Original Research Article

Short-term tillage and soil nutrient management on soil water movement in a Lixisol in a tropical climate

ABSTRACT

Aims: The study was conducted to assess the effects of different soil tillage practices and soil amendments on soil hydraulic characteristics.
Study design: The study was a 3 × 4 split-plot experiment arranged in randomized complete block design (RCBD) with 3 replications.
Methodology: The treatments comprised 12 main plots, namely no till (NT), plough-plant (PP) and plough-harrow-plant (PHP) and 36 sub-plots, namely no amendment (NA), NPK 60:40:40 (100% NPK), 4 tons/ha poultry manure (100% PM) and 2 tons/ha PM + NPK 30:20:20 [½(NPK + PM)]. Soil bulk density (BD), volumetric moisture content (VMC), total porosity (TP), aggregate stability (ASt), and infiltration parameters were measured under the different treatments.
Results: Among the different tillage operations, the NT plot had the lowest BD, but highest TP, VMC and ASt. With regard to the soil amendments, TP was highest under the ½(NPK + PM) treatment. The cumulative infiltration amount (*F*) and infiltration capacity (K_o) were highest in the NT plots. However, sorptivity (S_ϕ) was highest and lowest in the PP and NT plots, respectively. The infiltration parameters were highest in the ½(NPK + PM) plots. Further, the combined application of NT + ½(NPK + PM) resulted in the highest *F*, S_ϕ and K_o.
Conclusion: The, NT, ½(NPK + PM) and NT + ½(NPK + PM) improved the soil hydro-physical properties.

Keywords: Cumulative infiltration amount, Infiltration capacity, Sorptivity, Soil structure

1. INTRODUCTION

Soil fertility degradation, together with the accompanying problems of weeds, pests, and diseases, has been identified as a major biophysical cause of low per capita food production, as well as the dwindling food and nutrition security in Africa, particularly, in Sub-Saharan Africa (SSA) [1]. At the same time, natural resources are under significant threat due to non-optimal management and climate change. This explains the enormous food aid received continuously in SSA [2], which has over decades called for the adoption of more advanced technologies, such as the use of high-yielding fertilizer-responsive crop varieties and different fertilizer recommendation programs. A significant proportion of the required increase has also been overly dependent on increasing the acreage under cultivation. This intensification with its attendant pressure on natural resources has strengthened the concerns of competing users over soil resources in SSA. Consequently, soil resources of high quantity and quality are needed to sustain these growth rates and current welfare. As a result, extended fallow periods intended for the restoration of soil fertility and organic matter build-up are no longer practicable [3 – 5]. In addition, most of the current agricultural practices are not sustainable, and result in serious land degradation. Nevertheless, sustainable soil and water management cannot be achieved without close attention to maintaining and/or improving the physical conditions or quality of soil to a satisfactory level.

In Ghana, for instance, soil degradation in its several forms, is evident in all the agroecological zones of Ghana [6, 7]. Evidently, soil degradation resulting from soil erosion by water has resulted in the degradation of large parcels of land and is a major constraint to achieving sustainable food production in the country [8], and resulted in reduced soil depth, a buildup of silt in reservoirs and rivers. An unsustainable soil management practice is characterized by a little cover of soil in most farms. This impacts negatively on the soil's quality and productivity which ultimately results in low biomass and crop yields, threatened food security and poverty [9, 10]. Unsustainable soil management practices have severe negative effects on infiltration and drainage, which consequently result in surface runoff and/or erosion. To meet the ever-increasing demand for food, more sustainable and improved soil management practices are necessary. These can be achieved through appropriate tillage, soil amendments, soil water, and crop management strategies [11, 12].

Tillage is notably one of the key operations in agriculture throughout the years [13]. Regarding the various tillage systems, conventional tillage (CT) is regarded as key to the evolution of modern agriculture with regards to the crop yield and weed control [14]. In the short term, CT systems are reported to reduce soil bulk density within the tilled layer [15, 16], and increase soil porosity, hydraulic conductivity, and infiltration [17 – 19]. In contrast, minimum tillage (MT) and no-tillage (NT) have been widely accepted to CT. This, according to [20 – 23] is due to their contributions to farm sustainability and optimization of productivity through the reductions in the requirement for fossil fuel, enhancement of soil carbon storage, soil structure, and water infiltration. It is, however, worthy to note that the exclusion of ploughing could result in sever compaction of the topsoil, especially particularly in clay-rich and/or low organic matter soil [24, 25]. Consequently, studies [e.g., 19, 26, 27] have reported indicated the high demands for intensive tillage due to the growing demands for food worldwide. Thus, employing the appropriate tillage technique(s) can result in higher improvement in soil quality, increased crop yields and crop water use efficiency. Even though it is imperative to consider tillage as a very important agricultural practice, it is also one of the major energy consumers in agricultural production [28, 29].

