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TECHNICAL NOTE

Soil moisture dynamics in coastal savanna soils in the tropics under different soil management practices

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Abstract Soil moisture is important for crop cultivation and its adequacy to meet crop-water requirements is determined by the degree of soil management practised and the quantity of water applied to the soil. This study investigates soil moisture dynamics on three plots: Bare (clean, weeds removed), Weedy (kept weedy), and Mulched (cleared of weeds and fully covered with grass mulch) during rainy and dry periods at the Teaching and Research Farm at the University of Cape Coast, in the coastal savanna zone of Ghana. Soil moisture dynamics under different levels of soil compaction were also studied. A Massey Ferguson tractor (MF265) was used to compact the soil at various levels by making 0, 1, 5, 9 and 13 passes. During both the rainy and the dry periods, moisture retention in the soil under bare, weedy and mulched plots increased with depth. During the rainy period, the mean soil moisture retention was in the order: Mulched > Weedy > Bare at both 0–20 cm and 20–40 cm depths. Within a 7-day period, soil moisture measurements from a day after heavy rainfall (intensity > 7 mm h^{-1}) gave mean moisture losses of 2.7, 4.1 and 3.9% for the Bare, Weedy and Mulched plots, respectively. During the dry period, however, the mean soil moisture retention was of the order: Mulched > Bare > Weedy at both 0–20 cm and 20–40 cm depths. Mean moisture loss during a 7-day dry period was 4.5, 2.9 and 3.4% for the Bare, Weedy and Mulched plots, respectively. Under different levels of soil compaction, the mean moisture retention in the soil increased from 8.3% at 0 pass to 17.8% at 13 passes within the 0–20 cm depth, whilst it decreased from 13.3 to 5.9% from 0 to 13 passes, respectively, within the 20–40 cm depth. It was realized that at less than two passes, the mean soil moisture retention within the 0–20 cm depth was less than the mean moisture retention within the 20–40 cm depth, but the converse happened for more than two passes. The study showed that mulching the soil surface helped to retain enough soil moisture during both the rainy and the dry seasons. Also, soil with high sand content required some sort of soil compaction in order to retain enough moisture at the crop rooting zone.

Key words coastal savanna; crop-water; mulch; rooting zone; soil compaction; soil management; soil moisture dynamics

Dynamiques de l'humidité du sol dans des sols de savane côtière tropicale sous différentes méthodes de gestion du sol

Résumé L'humidité du sol est importante pour l'agriculture et sa capacité à satisfaire les besoins en eau des cultures est déterminée par le degré de gestion du sol pratiqué et par la quantité d'eau fournie au sol. Cette étude traite des dynamiques d'humidité du sol de trois sites de la ferme d'enseignement et de recherche de l'Université de Cape Coast, dans la savane côtière du Ghana: Nu (nettoyé et défriché), Jachère (laissé en jachère) et Mulch (défriché et complètement couvert d'un mulch d'herbe), pendant les saisons pluvieuse et sèche. Les dynamiques de l'humidité du sol ont également été étudiées selon différents niveaux de compaction du sol. Un tracteur de la marque Massey Ferguson (MF265) a été utilisé pour compacter le sol à différents niveaux, en faisant 0, 1, 5, 9 et 13 passages. Durant les saisons pluvieuse et sèche, la rétention de l'humidité dans le sol sous les sites Nu, Jachère et Mulch augmente avec la profondeur. Durant la saison humide, la rétention moyenne d'humidité est dans l'ordre: Mulch > Jachère > Nu aux profondeurs 0–20 ainsi que 20–40 cm. Au sein d'une période de 7 jours, la mesure de l'humidité du sol à partir du lendemain de fortes précipitations (intensité > 7mm h^{-1}) montre une perte d'humidité de 2.7, 4.1 et 3.9% respectivement pour les sites Nu, Jachère et Mulch. Cependant, durant la saison sèche, la rétention moyenne de l'humidité du sol est dans l'ordre: Mulch > Nu > Jachère aux profondeurs 0–20 ainsi que 20–40 cm. Sur une période de 7 jours sans pluie, la perte d'humidité moyenne est de 4.5, 2.9 et 3.4% pour les sites Mulch, Nu et Jachère. Sous différents niveaux de compaction du sol, la rétention moyenne de l'humidité augmente de 8.3 à 17.8% entre 0 et 13 passages, pour la profondeur 0–20 cm, tandis qu'elle diminue de 13.3 à 5.9% entre 0 et 13 passages, pour la profondeur 20–40 cm. Il est apparu que, pour moins de deux passages, la rétention moyenne de

