, such as micro-agregates composed of silt and clay. These results are consistent with those reported by Garcia-Franco [56], who observed significant increases in silt and clay particle sizes in the surface layer following reduced tillage. These increases in the abundance of small particles may benefit soil organic carbon sequestration, since very small aggregates have longer turnover times and greater stability than macro-aggregates. Indeed, the carbon associated with micro-aggregates is generally more stable than that associated with macro-aggregates [68] [69].

However, the results obtained indicate a general decline in the proportions of aggregates under tilled plots, with no significant difference between the two cropping systems in 2023, despite the differences observed in 2022. This prompts further inquiries into the extent and stability of these soil aggregates within a system cultivated in a semi-arid environment. Consequently, the indicators and profile of the stability of these small-sized aggregates in this context remain problematic and deserve further elucidation [70] [71].

4.4. Fallow Land Is More Effective at Retaining Water and Promoting Infiltration

The elevated soil moisture content can be attributed to the fact that fallowing limits water loss through both runoff and evaporation [72], thereby promoting infiltration [73]. The results of studies by Félix [74] have also shown the positive effect of soil cover on moisture content. More specifically, Masse [41] established that the fallow period restores water availability and soil fertility.

These results clearly demonstrate the importance of fallowing for restoring soil fertility, as evidenced by the higher rates of soil infiltration compared to tilled plots. These increases in soil humidity can notably stimulate the activity of soil macrofauna, such as termites and ants, creating porosity that favours soil structural development [43] [45]. The low bulk density values under fallow are therefore justified by this observation. Thus, vegetation under fallow avoids the destructive impact of raindrops on the soil "splash effect", creates macroporosity and improves water infiltration [46]. On this subject, Roose [2004] provides an explanation of the improvement in water infiltration capacity by the presence of litter on the soil surface and its strong transformation by earthworms and termites. Studies by Masse [41] also revealed that fallowing favours soil decompaction, improved infiltration and organic matter accumulation. Thus, the low bulk density values observed under fallow compared with shallow tillage could indicate hydrostructural stability arising from an increase in pore space in soils due to the activity of macrofauna. In this respect, Singh [75] has shown that bulk density can provide information on the level of soil compaction.

Furthermore, the results concerning the overall impact of measurement time and cropping systems and how these interact highlight the long-term effectiveness of these practices. While other studies have reported limited benefits of no-till farming with regard to organic carbon [50] [51] [76] [77], our results show that long-term fallow in a semi-arid environment can significantly improve the soil's physical fertility, whereas shallow tillage has a moderate effect on this fertility. On the other hand, one of the major challenges of fallowing in the Sahelian context is how long the land is left uncultivated, given population growth [21]. Consequently, shallow tillage could provide a valuable solution to the issue of land scarcity, which is leading to shorter fallow periods. Moreover, compared to no-till, which can often lead to increased herbicide use, reduced tillage would provide some advantages where moisture is a limiting factor. This is because it prevents the growth of undesirable plants and reduces the moisture in the soil, thus improving production [76].

However, the slight differences in soil temperature between the two systems suggest that variations in soil temperature are more closely linked to climatic conditions than to management practices within our agricultural systems. In hot, dry tropical climates, the temperature of the soil does not significantly impact the decomposition of debris on its surface. This result corroborates the hypothesis that, in tropical climates, rainfall drives decomposition even when soil temperature varies little or not at all [78]. By the way, it is asserted by Mrabet [79] that the effectiveness of fallowing and reduced tillage practices remains highly dependent on local pedoclimatic conditions.

4.5. Relationships between Physical Properties and Soil Organic Matter

The results indicate the soil parameters that can be improved by each cropping system within this agrosystem. The analysis shows that fallowing improves porosity and coarse soil particles, such as sand, labile organic matter and macro-aggregates. In contrast, shallow tillage increases clay content, but this practice can result in soil compaction through increases in bulk density and surface temperature. These results are consistent with those obtained by Schäffer [80] and Boivin [25].