Soil organic matter plays an important role in both short- and long-term availability of nutrients, which is vital for plant growth under the right management practices. The maintenance of soil organic matter in low-input agro-systems results in retention and storage of nutrients, increased buffering capacity in low activity clay soils and increased water holding capacity [30]. However, since organic resources are not easily available in adequate quantities, intensive farming can only be maintained through integrated organic and fertilizer inputs [31]. The combination of mineral fertilizers with practices that retain organic matter in the soil is reported to be a more sustainable system for ensuring crop production to meet the current food security demands [5]. Thus, crop residue retention and usage as soil amendments has the potential to augment the effectiveness of mineral fertilizers to boost the yield of crops and reduce large importations of mineral fertilizers. Tillage and integrated soil nutrients/fertility management are innovative strategies in improving agricultural productivity to meet the food demands of the growing world population. Information on the effect of these widely adopted practices is generally sparse in Ghanaian soils, and with varied results. The study will give more insight on the best soil management practices in terms of tillage, soil amendments and their contribution to make recommendations to farmers. The objective was to assess the process of water infiltration in response to different soil management practices (tillage and soil amendments) to ensure the sustainable use of agricultural lands.

2. MATERIAL AND METHODS

2.1 Description of study area and soil

The study was conducted at the Faculty of Agriculture Research Station located in Anwomaso, Kumasi. The area is located within the semi-deciduous forest zone of Ghana, with geographical reference to the approximate mid-point as W1^{o}31′32.88″ and N6^{o}41′51.24″. The soil in the area is described as the Kotei series under the Interim soil classification system of Ghana and Plinthic Vetic Lixisol (Profondic, Chromic) [32]. It developed from colluvial materials derived from granite and is predominantly sandy loam in the topsoil underlain by sandy clay loam subsoil. The mean pH of the soil is 5.1. The subsoil has a moderate to medium sub-angular blocky structure with fewer roots. The slope of the experimental plot is averagely 6%.

2.2 Field layout and experimental design

The study was set up in a 3 x 4 split-plot arranged in a randomized complete block design with 3 replications. It comprised a total of 12 main plots and 36 sub plots. The main plot factors were described by the different tillage practices, namely: no-till (NT), plough-plant (PP) and plough-harrow-plant (PHP). The sub plot factors were described by the various soil amendments, namely: no amendment (NA) or control, the full rate of mineral NPK fertilizer (60:40:40 – 100% NPK), the full rate of poultry manure (4 tons/ha – 100% PM) and 2 tons/ha PM plus 30:20:20 NPK (½NPK + PM).

2.3 Data collection and analysis

Soil bulk density (BD) was determined from oven-dried intact core samples collected to a depth of 20 cm by the core method [33]. The soil was then weighed and dried at 105°C to a constant weight. The volumetric moisture content (VMC), total porosity (TP), air-filled porosity (AP) and aggregate stability (ASt) were subsequently determined as described in [34]. Field infiltration was measured using the single ring infiltrometer with a diameter of 30 cm and a height of 40 cm as described by Khalid *et al*. [34, 35]. The slopes of the straight lines obtained from the plots of cumulative infiltration amount (F) against the square root of time for the initial five (5) minutes represented the sorptivity (S_{ϕ}) of the soil at the given moisture content. The slopes of the cumulative infiltration amount curves at different times scales represented the infiltration rates (f), which were plotted against time to obtain the infiltration capacity ($K_{\circ}$) when the infiltration rate curve became asymptotic to the time axis [34 – 37]. Data collected were subjected to the Analysis of Variance (ANOVA) using Genstat Edition 12.1.

3. RESULTS AND DISCUSSION

3.1 Effects of tillage and amendments on soil physical properties

Table 1 shows the effects of the different tillage operations and soil amendments on the physical properties of the soil. Bulk density (BD) ranged from 1.18 – 1.27 g cm^{-3} under the tillage treatments, with the lowest and highest values recorded in the NT and PHP plots, respectively. Evidently, there were significant differences in BD between NT and PP, and NT and PHP. Soil moisture contents ranged between 8.87% (under PP) and 11.39% (under NT). Significant differences were observed in moisture content between NT and PP, NT and PHP. Total porosity ranged from 51.7% (under PHP) to 55.15% (under NT). The NT plots had the highest porosities which were significantly higher than those of the PP and PHP plots.