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l'humidité du sol de la profondeur 0–20 cm est inférieure à celle de la profondeur 20–40 cm, mais que le contraire est apparu pour plus de deux passages. L'étude montre que l'application du mulch sur la surface du sol aide à retenir suffisamment d'humidité du sol pendant les deux saisons, pluvieuse et sèche. De plus, le sol à forte teneur en sable nécessite une certaine compaction pour retenir suffisamment d'humidité dans la zone racinaire.

Mots clefs savane côtière; culture-eau; mulch; zone racinaire; compaction du sol; gestion du sol; dynamiques d'humidité du sol

INTRODUCTION

Soil moisture is important for plant growth because it is a reactant in photosynthesis, acts as a solvent for plant nutrients and a medium for the moderation of temperature in plants and in soils. It also helps in the movement of assimilates to all parts of the plant, controls soil aeration and provides a good medium for microbial activities in the soil (Yayock *et al*., 1988). The major source of water for crop production, especially in developing countries where irrigation is inadequate, is rainfall. The effective rainfall depends on the quantity of the rain and the rate at which water is removed from the soil through runoff, deep percolation or drainage, and the evaporation from the soil surface (Fitzpatrick, 1986; Wallace, 1991). Evaporation of water from the soil surface and transpiration by plants are the major means through which water is lost from the soil, especially in hot and dry regions (FAO, 1998). According to Wild (1993), transpiration is a physiological process of the crop and, hence, farmers have little control over it to conserve soil moisture; however, evaporation is a physical process and therefore could be minimized by good soil management practices.

Soil moisture and its loss through evaporation from the soil surface are of paramount importance in dry areas where availability of water is a limitation to agriculture. According to Wallace (1991), soil moisture loss through evaporation could amount to about 30% of the total loss of rainfall in semiarid areas. Therefore, soil evaporation could be an important factor of the hydrological cycle in the tropics. Youdeowei *et al*. (1986) noted that the amount of moisture a soil could lose through evaporation depends not only on the evaporative power of the air, but also on the size and distribution of soil pores, and on the amount of water the surface could hold against drainage. Thus any form of soil cover could help reduce soil evaporation. Fryrear (1985) recommended the use of crop residue or other materials as mulch on croplands to reduce evaporation.

People's desire and eagerness to search for easier ways of tilling the land to meet the ever-increasing population demand for food, has resulted in the adoption of tractors and other heavy implements for tillage (Brady & Weil, 1996). This has accelerated soil compaction, which was not the case during the earlier times when locally made tools were used to till the land (Blay, 1994). Ankeny *et al*. (1990) noted that, by passing over the field frequently with tractors and other equipment during tillage, both surface and subsurface compactions were created, which seemed to be the major causes of poor infiltration in most mechanized farms. Blay (1994) also observed that tillage by the use of machinery could cause soil compaction resulting in changes in soil hydrological properties. According to Cassel (1982), soil compaction initiates the redistribution of pore size within the soil matrix because large pores are destroyed and small pores generated, leading to an increase in bulk density and a decrease in available soil moisture. Blay (1994) observed that soil compaction has both desirable and undesirable effects on plant growth, development and yield. It was suggested that soil compaction could promote good contact between the seed and the soil, which would speed up the rate of seed germination. In addition, compaction could reduce loss of soil moisture due to evaporation and, therefore, prevent soil around the growing seed from drying out, especially in coarse and medium textured soils. However, soil compaction could impede root growth, thereby limiting the amount of soil explored by the roots (Blay, 1994). Onwuala & Anazodo (1989) observed a decrease in the yield by 7.5% over a two-year period on the use of 4-tonne axle and 6-tonne axle loads on sandy loam soil prior to maize cultivation, since the soil compaction increased even though mean seasonal rainfall was about 525 mm. However, according to these authors, when the rainfall was low, about 350 mm, the maize yield increased, but then decreased as compaction was further increased. Therefore, they concluded that, under dry conditions, moderate compaction was beneficial but too much compaction could affect crop yield, whilst under wet conditions, any amount of compaction could decrease yield. Kayombo & Lal (1986) reported that treatment of a plot by four passes of a 2-tonne roller reduced plant emergence, plant height, leaf area index, root growth and yield of maize more than on untilled plots in three consecutive growing seasons on Alfisol in southwestern Nigeria. However, Onwuala & Anazodo (1989) observed that medium tractor-wheel compaction during mechanized tillage increased emergence and yield of maize on a sandy soil.

