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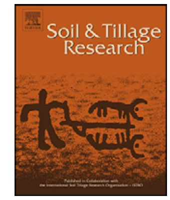

Effect of deep ploughing on the water status of highly and less compacted soils for coconut (*Cocos nucifera* L.) production in Sri Lanka

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ABSTRACT

Soil compaction limits soil water availability which adversely affects coconut production in Sri Lanka. Field experiments were conducted in coconut (*Cocos nucifera* L.) plantations with highly and less compacted soils in the intermediate climatic zone of Sri Lanka. Soil physical properties of sixteen major soil series planted with coconut were evaluated to select the most suitable soil series to investigate the effect of deep ploughing on soil water conservation. Soil compaction and soil water retention with respect to deep ploughing were monitored during the dry and rainy seasons using cone penetrometer and neutron scattering techniques, respectively. Evaluation of soil physical properties showed that the range of mean values of bulk density (BD) and soil penetration resistance (SPR) in the surface soil (0–10 cm depth) of major soil series in coconut lands was from 1.38 ± 0.02 to 1.57 ± 0.07 g/cm^3 and 55 ± 10 to 315 ± 16.4 N/cm^2 respectively. The total available water fraction increased with clay content of soil as a result of high micropores. However, due to soil compaction, ability of soils to conserve water and to remain aerated was low for those series. Deep ploughing during the rainy and dry periods in highly compacted soils (BD > 1.5 g/cm^3 and SPR > 250 N/cm^2) greatly increased conserved soil water in the profile, while in less compacted soils (BD < 1.5 g/cm^3 and SPR < 250 N/cm^2) conserved water content was adversely affected. Soil water retention in bare soils of both highly and less compacted soil series was higher than that of live grass-covered soil. Amount of water conserved in ploughed Andigama series with respect to bare soils and grass-covered treatments during the severe dry period was 10.4 and 16.9 cm/m, while water storage reduction in the same treatments with ploughed Madampe series was 6.55 and 5.45 cm/m respectively. In addition, deep ploughing even in the effective root zone with live grass-covered highly compacted soils around coconut tree was favorable for soil water retention compared to that of live grass-covered less compacted soils.

1. Introduction

Coconut (*Cocos nucifera* L.) is one of the major plantation crops in Sri Lanka, which covers about 416,000 ha being found on several different soil types with diverse moisture regimes. Amongst soil constraints, soil physical limitations including water deficiency of soils are known to be key factors adversely affecting the physiological and morphological adaptation of coconut roots (Vidhana Arachchi et al., 2000).

Compaction of soil is common in agricultural regions throughout the world and farmers are making progress in dealing with the problem. Soil water deficiency can occur due to low precipitation, while soil compaction could induce low soil water retention due to blocking of capillary fringes (Boone and Veen, 1994) and low infiltration, causing reductions in both crop growth and yield (Rawitz et al., 1983; Boone and Veen, 1994). Compaction may also decrease soil physical fertility through decreasing storage and supply of water and nutrient, which may lead to additional fertilizer requirement and increasing production cost (Hamza and Anderson, 2005). Therefore, deep ploughing in highly compacted soils of Sri Lanka, specially within the Red Yellow Podzolic and Red Yellow Latosols (USDA classification), is one of the options to alleviate soil compaction and enhance water infiltration, increase soil water retention and deep root penetration in drought susceptible crop-lands. Moreover, Tsimba et al. (1999) reported that deep ploughing in soils having bulk density (BD) greater than 1.6 g/cm^3 promoted nutrient and water absorption in the root zone of crops. Although the deep ploughing of sandy loam soils every 2 years was useful, the benefit was reported to be higher when deep ploughing is practiced at four yearly intervals in cotton (*Gossypium hirsutum* L.) cultivation (Arif et al., 2004). Deep ploughing on poorly drained, heavy clay soil promoted deep root penetration, but research studies on the water status of soil profile from deep ploughing are scarce (Chen et al., 2005).