Table 1: Effects of tillage practices on physical properties of the soil

Treatment	BD (g cm^{-3})	VMC (%)	TP (%)	AP (%)	ASt (%)
Tillage system					
NT	1.18	11.39	55.15	43.76	12.69
PP	1.26	8.87	52.65	43.75	9.39
PHP	1.27	10.34	51.73	41.39	4.04
LSD$_{0.05}$	0.05	1.01	1.03	1.07	1.81
CV (%)	5.0	3.4	2.3	3.0	23.6
Soil Amendment					
100% NPK	1.23	10.37	53.50	43.13	9.82
100% PM	1.25	9.48	52.67	43.19	9.14
½(NPK + PM)	1.22	10.35	54.17	43.82	8.78
NA	1.24	10.68	52.97	42.29	9.05
LSD$_{0.05}$	N/S	NS	1.03	N/S	N/S
CV (%)	5.0	3.4	2.3	3.0	23.6

BD = Bulk density; VMC = Moisture content; TP = Total porosity; AP = Air-filled porosity; ASt = Aggregate stability

The total porosities under the PP and PHP treatments were, however, not significantly different. Air-filled porosity ranged from 41.39 – 43.76%. There was no significant difference in the air-filled porosities in the NT and PP plots, however, significant differences were observed between NT and PHP, and PP and PHP. Aggregate stability ranged from 4.04 – 12.69% and differed significantly among the treatments in the order of NT > PP > PHP. The results as presented in Table 1 show that the bulk density from the NT plot was the lowest among the tillage treatments. This is due to the potential of tillage (Plough-harrow) to result in soil aggregate compaction due to machinery traction. Furthermore, Mrabet *et al*. [38] also found higher levels of water stable soil aggregates under NT compared to soils treated under disc cultivation and ploughing. However, this observation contradicts the earlier report by Vogeler *et al*. [39] who found that bulk density was lower (i.e., decreased soil strength) in soils treated under conventional tillage (Plough-harrow) when compared with NT. Apart from total porosity, soil amendments did not significantly influence the soil physical properties measured in the current study (Table 1). Total porosity measurements under the different soil amendments were in the order of 54.17% (½NPK + PM) > 53.5% (100% NPK) > 52.97% (NA) > 52.67% (100% PM). Significant differences were observed between ½(NPK + PM) and NA, and 100% PM, however, all other treatment pairs did not differ significantly.

The observed no significant effects of soil amendments on BD, VMC, AP and ASt could be due to the application rates and the short-term application of the amendments. Similar observations were made in the measurement of BD by Aluko and Oyedele [40], and Agbede *et al*. [41]. The results also show that TP of soils in the ½(NPK + PM) plots were the highest. Cogger [42] reported that the use of organic amendment (PM) during turf grass establishment has been shown to increase soil porosity thereby providing an environment that will allow for the growth of healthy root systems. Rivenshield and Bassuk [43] reported that applying organic amendments at higher rates led to more pronounced improvements in macroporosity. Increased in porosity can be attributed to the interactive effect of the treatments. Similar to this study, Hati *et al*. [44] found that ½(NPK + PM) resulted in an improvement in the soil water holding capacity and reduction in soil bulk density. Although the sole application of PM did not produce considerable differences in the soil physical properties, it is a well-established fact that addition of organic matter from organic amendments such as PM enhances soil physical properties such as structure and aggregate stability, aeration, water holding capacity and hydraulic conductivity [45, 46]. This according to Pagliai *et al*. [47] is as a result of the protection of the soil surface and the maintenance of continuous transmission pores through the profile by organic matter.