The rainfall regime in Ghana is seasonal, unreliable, and erratic and, in most instances, not sufficient for crop water requirement. Also, the soils for crop production in the coastal savanna zone are mostly coarse and medium textured. In the majority of cases, the land is made bare, or allowed to grow weeds especially during the dry season, or mulch is applied; most of the time, tractors are used in land preparation for maize production. However, there is insufficient evidence of the effect of these soil management practices on soil moisture content. There is therefore a need to accumulate knowledge in this area in order to work toward conserving moisture in the soil for crop use. The objectives of this study were to investigate: (a) the effects of different cultural practices—Bare plot, Weedy plot and Mulched plot—on soil moisture retention; and (b) the effects of different passes of a tractor on soil compaction, as measured by soil moisture retention.

MATERIALS AND METHODS

The study was conducted at the University of Cape Coast Research Farm within the coastal savanna zone in the central region of Ghana. The site is located at 1°15′W and 5°7′N. The soils are deep, yellowish red to yellowish brown, well- to moderately well-drained alluvial clays with pH between 5.6 and 6.5 (Asamoah, 1973). The soils belong to the Benya series and could be classified as Acrisol (FAO) and Ultisol (USDA). The site has an average annual rainfall of about 920 mm with bi-modal rainy seasons. The long rainy season runs from March to July with maximum rainfall in June, and the short rainy season is from September to November. Temperatures are generally high throughout the year, with mean annual minimum of about 24°C and the maximum of about 30.5°C. Relative humidity is high—between 90 and 99% at night, dropping to 70% in the afternoons (Asare, 2005). Lower relative humidity is usually recorded between December and February, when the dry harmattan winds from the Sahara Desert are experienced across the entire country. However, relative humidity does not fall below 60% during this period because of the sea influence (Asare, 2005). The site has been under continuous cultivation for over 15 years and is only allowed to lie fallow during the main dry season. The vegetation is grass interspersed with shrubs and, at times, crop residues of maize cultivated during the previous crop season.

A Completely Random Design (CRD) was used for the study with different cultural practices as treatments. A total area of about 0.05 ha was demarcated into three different plots and each plot subdivided into three with dimensions of 12 m × 4 m as replicates. The three cultural practices used were: clean, weeds-removed plot (Bare plot), plot kept weedy (Weedy plot), and plot cleared and the plot surface mulched (Mulched plot). The site was allowed to lie fallow for a year before the study was conducted. Two types of core soil samples were randomly collected from six points on each plot within depths of 0–20 cm and 20–40 cm. One type was collected during the rainy period (wet season) on five different heavy rainy days. Further such samples were collected a day after it had rained—to allow gravitational drainage to complete—and the samples were collected at 2-day intervals thereafter on four consecutive occasions. Rainfall was considered heavy when its intensity was more than 7.5 mm h^{-1} (Gupta & Gupta, 1992). The other type of soil samples was collected during the dry period (Dry season) when there was no rainfall or the rainfall intensity was less than 1 mm h^{-1}. Rainfall information was collected from the Department of Geography (DoG) Weather Station, about 300 m from the study site. The samples were collected in the same manner and the same number of times as for the rainy period. Disturbed soil samples were also taken for particle-size distribution analysis.