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In addition, the aeration status of soils plays a major role in the growth and activity of coconut roots (Vidhana Arachchi and Somasiri, 1997) and surface ploughing is often practiced in coconut plantations in Sri Lanka on less compacted poorly drained soil, to increase aeration. Excess water in poorly drained soils belonging to Sandy Regosols is a limiting condition for the movement of air through the soil, resulting in reduction of crop growth, directly by impairing root function and indirectly by restricting the availability of plant nutrients due to washing out nutrient through runoff and deep percolation of water (Boone and Veen, 1994; Soane and Van Ouwerkerk, 1994; Gerad et al., 1982). Yavuzcan et al. (2005) reported that deep ploughing in a typical Bavarian soil (Regosol) in Germany, further increased soil compaction and resulted in an increase bulk density and soil strength, and decreased porosity and saturated hydraulic conductivity due to reduction of pore volume with respect to heavy weight of machinery during land preparation. Coconut (*C. nucifera* L.) roots in poorly drained soils tend to proliferate and limit their distribution to top soil layers, resulting root mat formation. However, during the dry period, those surface roots are exposed to heat damage and become inactive for nutrient and water absorption. Excess water in the root zone has a negative impact on root activity by restricting gas exchange in and out of the soil. This keeps spring soil temperature low, forcing new roots to grow just below or even on the soil surface, making the root system more susceptible to attack by soil pathogens and contributing to the well established problem of tree leaning (Fuller, 1999). Moreover, soil drying and compaction have large species-specific effects on the distribution, growth and physiology of roots. Both soil drying and compaction significantly simulated the accumulation of root abscisic acid (Liang et al., 1999). Therefore, coconut farmers in Sri Lanka attempt to harrow/plough these types of lands to cut inactive roots in order to induce new root formation for nutrient and water absorption during rainy seasons (Vidhana Arachchi and Somasiri, 1997).

However, farmers presently misuse these soil management practices without adequate knowledge of their land characteristics specially based on the degree of soil compaction, existing with clay and gravel and, as consequence; these practices may adversely affect the soil water status of their lands. Moreover, deep ploughing could damage to naturally developed pore structure of less compacted soil, thereby low water retention. Therefore, deep ploughing needs to be undertaken with respect to the land characteristics, in order to fulfill the objectives of increasing soil water retention and activate crop root growth. The objective of this study was to evaluate the soil water status of less and highly compacted lands, with respect to deep ploughing.

2. Materials and methods

2.1. Experimental sites and treatments

Based on the visual characteristics of soil profiles and coconut yield, sixteen major soil series in Sri Lanka were classified into low and high productivity soils (Somasiri et al., 1994). Coconut production was mainly limited by high compaction and unfavorable soil water status (Vidhana Arachchi, 1998). Surface (0–10 cm depth) soil physical properties of sixteen major soil series were initially evaluated (Table 1) and based on the results of soil physical characteristics, highly compacted Andigama series from low productivity soil and less compacted Madampe series from high productive soils were selected to evaluate the effect of deep ploughing on soil water status.

Field experiments were therefore conducted for two soil series namely, Andigama and Madampe series. The field experiment conducted in Andigama series was located at Rathmalagara Estate, Madampe in the Low Country (08°02N, 79°E; 35 m altitude) Intermediate climate zone (the annual rainfall and ambient temperature were 1660 mm and 23.8–30.4 °C) of Sri Lanka. Madampe series (light-textured high productive soil) was located in Bandirippuwa Estate, Lunuwila in the low country Intermediate climate zone (08°02N, 79°E, 35 m altitude). Andigama and Madampe soil series belong to the great soil groups Red Yellow Podsolic (Rhodudults/Tropudults; USDA classification) and Latosols and Regosols on old Red and Yellow Sands (Quartzipsamments; USDA classification), respectively.

The coconut plantations at both experimental sites were 45 years old and planted at each corner of square systems (7.7 m × 7.7 m) with a density of 137 trees/ha. The square planting system is generally recommended for monoculture coconut plantations and mid position of the square planting system was named as the centre of square. Grass (*Brachiaria milliformis*) cover was maintained throughout the plantation. Soils of both Andigama and Madampe series at the center square of coconut plants (5 m × 5 m area) and around the base of coconut palm covering 1.75 m radius (effective root zone of coconut) were deeply

Table 1
Soil physical properties in surface of major soil series of coconut lands in Sri Lanka.

