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Long-term effects of tillage, sub-soiling, and profile strata on properties of a Vitric Andosol in the Kenyan highlands

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Abstract

Tillage alters the structure and composition of soil aggregates affecting infiltration rate (IR) and hydraulic conductivity (K). This study investigated the long-term effects of conventional, minimum, and no-tillage with or without subsoiling on aggregate stability, soil organic carbon (SOC), bulk density, IR, and K of a stratified Vitric Andosol in Kenyan highlands. The experiment was laid out in a spilt-split plot design with three replicates. Stepwise profiles were dug in order to expose the soil layers at 0 to 30, 30 to 60, and 60 to 90 cm depths. Soil bulk density was 6% lower in the minimum tilled and 12% lower in the conventionally tilled plots that were subsoiled compared to treatments with no subsoiling and tillage. Subsoiled treatments also increased sequestration of SOC by 20% in the 30 to 60 cm layer. Conventional tillage, however, decreased aggregate stability by 32% compared to no-tillage treatments. Subsoiling in combination with minimum tillage decreased IR by 25% but increased IR about three-fold in conventionally tilled plots. Hydraulic conductivity in the 60 to 90 cm layer was lowest, which constrained water movement in this stratified soil.

Keywords: Bulk density, Hydraulic conductivity, Infiltration rate, Soil organic carbon.

Introduction

Tillage, in the long term, can lead to structural degradation of soils resulting in the formation of fine aggregates with low organic carbon SOC, which in turn, may adversely affect the infiltration rate (IR) and hydraulic conductivity (K) of soils (Holland, 2004). Therefore, reduced tillage practices are often advocated to maintain improved soil organic matter status. Paustian et al. (1997), based on data compiled from several long-term field studies, showed that there is an increase in soil organic carbon (SOC) under minimum tillage in most cases and they attributed this to reduced litter decomposition and less soil disturbance. Reduction in tillage from conventional to minimum tillage also increased the mean weight diameter (MWD) of aggregates by 27 to 45% compared to no-tillage in a tropical dryland agroecosystem of India (Kushwaha et al., 2001).

Although some authors suggest that the properties of the soil layers below the plough layer influence the physical behaviour of the top soil (e.g., Sillon et al., 2003), such studies mostly have been restricted to the plough layer only (Pikul and Aase, 2003). Nonetheless, subsoiling is practised as a remedial measure to break the confining layer within the profile. Abu-Hamdeh (2003) observed that subsoiling reduces soil bulk density by an average of 2.6% in the top 40 cm layer of the profile. Likewise, Ghuman and Sur (2001) found that bulk density in the 0 to 10 cm soil layer was significantly lowered by about 0.05 kg cm^{-3} in the minimum-tillage plots than in the conventionally tilled treatments, despite inter layer variations.

The effects of tillage systems on soil water movement are, however, inconsistent. While Vervoort et al. (2001) reported that IR increased for minimum tillage compared to conventional tillage treatments, Lindstrom et al. (1984) obtained contrary results, and Gomez et al. (1999) could not establish any difference in IR between conventionally

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tilled and minimally tilled soils. Although Pikul and Aase (2003) showed that infiltration was consistently greater under subsoiling, compared to conventionally tilled plots with no subsoiling, the benefits of subsoiling were not obvious. Unger (2001) postulated that decreased soil disturbance in no-tillage systems leads to the development of biopores and improved aggregate stability, giving rise to development of less tortuous and more continuous pores and hence greater IR.

Although minimum-tilled croplands have an initially high K, steady-state IR in minimum tillage and no-tillage treatments were similar (Schwartz et al., 2003). Despite such variability in the effects of tillage on soil properties, the combined long-term effects of tillage systems, subsoiling, and soil profile stratification has rarely been explored. In this study, we tested the assumption that subsoiling and long-term tillage operations significantly alter the properties of a stratified Vitric Andosol in a high altitude site in Kenya, in turn, affecting IR and K. The specific objectives were to investigate the long-term effects of subsoiling and subsequent application of conventional, minimum, and no-tillage systems on aggregate stability, SOC, bulk density, IR, and K.