For the different levels of compaction, Completely Random Design (CRD) was again used on a total of about 0.06 ha of land at the same site. The whole plot was ploughed, harrowed and watered. Disturbed and core soil samples were first collected randomly at 0–20 cm and 20–40 cm depths to serve as data for control. The land was then divided into four plots, each measuring 12 m × 4 m and each replicated three times. A Massey Ferguson (MF 265) farm tractor weighing 2540 kg was used to compact the soil. The operator of the tractor weighed 120 kg. Each of the plots was compacted differently by the number of tractor passes, being: 1, 5, 9 and 13. The plots were then watered and another set of core soil samples was randomly collected from each plot at 0–20 cm and 20–40 cm depths.

The disturbed soil samples from each depth were bulked into a composite sample. Composite sampling was done in quadruple. Each composite was mixed thoroughly, air dried till free from moisture, and sieved through a 2-mm mesh. The fine earth was used for particle-size distribution analysis using the hydrometer method, as described by Gee & Bauder (1986). The core soil samples were used for the analysis of soil moisture content and soil bulk density. The soil moisture content was determined by the gravimetric method, as described by Hillel (1980). The soil bulk density was determined by the core method, as outlined by Blake & Hartge (1986).

RESULTS AND DISCUSSION

Table 1 shows the particle-size distribution and bulk density of the soil at the study site. The textural class of the soil within both 20 and 40 cm depths was sandy loam.

Table 1 Particle-size distribution and bulk density of soils from the study site.

Depth (cm)	Parameters*	Sand (%)	Silt (%)	Clay (%)	Bulk density (gcm^{-3})	Textural class
0–20	Mean	75.5	10.1	14.4	1.58	Sandy loam
	SD	1.7	0.6	0.6	0.07	
	CV	2.1	5.7	3.8	4.43	
	SE	0.7	0.3	0.3	0.03	
20–40	Mean	76.3	7.5	16.2	1.61	Sandy loam
	SD	0.8	0.3	0.6	0.03	
	CV	1.0	3.7	3.6	1.86	
	SE	0.3	0.1	0.3	0.01	

SD: standard deviation; CV: coefficient of variation; SE: standard error.

Both the sand and clay contents increased with depth while the silt content decreased, though the differences were very marginal. The sand content was very high, ranging from 75 to 76%, while the silt ranged from 7 to 10% and the clay from 14 to 16%, as shown in Table 1. This indicated that the soil could be very porous and therefore required some soil management practices to retain adequate moisture for crop use. The bulk density at 0–20 and 20–40 cm depths was 1.59 and 1.61 g cm^{-3}, respectively (Table 1). The low value of the bulk density reflected the sandy nature of the soil.

Figures 1 and 2 show the mean moisture retention in the soil under different cultural practices. Both figures indicate that the mean soil moisture retention increased with depth in all seasons. This could be attributed to exfiltration as a result of evaporation from the soil surface and evapotranspiration from live weeds on the plots, and also the easy downward flow of moisture from the upper layer to the lower layer due to the sandy nature of the soil. In both rainy and dry periods, the Mulched plot retained significant (p = 0.05) moisture compared to the Bare and Weedy plots at all the depths (Figs 1 and 2). This confirmed the observation made by Jalota (1993) and reported in IPCC (1998) that surface mulch shields the soil surface from the influence of atmospheric evaporativity caused by high solar radiation, high temperatures and high wind speed and enhances the reduction in soil moisture loss through evaporation.

Figure 1(a) and (b) shows the trend of mean soil moisture content under Bare, Weedy and Mulched plots at 0–20 cm and 20–40 cm, respectively, during the rainy period. Within the top 20 cm of soil, the Mulched plot lost 2.7% moisture (SD: 0.7–1.4%, CV: 3.0–7.2%) whilst the Bare plot lost 4.1% moisture (SD: 1.0–2.3%, CV: 8.5–10%) the Weedy plot lost 3.9% moisture (SD: 1.0–2.5%, CV: 5.0–7.6%) seven days after gravitational drainage (Fig. 1(a)). The higher moisture loss from the Bare and Weedy plots could be due to excessive evaporation and evapotranspiration, respectively, owing to the wider surface exposure of the Bare plot to the atmosphere and to excess water intake by the weeds on the Weedy plot where rooting depths were within the upper 20 cm soil layer. Within the same seven days, the mean soil moisture lost within 40 cm depth was: Mulched plot: 1.6% (SD: 1.2–3.5%, CV: 4.0–6.3%); Bare plot: 4.0% (SD: 0.8–1.4%, CV: 4.0–6.4%); and Weedy plot: 4.0% (SD: 1.4–2.7%, CV: 5.0–6.8%) (Fig. 1(b)). This trend of moisture loss could be due to the top soil layer under the Mulched having higher moisture retention, requiring smaller moisture replacement from the sub-layers to meet the evaporative demands of the atmosphere,