This result highlights the importance of SOM and small aggregates in the retention of soil water, which provides a favourable environment for flora and fauna. However, the negative relationship with micro-aggregates could provide further insight into the SOM fraction involved. In this regard, studies by Derrien [55] showed that labile soil organic carbon (SOC) fractions play a significant role in aggregate stabilisation. Specifically, it was the humic fractions that were mainly responsible for binding microaggregates in order to form macroaggregates [81] [82]. Specifically, Li [71] indicated that soil organic carbon (COS) is linked to silt and clay; COS and its fractions were also linked to plant biomass in alpine grasslands. Therefore, further research is required into SOM fractions and their role in forming the various aggregate fractions in these agrosystems. In fact, additional data on several soil types are needed to better understand the physical health of soils in these agrosystems [83].

The significant relationship observed between infiltration and macro-aggregates as well as between silt and micro-aggregates suggests that macro-aggregates improve soil porosity through SOM [84], and that silts play a key role in developing micro-aggregates. Additionally, the strong negative relationships recorded between sand and clay, between bulk density and infiltration, and between bulk density and macro-aggregates clearly indicate the importance of SOM in the formation of macroaggregates and its positive impact on soil porosity. This can reduce compaction, thereby facilitating particle granulation. As a result, soil porosity is improved, as is its aeration, making soils lighter and easier to manage. In this regard, Sanou [8] explains that exogenous organic matter plays a key role in improving soil structure, particularly in the formation of humus. As argued by Coppens [72], organic matter plays a pivotal role in regulating soil moisture. This is achieved by increasing porosity, which promotes hydraulic conductivity. Nevertheless, tillage is one of the main factors that can explain the inverse relationship between sand and clay. Tillage has been shown to affect the soil profile in two ways. Firstly, it brings clay up from the lower horizons to the surface. Secondly, it involves repeated trampling of the land, which favours compaction and reduces porosity by destroying large aggregates. This result provides a theoretical basis for the inverse relationship noted between bulk density, infiltration and macro-aggregates. The conclusions of the present study are consistent with those of previous studies, which showed that higher carbon levels in soil with no-tillage compared to conventional tillage are due to less soil disturbance, reduced erosion, increased microbial activity and larger macro-aggregates [19] [85]-[87]. Moreover, numerous studies have examined the impact of tillage on the stability of soil structure and moisture content [20] [25] [28] [29]. The results therefore indicate that shallow tillage displays a positive trend in terms of mobilising the fine soil fraction of the topsoil. However, the number of times each plot is tilled remains a key factor in maintaining the soil's structural integrity.

Moreover, this study suggests that the use of a single site for the experiment could limit the spatio-temporal benefits of this practice. Similarly, further research is needed covering several years of measurements, the impacts on the lower soil depths and the actual contribution of the crops involved. This will enable appropriate responses to be provided to the main limitations and will lead to a better understanding of the practical implications of the results.

5. Conclusion

This study has shown that shallow tillage of the soil cultivated with sorghum in semi-arid conditions allows fine elements, such as clay, silt and microaggregates, to rise to the topsoil. This practice therefore exhibits beneficial long-term trends in soil organic carbon sequestration, given that fine elements have longer renewal times than macro-aggregates, which are more favoured by fallow plots left to remain uncultivated. Furthermore, our results showed that shallow tillage could lead to a gradual increase in soil carbon storage in the lack of organic inputs. However, the key soil parameters (soil moisture, infiltration and SOM) show that, as well as light tillage, additional organic matter is needed, probably due to SOM's role in soil macrofauna activity. Therefore, although the disturbance to the hydrostructural stability was minimal, it was not sufficient to significantly improve the overall physical properties of the soil. In this regard, the long-term effect of diverse organic matter fractions on soil aggregation requires further investigation to optimize tropical soil management strategies. However, the limited amount and poor quality of organic matter in these ecosystems could mean that shallow tillage is an alternative. This is because it can help to address the shortage of organic matter and the increasing scarcity of fallow practices. These are both becoming increasingly rare in Sahelian agrosystems, due to numerous environmental challenges. This study could reduce the need for intensive tillage and provide an effective solution to water erosion. It could be adopted as a sustainable approach to increasing production in Sahelian cropping systems.

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Author Contributions

The authors confirm their contributions to the paper as follows: conceptualization and experimental design: Guebre D, Ouedraogo H, Traore S, Hien E; data analysis and interpretation: Guebre D, Ouedraogo H, Ganeme A, Traore S, Hien E; data collection: Guebre D, Ilboudo A, Ouedraogo H, Boussim ZI; manuscript drafting: Guebre D, Ouedraogo H, Boussim ZI, Hien E. All authors reviewed the results and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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