Materials and Methods

The study site was located on a large farm (Menengai Feedlots; ~1200 ha) in the Rongai area of Nakuru District, Kenya (~ 00°13' S and 35° 58' E at an altitude of 2068 m above sea level). This site receives a mean annual rainfall approximately 1200 mm and experiences a mean annual temperature range of 16 to 18°C. The soil is derived from volcanic ash and has been classified as Vitric Andosol (Jaetzold and Schmidt, 1983). There are three layers within the top 1 m of the soil profile. These consist of the top cultivated horizon covering approximately 30 cm depth followed by a pumice layer approximately 30 to 60 cm that overlie a well developed dark coloured soil layer at 60 to 90 cm depth (Fig. 1). Rain-fed large-scale wheat (*Triticum aestivum* L. cv Njoro BW2) production was the dominant land-use practice in the farm.

In the 1960s, subsoiling was done in 2 m wide strips at

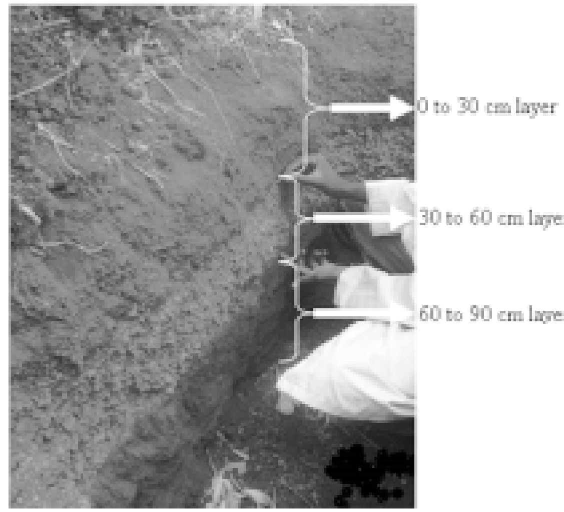

Figure 1. The soil profile showing the three layers of the Vitric Andosol of the Kenyan highlands.

approximately 20 m intervals throughout the farm. The aim was to break the pumice (30 to 60 cm depth) layer to allow for laying pipes to supply water during the short dry spells occasionally experienced in this region. Following this, conventional and minimum tillage have been practiced for about 30 years in different portions of the farm, each measuring about 50 ha. Untilled 10 m wide buffer strips under natural pasture separated the cultivated portions from each other. Non-selective pre-emergence herbicides were used to control weeds before planting in the portions under minimum tillage while disc plough in combination with disc harrow was used to adequately pulverise the soil in the conventional tillage treatments once every two years.

The experiment was laid out in split-split plot design. The main plot treatments were conventional tillage, minimum tillage, and no-tillage, randomly allocated to the relevant existing farm portions. The subplots, with and without subsoiling were allocated within each main plot. Soil sampling depths, viz., 0 to 30, 30 to 60, and 60 to 90 cm, constituted the sub-sub units and were randomly allocated to each sub-unit. The treatments were replicated three times resulting in 54 sampling points. Staircase profiles were dug in order to expose the soil layers at 0 to 30, 30 to 60, and 60 to 90 cm depths, respectively. The core method (Rowell, 1994) was used to obtain undisturbed soil cores for bulk density determinations. Core rings (5 cm diameter and 5 cm height) were carefully driven vertically and uniformly into the soil using a double cylinder, hammer driven core sampler. The soil cores were taken to the laboratory and dried in an oven at 105°C and the bulk density estimated as follows:

$$\rho_b = \frac{m_s}{V_t} \quad \text{(Eq. 1)}$$

where ρ_b is the bulk density (g cm^{-3}), m_s is the mass of soil solids (g), and V_t is the total core volume (cm^3).