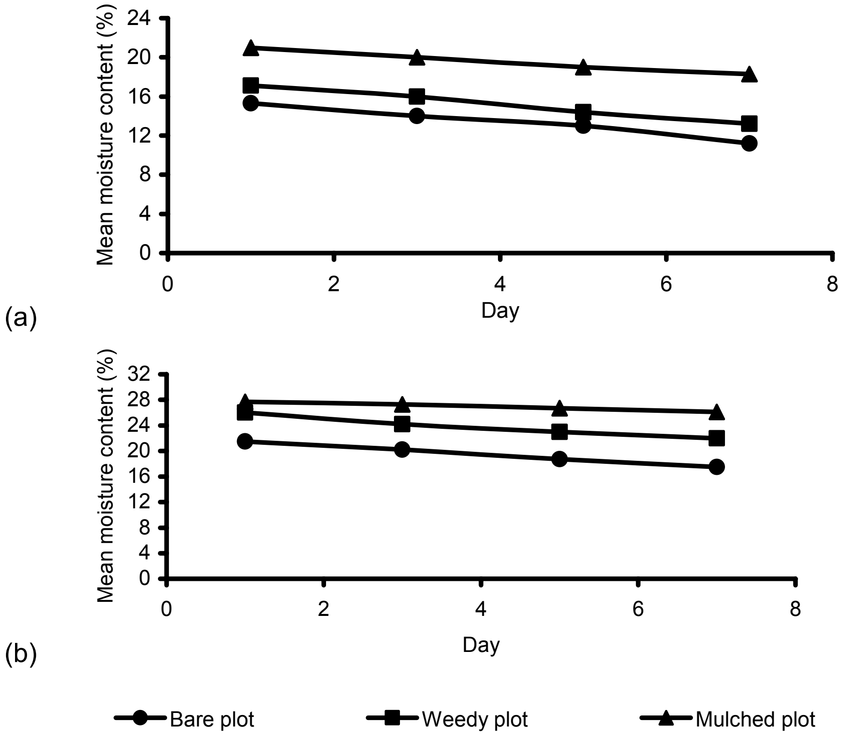

Fig. 1 Soil moisture dynamics on different plot within (a) 0–20 cm depth and (b) 20–40 cm depth during the rainy period.

whilst the top layers of the Bare and the Weedy plots required higher moisture replacement from their respective sub-layers due to their low moisture retention.

Figure 2 (a) and (b) also shows the trend of mean soil moisture content of the three cultural practices at 0–20 cm and 20–40 cm depths, respectively, during the dry period. At all depths, the Mulched plot again retained more mean soil moisture than the other plots. However, in contrast to the trend of the mean soil moisture retention during the rainy period, where the Weedy plot had higher mean moisture retention at all times and depths than the Bare plot (Fig. 1), during the dry period, there was no significant (p = 0.05) difference in the mean soil moisture retention on both Bare and Weedy plots at all times and depths. This converse trend could be that, during dry periods, the limited availability of moisture in the dry layer on the Bare plot surface exerted a controlling influence (soil mulch) on the soil evaporation, thereby causing the evaporation to drastically decrease or even cease (Bonsu, 1997; FAO, 1998). The water stress on the Weedy plot would also have forced the weeds to reduce photosynthesis and transpiration (Bonan, 2002), but to almost the same magnitude as the evaporation. The Mulched plot had mean soil moisture content dropping from 12.1 to 7.6% (SD: 0.2–0.8%, CV: 1.7–3.5%) at 0–20 cm depth and from 16.5 to 12.6% (SD: 0.4–1.5%, CV: 3.0–4.2%) at 20–40 cm depth within seven days, whilst that in the Bare plot dropped from 9.5 to 6.1% (SD: 0.4–0.9%, CV: 6.6–9.5%) and from 10.6 to 8.6% (SD: 0.5–0.7%, CV: 5.8–7.6%) at 0–20 and 20–40 cm depths, respectively, within the same period. Mean soil moisture content in the Weedy plot dropped from 8.3 to 5.4% (SD: 0.5–2.6%, CV: 6.0–11.1%) and from 10.3 to 8.0% (SD: 0.5–1.7%, CV: 4.9–7.5%) at 0–20 and 20–40 cm depths, respectively, within the same 7-day period (Fig. 2). The higher