Soil series	Bulk density (g/cm^3)	Penetrometer resistance (N/cm^2)	Total available water (vol.%)	Macropores (%)	Micropores (%)	Sand (%)	Silt (%)	Clay (%)
Andigama	1.55 ± 0.08	300 ± 18.5	9.05 ± 1.23	26.40 ± 2.65	15.20 ± 2.45	80.85 ± 6.21	4.80 ± 1.13	14.32 ± 2.13
Kuliyapitiya	1.51 ± 0.06	280 ± 13.3	9.60 ± 1.65	27.21 ± 3.45	16.72 ± 3.12	78.12 ± 4.55	7.76 ± 2.31	14.12 ± 2.44
Kurunagala	1.52 ± 0.07	285 ± 15.7	9.45 ± 1.22	27.88 ± 4.31	16.11 ± 2.76	77.23 ± 3.56	8.21 ± 1.76	13.98 ± 1.99
Boralu	1.57 ± 0.07	315 ± 16.4	8.05 ± 0.98	28.34 ± 3.15	12.67 ± 2.46	80.97 ± 5.76	5.54 ± 2.11	13.34 ± 3.45
Madampe	1.48 ± 0.02	240 ± 16.3	5.71 ± 0.89	34.40 ± 3.21	9.80 ± 1.23	86.10 ± 5.43	2.68 ± 0.97	10.80 ± 2.63
Rathupasa	1.49 ± 0.03	248 ± 12.6	7.54 ± 0.98	32.67 ± 3.34	11.12 ± 0.96	84.54 ± 3.42	3.21 ± 0.67	11.98 ± 3.12
Katunayake	1.43 ± 0.02	225 ± 8.5	5.23 ± 0.87	38.12 ± 2.34	8.90 ± 1.20	88.45 ± 3.21	4.12 ± 0.23	9.87 ± 3.56
Pallama	1.48 ± 0.02	245 ± 10.2	7.89 ± 1.21	33.60 ± 3.70	10.24 ± 3.40	83.70 ± 4.23	4.45 ± 2.10	12.67 ± 2.45
Wariyapola	1.52 ± 0.03	275 ± 14.4	10.00 ± 1.42	25.32 ± 4.65	17.12 ± 3.33	76.12 ± 4.56	10.12 ± 2.10	13.76 ± 3.23
Melsiripura	1.49 ± 0.02	245 ± 16.5	8.92 ± 1.02	31.01 ± 2.10	12.96 ± 1.66	82.67 ± 3.24	5.43 ± 1.65	12.56 ± 2.11
Gambura	1.48 ± 0.01	248 ± 8.5	7.11 ± 1.54	32.10 ± 2.31	11.34 ± 1.32	83.70 ± 2.24	4.88 ± 1.99	12.11 ± 1.99
Wilpattu	1.52 ± 0.05	275 ± 12.2	9.97 ± 0.98	26.21 ± 1.23	16.18 ± 2.45	77.31 ± 4.65	10.21 ± 1.23	12.48 ± 2.12
Mavillu	1.48 ± 0.03	248 ± 8.5	7.23 ± 0.34	33.13 ± 0.98	12.88 ± 1.55	82.73 ± 3.65	4.32 ± 1.65	13.01 ± 2.66
Borupan	1.47 ± 0.01	245 ± 15.0	7.76 ±± 1.20	33.90 ± 2.70	10.90 ± 1.33	83.10 ± 4.31	2.98 ± 0.96	13.13 ± 2.34
Welikatiya	1.38 ± 0.02	55 ± 10.0	1.38 ± 1.01	41.93 ± 2.54	6.82 ± 0.98	96.78 ± 2.43	1.98 ± 0.45	1.55 ± 0.45
Sudu	1.41 ± 0.02	60 ± 15.6	1.41 ± 0.32	40.12 ± 5.66	7.52 ± 1.33	96.12 ± 2.21	2.21 ± 0.98	1.67 ± 0.76
LSD ($p < 0.05$)	0.16	30.8	2.5	5.1	2.2	6.5	2.1	2.8

±SD; $n = 10$.

ploughed (up to 30 cm depth) 2 days after rains using a moldboard plough connected to a 2-wheel hand tractor (5 HP; YANMAR; 9 PS, NFD9-L). The moldboard plough caused total inversion of the soil sod and relied on the digging point for penetration. Initial gravimetric moisture content at the ploughing for 30 cm depth of both Andigama and Madampe soil series were 10.6% $\pm$ 0.5 and 6.8% $\pm$ 0.8 respectively. Grass in similar locations in different plots were cleared and considered as a bare soil treatment and the plots with only grass were considered as the control treatment.