Disturbed soil samples (~1 kg), one sample from each plot, were collected using a flat square cornered spade, for SOC and aggregate stability determinations. The samples were air-dried and large clods broken by hand and sieved to pass through 4 mm sieve for aggregate stability determination and through 0.5 mm sieve for SOC determination. Aggregate stability was determined following the fast wetting framework proposed by Le Bissonnais (1996). After air-drying, the samples with aggregate size of 2 to 4 mm were oven dried at 40ºC for 24 h so that they were at a constant matric potential. Five grams of oven-dry aggregates from each soil sample were gently immersed in a beaker containing 50 cm^3 of water for 10 min. The water was sucked off using a pipette. The soil material was transferred to a 63 µm aperture sieve that had previously been immersed in ethanol and was gently moved up and down in ethanol five times to separate fragments less than 63 µm diameter from the bigger ones. The greater than 63 µm diameter fraction was oven-dried and gently dry-sieved by hand on a column of six sieves with 63, 100, 180, 500, 1000, and 2000 µm apertures. The weight of each size fraction was calculated as follows: the fraction less than 63 µm diameter was derived as the difference between initial weight and the sum of the weights of the six other fractions. Aggregate stability of each breakdown mechanism was expressed by calculating the MWD of the seven classes, which is the sum of the weight fraction of soil remaining on each sieve after sieving, multiplied by the mean aperture of the adjacent mesh:

$$MWD = \sum_{i=1}^{7} \bar{x}_i w_i \quad \text{(Eq 2)}$$

where, MWD is mean weight diameter (mm), w_i is total weight fraction of aggregates in the size class i with a diameter $\bar{x}_i$.

Due to substantial rock fragments (>2000 µm size), correction of aggregates in this size fraction was necessary (Elliott et al., 1991). Therefore, after weighing the >2000 µm size fraction of aggregates, they were transferred into dispersing cups. About 300 ml of water was added and the suspension stirred for 2 min. using high-speed electric mixer to disperse the macro aggregates, sieved through 2000 µm aperture sieve, and washed with water until the water passing through the sieve was clear. Pebbles-corrected aggregation was determined as a percentage of total air dry soil mass:

$$PCA = \frac{(W_{ASF} - W_{ASP})}{\Sigma W_A} \times 100 \quad \text{(Eq. 3)}$$

where PCA is pebbles-corrected aggregation, W_{ASF} is aggregate size fraction, W_{ASP} is aggregate sized pebbles and ΣW_A is all fractions.

Infiltration rate and K were determined at each of the 54 sampling points using a tension infiltrometer with a 20 cm diameter disc (Fig. 2). Measurements were taken at two tensions: –15 cm and –5 cm and K was determined by applying the Wooding (1968) equation (Eq. 4) for approximating unconfined IR in conjunction with Gardner (1958) equation based on one particular conductivity pressure relation (Eq. 5).

$$Q = \Pi r^2 K \left[1 + \frac{4}{\Pi r \alpha} \right] \quad \text{(Eq. 4)}$$

where Q is the volume of water entering the soil per unit time (cm^3 h^{-1}); K is the hydraulic conductivity (cm h^{-1}); r is the radius of the tension infiltrometer disc (cm) and α is a constant.

$$K(h) = K_S \exp(h\alpha) \quad \text{(Eq. 5)}$$

where K_s is the saturated hydraulic conductivity (cm h^{-1}) and h is the matric potential or tension at the source.