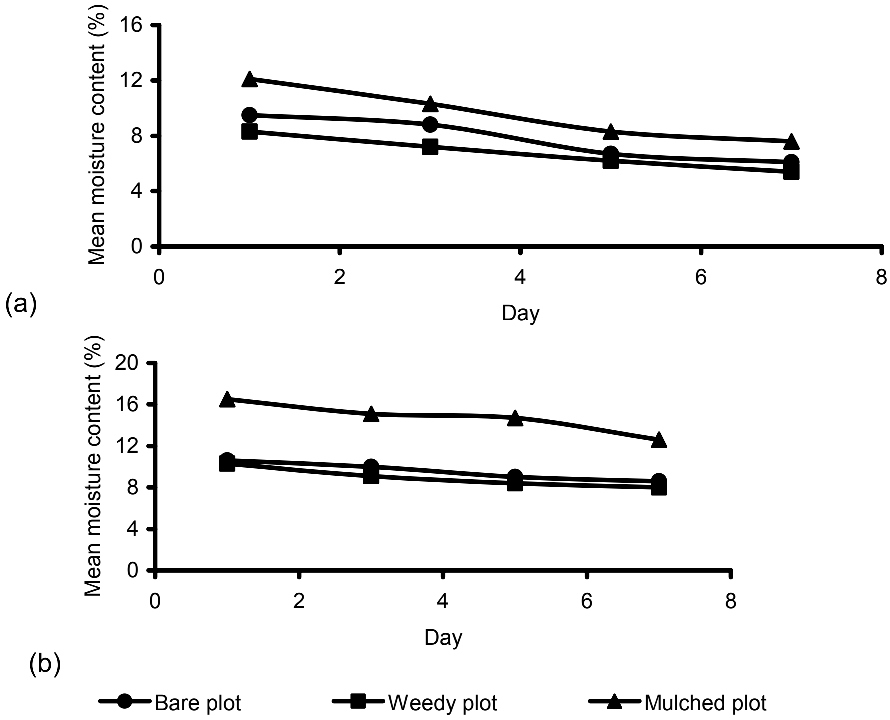

Fig. 2 Soil moisture dynamics on different plots within (a) 0–20 cm depth and (b) 20–40 cm depth during the dry period.

moisture loss of 4.5% from the Mulched plot indicated that the plot had sufficient moisture to be released to meet atmospheric evaporative demands during the dry period. This confirms an observation by Enz *et al.* (1988) that, depending on the time of exposure of the soil, evaporation from stubble mulched soil could be greater than that from bare soil. It was realized that the subsurface soil moisture drop of 3.9% from the Mulched plot was also higher than those of 2.0% and 2.3% from Bare and Weedy plots, respectively. This could be due to the subsurface layer under the Mulched plot having a larger quantity of soil moisture, thus enabling it to release moisture to the surface layer to meet the excess evaporative demands of the atmosphere during the dry season.