3.2 Effects of tillage practices and soil amendments on infiltration parameters

The various infiltration parameters, viz, cumulative infiltration amount (*F*), sorptivity (S_ϕ) and infiltration capacity (K_o) under the various tillage and soil amendment treatments are summarized in Table 2. For the different tillage plots, *F* ranged from 1.73 – 6.83 cm, with the highest and lowest values observed in the NT and PP plots, respectively. The value of *F* in the PP plot was significantly lower than those in NT and PHP plots. The K_o under the PP treatment was significantly lower than those under NT and PHP treatments, however, those observed under the NT and PHP treatments were statistically similar. Sorptivity ranged from 0.50 – 0.74 cm $s^{-0.5}$ under the different tillage practices, with the highest and lowest values recorded in the PP and NT plots, respectively. Significant differences were observed in S_ϕ between NT, and both PP and PHP. The K_o ranged from 1.08 – 1.73 cm h^{-1} under the various tillage practices. The higher *F* and K_o observed under NT reflects the lowest BD and highest TP induced by the treatment. This could also imply a larger number of macropores and increased faunal activity [48, 49]. Thus, the relatively low *F* and K_o in the conventional tillage plots, especially under PP could have resulted from the disruption in the continuity of macropores [50]. On the contrary, Ferreras *et al*. [51] and Barzegar *et al*. [52] reported lower *F* under NT than conventional tillage as a result of the loosening and/or pulverization of soil by tillage implements as evidenced under PHP in the present study.

Table 2: Effects of tillage and soil amendments on soil water infiltration

Treatment	***F* (cm)**	**S_ϕ (cm $s^{-0.5}$)**	**K_o (cm h^{-1})**
Tillage			
NT	11.73	0.50	1.73
PP	6.83	0.74	1.08
PHP	11.54	0.72	1.68
$LSD_{0.05}$	1.67	0.18	0.17
CV (%)	11.70	16.10	10.80
Soil Amendment			
100% NPK	10.07	0.66	1.57
100% PM	8.84	0.55	1.19
½ (NPK + PM)	13.12	0.83	1.94
NA	8.08	0.57	1.30
$LSD_{0.05}$	1.17	0.10	0.16
CV (%)	11.70	16.10	10.80

F = Cumulative infiltration amount; S_ϕ *= Sorptivity;* K_o *= Infiltration capacity*

Under the different soil amendments, *F* ranged from 8.08 – 13.12 cm, with significant differences among all treatments, except for those between the NA and 100% PM plots. The cumulative infiltration amount was highest under the ½(NPK + PM) treatment, and differed significantly from those under the other soil amendments. Under the 100% NPK treatment, *F* was significantly higher than that of the NA, however, it was statistically at par under the 100% PM and NA plots. Furthermore, the soil amendments significantly affected S_ϕ, with values ranging from 0.55 – 0.83 cm s$^{-0.5}$. The highest S_ϕ was recorded in the ½(NPK + PM) plots and was significantly higher than those under the other soil amendments. Additionally, the value of S_ϕ under the 100% NPK treatment was significantly higher than that of the 100% PM treatment. Also, the soil amendments had a significant effect on K_o, with values ranging from 1.19 – 1.94 cm h^{-1}, being fastest and slowest under the ½(NPK + PM) and 100% PM, respectively. Contrary to these observations several studies [e.g., 53 – 57] have reported high F and K_o in organic amended soils. The high infiltration in the NPK amended soils, i.e., 100% NPK and ½(NPK + PM) could have resulted from increased soil affinity to water (i.e., matric potential) as evidenced by the high S_ϕ. This could have been as a result of the increased concentration of solutes (i.e., osmotic potential) due to the inorganic fertilizer.

Although organic amendments are known to increase the organic matter content of soils, with a subsequent improve in soil structure for enhanced infiltration rates, the results of the present study show that the 100% NPK amendment rather significantly enhanced the F and K_o as compared to the 100% PM treatment. This, according to Gupta and Gupta [57] could be due to the clogging of soil pores by the very fine particles from the organic amendment (colloids); the swelling of mineral colloids contained in the organic amendment in the soil pores upon hydration; the formation of slurry from the PM upon mixing with water [58] and the subsequent increase in hydraulic resistance due to the formation of surface seal; and water repellency resulting from organic coatings on soil particles following desiccation [34, 35]. On the contrary, Zerihun *et al*. [59] and Oyonarte *et al*. [60] recommended PM as a good soil amendment with a high potential to improve soil water infiltration rates. Thus, application of organic amendments in frequently small amounts is highly recommended as compared to applications in very large quantities less frequently [61].