The data were subjected to analysis of variance using the General Linear Model for a split-split plot design

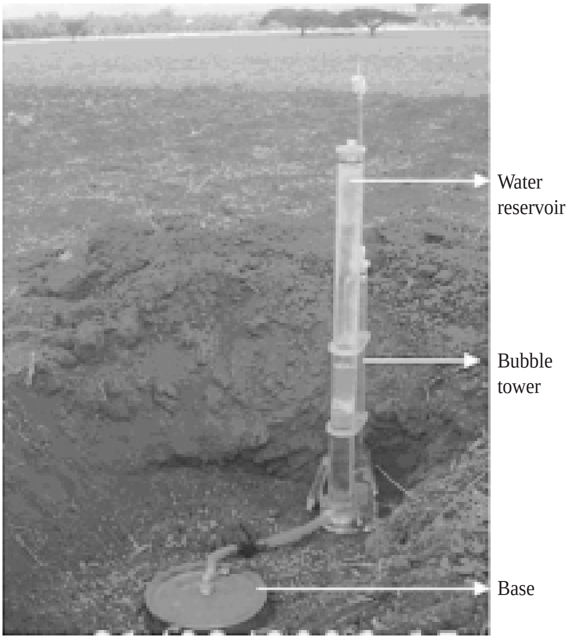

Figure 2. The tension infiltrometer.

to obtain an F value of the significant effect of the model. Differences between treatment means were examined using Duncan's new multiple range test (Buysse et al., 2004).

Results and Discussion

Bulk density at various depths of the soil profile as affected by tillage and subsoiling in the stratified Vitric Andosol in Kenya is shown in Table 1. In general, soil bulk density was less than 1 kg m^{-3} and the 30 to 60 cm depth had the least bulk density in all the three tillage systems. This observation was attributed to the composition of each layer. The upper 30 cm of the profile was mainly composed of mineral soil with various amounts of organic matter. The 30 to 60 cm layer was composed of loosely packed pumice material and the soil in the 60 to 90 cm depth was composed of well developed mineral soil (Fig. 1). The bulk density in 0 to 30 cm was about 6% higher under minimum tillage and about 12% lower under conventional tillage compared to that under no-tillage (Table 1). The low bulk density under conventional tillage treatment in 0 to 30 cm reflects the loosening effect of this tillage system. Conversely, elimination of soil mechanical loosening caused by tillage operations was most probably responsible for the higher bulk density under minimum tillage system in the 0 to 30 cm layer. Significant differences in bulk density brought about by the three tillage systems occurred only in the top 30 cm depth of the profile (Table 1).

Subsoiling affected the bulk density in all three depths (Table 1). At 0 to 30 cm, subsoiling decreased the bulk density by about 0.05 kg m^{-3} compared to treatments without subsoiling. At 30 to 60 cm, subsoiling increased bulk density by about 0.08 kg m^{-3} compared to no subsoiling while in the 60 to 90 cm depth, subsoiling treatment decreased bulk density by about 0.03 kg m^{-3}.

Table 1. Soil bulk density at various depths of the soil profile as affected by tillage and subsoiling in a stratified Vitric Andosol of the Kenyan highlands.

Interactions/treatments	Soil bulk density (kg m^{-3})		
Tillage system × Soil depth interaction	Soil depth (cm)		
	0 to 30	30 to 60	60 to 90
No-tillage	0.69^{c}	0.53^{e}	0.77^{ab}
Minimum tillage	0.73^{b}	0.51^{e}	0.78^{a}
Conventional tillage	0.61^{d}	0.52^{e}	0.79^{a}
Subsoiling × Soil depth interaction			
Subsoiling	0.65^{b}	0.65^{b}	0.65^{b}
No subsoiling	0.67^{ab}	0.69^{a}	0.69^{a}
Subsoiling × Tillage system interaction	No-tillage	Minimum tillage	Conventional tillage
Subsoiling	0.65^{b}	0.65^{b}	0.66^{b}
No subsoiling	0.67^{ab}	0.69^{a}	0.62^{c}

Values in the same row or column with the same letter superscripts are not significantly different, α =0.05

Subsoiling led to mixing of the higher bulk density mineral soil of 0 to 30 cm and 60 to 90 cm depths with the lower bulk density pumice material at 30 to 60 cm depth resulting in the observed decrease in bulk density of the mineral soil at 0 to 30 cm and 60 to 90 cm depths and increase in bulk density of the 30 to 60 cm layer. We conclude that subsoiling evened out the bulk density of the stratified profile under no-tillage, minimum, and conventional tillage.