Figure 3 shows the trend of soil moisture content under different levels of soil compaction. Within the 0–20 cm depth, the soil moisture content increased as the number of passes increased. With 0 passes, soil moisture content was the lowest at 8.3%, while 13 passes resulted in the highest soil moisture content at 17.8%, followed by 9, 5 and 1 pass(es) with soil moisture contents of 15.8, 14.0 and 12.3%, respectively (Fig. 3). At 20–40 cm depth, however, the soil moisture content decreased with increase in the number of passes, with 0 passes having the highest moisture content of 13.3%, while 13 passes had the least (5.9%) (Fig. 3). The sharp differences in trends of soil moisture content at the two depths indicated an increase in compaction at the upper layer as the number of passes increased. Compacting the soil reduced its macropores to micropores and, consequently, prevented moisture redistribution to the soil layer below; therefore, moisture was likely to have accumulated in the surface layer instead of being redistributed to the subsurface layer. It could be said that the ability of the soil to impede downward moisture flow within the top layers increased as the level

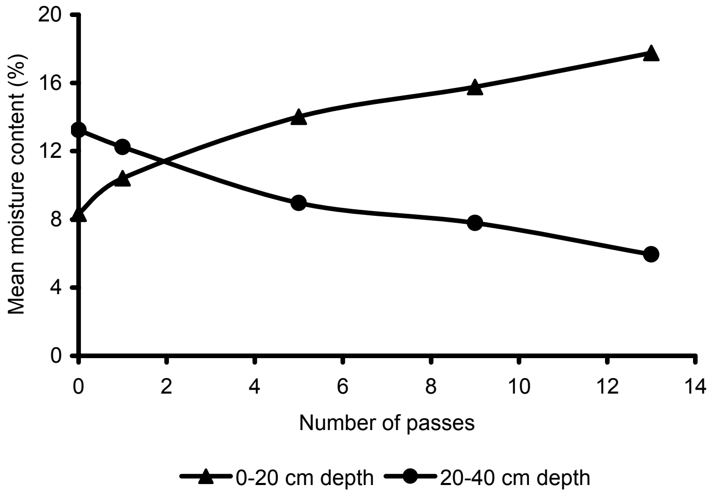

Fig. 3 Soil moisture pattern under different number of tractor passes.

of compaction increased. From Fig. 3, it was observed that, between 0 and 2 passes the moisture was higher at the 20–40 cm depth than at the 0–20 cm depth. This could be explained by the fact that, at fewer than two passes, the compaction in the upper layer was not enough, considering the sandy nature of the soil, to decrease the moisture redistribution or impede the downward moisture flow from the upper layer to the lower layer. This, coupled with higher evaporation usually occurring at the soil surface compared to the lower layer, could account for the higher moisture content at 20–40 cm depth.

CONCLUSION

During both the rainy and dry periods, the Mulched plot retained higher moisture than Weedy and Bare plots, even though the Mulched plot lost more moisture to the atmosphere during the dry period. This indicated that mulching could help the soil to meet the evaporative demand of the atmosphere and was able to retain relatively higher moisture in the soil. The Weedy plot retained more moisture than the Bare plot during the rainy period, yet both plots retained almost the same moisture during the dry period. This therefore showed that, within the context of the period of study, whether a plot is left weedy or bare, almost the same moisture could be conserved in the soil during dry periods. In the tropics where soil moisture loss through evaporation and evapotranspiration could be very serious, the use of dead mulch could help as means of conserving soil moisture to meet crop water needs. Farmers could therefore leave crop residues after harvesting, as well as cleared weeds, on their fields to serve as mulch in order to retain moisture for crop use, especially during dry periods.

The study again showed that soils with high sand content had less soil moisture retention in the upper 20 cm layer than in the lower 20 cm layer. However, as the level of soil-surface compaction increased, the soil moisture retention in the upper 20-cm layer increased. It can therefore be concluded that, for soils with high sand content to retain moisture for crop use, there should be some level of soil compaction, such as allowing tractor or vehicular movement over the soil surface.

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REFERENCES

Ankeny, M. A., Kaspar, T. C. & Houtor, R (1990) Characterization of tillage and traffic on unconfined infiltration measurements. *Soil Sci. Soc Am. J.* **54**, 810–837.

Asamoah, G. K. (1973) Soils of the proposed farm site of the Univ. of Cape Coast. Soil Research Inst. Tech Report no. 88, Univ. of Cape Coast, Ghana.

Asare, M. (2005) *Effect of Climatic Change on Food Production in some districts in the Central Region.* BSc Dissertation, Dept of Soil Sci., Univ. of Cape Coast, Ghana.