3.3 Combined effects of tillage and soil amendments on soil water infiltration

Regarding the combined effects of the various tillage operations and soil amendments, F ranged between 1.86 and 24.35 cm (Table 3), with significant differences observed among the different treatment combinations. The interaction between NT x ½(NPK + PM) resulted in the highest F, which was significantly different from the other treatment combinations. This was followed by the combination of PP x 100% NPK and PP x PM, which also differed significantly from the remaining treatment combinations. The lowest F was recorded under the PP x 100% PM (1.86 cm) treatment combination, which was significantly different from the other treatment combinations. There were significant differences among the treatment combinations, especially between the highest and the lowest S_ϕ. The NT x ½(NPK + PM) treatments combination had the highest S_ϕ and PP x 100% PM had the lowest. However, PP x 100% PM was similar to PP x ½(NPK + PM), NT x 100% NPK, NT x 100% PM, NT x PHP and NT x NA. Further, K_o ranged between 0.33 – 3.60 cm/h, with the lowest and highest values recorded under the PP x 100% PM and NT x ½(NPK + PM) treatments, respectively. Under the NT x SA treatments, significant differences were observed between NT x ½(NPK + PM) and all other treatments. Likewise, K_o under NT x 100% PM and NT x NA were significantly different from NT x 100% NPK. All treatment combinations under the PP x SA treatments were significantly different. Under the PHP x SA treatments, K_o under PHP x 100% NPK and PHP x 100% PM were significantly different from those recorded under PHP x ½(NPK + PM) and PHP x NA.

Table 3: Interactive effects of tillage and soil amendments soil water infiltration

Treatment	***F* (cm)**	**S_ϕ (cm $s^{-0.5}$)**	**K_o (cm h^{-1})**
No-Till x Soil Amendment (NT x SA)			
NT x 100% NPK	4.29	0.38	0.80
NT x 100% PM	9.22	0.44	1.23
NT x ½(NPK + PM)	24.35	1.45	3.60
NT x NA	9.05	0.68	1.30
Plough-Plant x Soil Amendment (PP x SA)			
PP x 100% NPK	10.88	0.69	1.67
PP x 100% PM	1.86	0.28	0.33
PP x ½(NPK + PM)	6.32	0.46	1.00
PP x NA	8.25	0.56	1.33
Plough-Harrow-Plant x Soil Amendment (PHP x SA)			
PHP x 100% NPK	15.00	0.91	2.23
PHP x 100% PM	15.45	0.95	2.00
PHP x ½(NPK + PM)	8.70	0.57	1.23
PHP x NA	6.96	0.48	1.27
$LSD_{0.05}$	1.92	0.21	0.27
CV (%)	11.70	16.10	10.80

F = Cumulative infiltration amount; S_ϕ = Sorptivity; K_o = Infiltration capacity

The highest *F*, S_ϕ and K_o recorded under the NT x ½(NPK + PM) treatment combination could have resulted from several factors including the initial soil VMC, BD, TP, etc. This could be attributed to the additive effect of NT x ½(NPK + PM) which resulted in the improvement of soil structure, and consequently allowing larger volumes of water entry into the soil through the surface. Again, the NT x ½(NPK + PM) increased the affinity of the soil to water as evidenced by the S_ϕ. Thus, under this treatment, the activities of soil macro and microorganisms was enhanced, which resulted in the improvement of the soil pore structure with a subsequent improvement in water absorption, entry, and transmission through the soil. Accordingly, a report by Aluko and Oyedele [40] revealed that the application PM to soil has the potential to improve water absorption and retention as a result of improved soil structure.

CONCLUSION

Compared to the soil amendments, tillage operations had significant impacts on all the soil physical properties. Among the different tillage operations, PP and PHP, NT had lowest bulk density, and highest moisture content and aggregate stability. Similarly, *F* and K_o were highest under NT, whereas S_ϕ was highest under PP. With regard to the soil amendments, ½(NPK + PM) plots had the highest *F*, S_ϕ and K_o. The combination of NT + ½(NPK + PM) also resulted in the highest *F*, S_ϕ and K_o. The study indicates that NT, ½(NPK + PM) and combination of NT + ½(NPK + PM) have positive effects on soil water holding capacity, structure and hydraulic and hydrological properties, which are valuable to high soil quality and crop yield. Despite the observed effects of on the contribution of NPK to soil water infiltration in the present study, it remains unclear to what extent and by what mechanism it influences the soil hydraulic and hydrological properties and processes. This is particularly important for understanding the hydro-physical behaviour of inorganic soil fertilizers in an agricultural context, where soil physical and hydrological factors are essential for soil productivity.

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any studies with human participants performed by any of the authors.

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