SOC generally accumulated in the 0 to 30 cm depth in all tillage systems (Table 2) as expected for most soils. Conventional tillage and minimum tillage treatments reduced SOC by about 43% and 16% respectively in 0 to 30 cm layer compared to no-tillage treatment, affirming that conventional tillage and minimum tillage treatments allowed redistribution and faster mineralization of SOC. Many previous workers also showed that no-till was the best management practice in terms of enriching soil organic carbon levels (e.g., Aase and Pikul 1995). Subsoiling also led to a significant increase in SOC concentrations in the 30 to 60 cm depth from 2.84% in no subsoiling to 3.41% in subsoiled treatment (Table 2). It implies that subsoiling redistributed SOC from 0 to 30 cm to 30 to 60 cm depth, but there was no evidence that subsoiling affected the SOC content beyond 60 cm depth. In the high altitude Vitric Andosol, the effect of tillage systems on SOC sequestration was in the order of no-tillage ≥ minimum tillage > conventional tillage and was limited to 0 to 30 cm depth. Moreover, subsoiling contributed to SOC sequestration in the 30 to 60 cm depth.

Aggregate stability is shown in Table 3. Conventional tillage reduced aggregate stability by about 15% in the 0 to 30 cm layer compared to that for the same depth under no-tillage and minimum tillage. No-tillage and minimum tillage maintained aggregates of about 10% higher stability in the 0 to 30 cm depth compared to 30 to 60 and 60 to 90 cm depths. This is generally consistent with the observations of Kushwaha et al. (2001) who noted increased mean weight diameter (MWD) of soil aggregates following reduction of tillage from conventional to minimum, although the magnitude of increase obtained in the present study was lower than what they reported (27 to 45%).

Table 2. Soil organic carbon at various depths of the soil profile as affected by the tillage and subsoiling in a stratified Vitric Andosol of the Kenyan highlands.

Interactions/treatments	Soil organic carbon (%)		
Tillage system × Soil depth interaction	Soil depth (cm)		
	0 to 30	30 to 60	60 to 90
No-tillage	4.49[a]	2.90[c]	2.83[c]
Minimum tillage	3.77[ab]	2.97[c]	2.74[c]
Conventional tillage	3.00[c]	3.51[bc]	2.76[c]
Subsoiling × Soil depth interaction			
Subsoiling	3.58[ab]	3.41[ab]	2.67[c]
No subsoiling	3.93[a]	2.84[c]	2.89[c]
Subsoiling × Tillage system interaction	No-tillage	Minimum tillage	Conventional tillage
Subsoiling	3.41[a]	3.19[a]	3.13[a]
No subsoiling	3.40[a]	3.19[a]	2.98[a]

Values in the same row or column with the same letter superscripts are not significantly different $\alpha = 0.05$

Conventional tillage, however, maintained aggregates of similar stability in the 0 to 30, 30 to 60, and 60 to 90 cm depths (Table 3). Subsoiling increased aggregate stability by about 5% in 0 to 30 cm but decreased it by about 12% in the 30 to 60 and 60 to 90 cm depths (Table 3). Therefore, it was concluded that subsoiling moderated the effect of conventional tillage in the 0 to 30 cm layer and that the aggregates in the 30 to 60 cm and 60 to 90 cm layers were finer than those in the 0 to 30 cm layer (Table 3). Aggregates of 2–4 mm size in 0 to 30 cm

Table 3. Aggregate stability at various depths of the soil profile as affected by the tillage and subsoiling in a stratified Vitric Andosol of the Kenyan highlands.