Blake, G. R. & Hartge, K. H. (1986) Bulk density. In: *Methods of Soil Analysis*, Part 1 (ed. by A. Klute), 363–375. Second edn. Agro. Ser. no. 9, Am. Soc. of Agron. Inc. & Soil Sci. Soc. Am. Inc., Madison, Wisconsin, USA.

Blay, K. (1994) Soil compaction by the farm tractor. BSc Dissertation. Dept of Soil Sci., Univ. of Cape Coast, Ghana..

Bonan, G. (2002) *Ecological Climatology – Concepts and Applications*. Cambridge University Press, Cambridge, UK

Bonsu, M. (1997) Soil water management implications during the constant rate and falling rate stages of soil evaporation. *Agric. Water Manage*. **33**, 87–97.

Brady, N. C. & Weil, R. R. (1996) *The Nature and Properties of Soil*. 11th edn. Macmillan Publishing Co., New York, USA.

Cassel, D. K. (1982) Tillage effect on soil bulk density and mechanical impedence. In: *Prediction Tillage Effect on Soil* (ed. By D. W. Unger & K. M. Van Doren), 45–67. ASA Spec. Publ. 44, ASA and SSSA, Madison, Wisconsin, USA.

Enz, J. W., Brum, L. J. & Larsen, J. K. (1988) Evaporation and energy balance for bare and stubble covered soils. *Agric. For. Met*. **43**, 59–70.

FAO (1998) Crop evaporation – Guidelines for computing crop water requirements. *FAO Irrigation and Drainage paper 56.*

Fitzpatrick, E. A. (1986) *Introduction to Soil Science*. Second edn. Longman Group Ltd., London, UK.

Fryrear, D. W. (1985) Soil cover and wind erosion. *Trans. Am. Soc. Agric. Engrs* **28**(3), 781–784.

Gee, G. W. & Bauder, J. W. (1986) Particle size analysis. In: *Methods of Soil Analysis,* Part 1 (ed. by A. Klute), 383–411, Second edn, Agro. Ser. no. 9, Am. Soc. of Agron. Inc. & Soil Sci. Soc. Am. Inc., Madison, Wisconsin, USA

Gupta, B. L. & Gupta, A. (1992) *Engineering Hydrology,* second edn. Standard Publishers Distributors. 1705-B. Nai Sarak, Delhi, India.

Hillel, D. (1980) *Fundamentals of Soil Physics.* Academic Press Inc, San Diego. California, USA.

IPCC (Intergovernmental Panel on Climate Change) (1998) *The Regional Impacts of Climate Change: An Assessment of Vulnerability.* IPCC Special Report. Cambridge University Press, Cambridge, UK.

Jalota, S. K. (1993) Evaporation through soil mulch in relation to mulch characteristics and evaporativity. *Aust. J. Soil Res.* **31**, 131–136.

Kayombo, B. & Lal, R. (1986) Effects of soil compaction by rolling on soil structure and development in no-till and dicing system on tropical Alfisol. *Soil and Tillage Res.* **17**, 117–134.

Onwuala, A. P. & Anazodo, U. G. N. (1989) Soil compaction effects on maize production under various tillage methods in a derived savanna zone of Nigeria. *Soil and Tillage Res.* **14(2)**, 99–114.

Wallace, J. S. (1991) The management and modelling of evaporation from semiarid land. In: *Soil Water Balance in the Sudano-Sahelian Zone* (ed. by M. V. K. Sivakumar, J. S. Wallace, C. Renard & G. Giroux), 131–148. IAHS Publ. 199. IAHS Press, Wallingford, UK.

Wild, A. (1993) *Soil and Environment, An Introduction*. Cambridge Univ. Press, UK.

Yayock, J. Y., Lombin, G. & Owonubi, J. J. (1988) *Crop Science and Production in Warm Climates.* Macmillan Intermediate Agric. Series. Macmillan Publishers.

Youdeowei, A., Ezedinma, F. O. C. & Onazi, O. C. (1986) *Introduction to Tropical Agriculture.* Longman Group Ltd. Harlow, UK.

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