Interactions/treatments	Aggregate stability (Mean weight diameter; mm)		
Tillage system × Soil depth interaction	Soil depth (cm)		
	0 to 30	30 to 60	60 to 90
No-tillage	2.61[a]	2.51[b]	2.16[c]
Minimum tillage	2.60[a]	2.48[b]	2.13[c]
Conventional tillage	2.22[c]	2.17[c]	2.16[c]
Subsoiling × Soil depth interaction			
Subsoiling	2.53[a]	2.19[b]	2.18[b]
No Subsoiling	2.42[b]	2.50[c]	2.49[c]
Subsoiling × Tillage system interaction	No-tillage	Minimum tillage	Conventional tillage
Subsoiling	2.30[c]	2.21[cd]	2.15[d]
No subsoiling	2.73[a]	2.55[b]	2.19[cd]

Values in the same row or column with the same letter superscripts are not significantly different α =0.05

layer were 90, 80, and 58% for no-tillage, minimum, and conventional tillage, respectively. In general, most aggregates were >2 mm and most breakdowns occurred where there was conventional tillage. The effect of tillage systems on aggregate stability following subsoiling was limited to the upper 30 cm of the stratified soil profile. Moreover, while no-tillage and minimum tillage maintained more stable aggregates than conventional tillage, the effects of conventional tillage were moderated by subsoiling.

Infiltration rates at various depths of the soil profile as affected by the tillage and subsoiling in the stratified Vitric Andosol are shown in Table 4. At 0 cm, IR was 10% lower and 26% more in the minimum and conventional tillage treatments respectively compared to that in no-tillage treatment. IR was about three times higher at 30 cm compared to IR at 60 cm depth in all three tillage systems. Subsoiling decreased IR by 25% in minimum tillage but increased IR about three-fold in the conventionally tilled plots. In general, IR was inversely related to bulk density (Table 1) and directly related to hydraulic conductivity. Furthermore, hydraulic conductivity in the 60 to 90 cm depth was lowest and hence controlled water movement in this soil profile (Table 5).

Table 4. Infiltration rates at various depths of the soil profile as affected by the tillage and subsoiling in a stratified Vitric Andosol of the Kenyan highlands.

Interactions/treatments	Infiltration rate (cm h^{-1})		
Tillage system × Soil depth interaction	Soil depth (cm)		
	0 to 30	30 to 60	60 to 90
No-Tillage	60.51[b]	79.55[a]	25.50[c]
Minimum Tillage	54.59[bc]	58.51[ab]	22.58[c]
Conventional Tillage	76.52[a]	70.40[a]	17.02[bd]
Subsoiling × Soil depth interaction			
Subsoiling	48.52[a]	51.04[a]	15.55[b]
No Subsoiling	41.52[b]	57.01[a]	16.45[cb]
Subsoiling × Tillage system interaction	No-tillage	Minimum tillage	Conventional tillage
Subsoiling	66.01[a]	18.02[b]	60.00[a]
No Subsoiling	78.02[a]	24.03[c]	18.03[cb]

Values in the same row or column with the same letter superscripts are not significantly different α =0.05

Table 5. Hydraulic conductivity at various depths of the soil profile as affected by the tillage and subsoiling in a stratified Vitric Andosol of the Kenyan highlands.

Interactions/treatments	Hydraulic conductivity (cm h^{-1})		
Tillage system × Soil depth interaction	Soil depth (cm)		
	0 to 30	30 to 60	60 to 90
No-tillage	1.59^{c}	1.70^{c}	0.45^{e}
Minimum tillage	0.73^{ab}	2.41^{a}	0.52^{e}
Conventional tillage	0.61^{d}	2.04^{b}	0.56^{e}
Subsoiling × Soil depth interaction			
Subsoiling	1.20^{c}	1.90^{b}	0.54^{e}
No subsoiling	0.79^{d}	2.19^{a}	0.48^{e}
Subsoiling × Tillage system interaction	No-tillage	Minimum tillage	Conventional tillage
Subsoiling	1.27^{a}	1.16^{a}	1.13^{a}
No subsoiling	1.22^{a}	1.30^{a}	1.21^{a}

Values in the same row or column with the same letter superscripts are not significantly different $\alpha = 0.05$

Overall, the effects of tillage systems on bulk density, SOC and aggregate stability were limited to the upper 30 cm of the Vitric Andisols of Kenya. No-tillage and minimum tillage maintained more stable aggregates than conventional tillage and the effects of conventional tillage were moderated by subsoiling. IR was inversely related to bulk density and directly related to hydraulic conductivity. Hydraulic conductivity in the 60 to 90 cm depth was lowest and hence controlled water movement in this soil profile.

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References

Abu-Hamdeh, H.N. 2003. Compaction and subsoiling effects on corn growth and soil bulk density. Soil Sci. Soc. Am. J., 67: 1213–1219.

Buysse, W., Stern, R., and Coe, R. 2004. GenStat discovery edition for everyday use. ICRAF Nairobi, Kenya, 114p.

Elliott, E.T., Palm, C.A., Reuss, D.E., and Monz, C.A. 1991. Organic matter contained in soil aggregates from a tropical chronosequence: correction for sand and light fraction. Agric. Ecosyst. Environ., 34: 443–451.

Gardner, W.R. 1958. Some steady state solutions of unsaturated moisture flow equations with application to evaporation from water table. Soil Sci. Soc. Am. J., 85: 228–232.

Ghuman, B.S. and Sur, H.S. 2001. Tillage and residue management effects on soil properties and yields of rainfed maize and wheat in a subhumid subtropical climate. Soil Till. Res., 58: 1–10.

Gomez, J.A., Geraldez, J.V., Pastor, M., and Fereres, F. 1999. Effects of tillage method on soil physical properties, infiltration and yield in an olive orchard. Soil Till. Res., 52: 167–175.

Holland, J.M. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric. Ecosyst. Environ., 103: 1–25.

Jaetzold, R., and Schmidt, H. 1983. *Farm Management Handbook of Kenya*. Vol. II. Central and Rift valley province. Ministry of Agriculture, Nairobi, 399p.

Kushwaha, C.P., Tripathi, S.K., and Singh, K.P. 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Applied Soil Ecol., 16: 229–241.

Le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. Soil Sci. J., 47: 425–437.

Lindstrom, M.J., Voorhees, W.B., and Onstad, C.A. 1984.

Tillage system and residue cover effects on infiltration in northwestern corn belt soils. J. Soil Water Conserv., 39: 64–68.

Paustian, K., Collins, H.P., and Paul, E.A. 1997. Management controls on soil carbon. In: E.A. Paul, E.A., Elliott, E.T., Paustian, K., and Cole, C.V. (eds). *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America*. CRC Press, Boca Raton, FL, pp. 15–49.

Pikul, Jr. J.L. and Aase, K.J. 2003. Water infiltration and storage affected by subsoilling and subsequent tillage. Soil Sci. Soc. Am. J., 67: 859–866.

Rowell, D.L. 1994. *Soil Science Methods and Applications*. Longman Scientific. London, 350p.

Schwartz, R.C., Evett, S.R., and Unger, P.W. 2003. Soil hydraulic properties of cropland compared with reestablished and native grassland. Geoderma, 116: 47–60.

Sillon, J.F., Richard, G. and Cousin, I. 2003. Tillage and traffic effects on soil hydraulic properties and evaporation. Geoderma 116: 29–46.

Unger, P.W. 2001. Total carbon, aggregation, bulk density, and penetration resistance of cropland and nearby grassland soils. In: Lal, R. (ed.), *Carbon Sequestration and the Greenhouse Effect*. SSSA Special Publication, vol. 57. Soil Sci. Soc. Am. Madison, WI, pp. 77–92.

Vervoort, R.W., Dabney, S.M. and Roinkens, R.M. 2001. Tillage and row position effects on water and solute infiltration characteristics. Soil Sci. Soc. Am. J., 65: 1227–1234.

Wooding, R.A. 1968. Steady infiltration from a shallow circular pond. Water Resour. Res., 4: 1259–1273.