2.2. Soil physical properties

Physical properties of soils belonging to major soil series in mature coconut stands in Sri Lanka were measured (Table 1) using 10 randomly selected centers of coconut squares. Soil samples were taken from the soil surface (0–10 cm) of each series, to determine the texture, bulk density and soil water status. Undisturbed soil samples were taken for bulk density, aeration and moisture determination using steel core samplers, the dimensions of which were 7.5 cm diameter and 5 cm height for bulk density and 4.5 cm diameter and 3.5 cm height for soil moisture determination. Soils in the core sampler for moisture determination were transferred to aluminum rings (4.5 cm $\times$ 3 cm) for water retention measurements. The core samples were wrapped in polythene to prevent drying and transported to the laboratory. Undisturbed samples were saturated and water retention measurements were taken using standard pressure plate apparatus as described by Klute (1986) for determination of total available water. The gravimetric water content at each suction level was estimated and converted to the volumetric water content using the corresponding bulk densities. Total porosity was used as the volumetric water content at saturation corresponding to zero suction level. Pores which were unable to hold water at 10 kPa (diameter 0.03 mm) were designated as macropores and the rest as micropores.

The degree of soil compaction, which is a measure of resistance to root penetration, was examined using a cone penetrometer (Penetrograph STIBOKA, The Netherlands) as described by Bradford (1986). A uniform pressure was applied to the hand grips of cone penetrometer and the cone (2 cm, diameter) was pushed vertically into the ground at a constant rate of 2 cm/s. Penetrometer readings were then taken at 10 cm depth of soil profile after removing surface soil. Ten centimeter depth was considered suitable for the measurements of soil strength as Sun et al. (2006) stated that the maximum operating depth for a combined horizontal penetrometer was 20 cm of soil profile. Measurements were taken in the dry period to minimize the error that may occur due to the different antecedent soil moisture levels.

2.3. Soil water depletion

Soil moisture measurements of each treatment were taken using neutron moisture meter (Troxler, Model 4302 and Serial No. 166). Aluminum access tubes were installed in every treatment plot using a steel guide tube up to a depth of 1 m, leaving 20 mm exposed above ground level. The tubes were then sealed with rubber bungs. The neutron probe was calibrated with respect to each soil horizon of Andigama and Madampe soil series.

The soil moisture was measured during the period from January 1998 to December 1998 in ploughed and un-ploughed soil profiles near the coconut tree, in the center squares of coconut palms, bare soil, and grass-covered soils (control) of both Andigama and Madampe series. Total soil moisture fluctuation of each treatment during the experimental period was calculated following the method of Bell (1987).

2.4. Data analysis

A completely randomized design with five replicates for treatments was used and all data were analyzed using JMP Statistical Discovery Software Package (Version 3.2.2) produced by SAS Institute. Analysis of variance and the mean comparison of treatments were performed using Tukey–Kramer Honestly Significant Difference (HSD) test at different probability levels ($p < 0.05$, <0.01, and <0.001).

3. Results and discussion

3.1. Physical properties of major soil series

The range of mean values of bulk density and soil penetration resistance (SPR) in the surface soil layer (0–10 cm depth) of the major soil series in Sri Lanka coconut lands varied from 1.38 $\pm$ 0.02 to 1.57 $\pm$ 0.07 g/cm^3 and 55 $\pm$ 10 to 315 $\pm$ 16.4 N/cm^2, respectively (Table 1). When soil bulk density increased from 1.12 to 1.62 g/cm^3, root growth of *L. glutinosa* was severely affected (Liang et al., 1999). A high proportion of clay particles accumulated in the soil profile cemented with gravel particles formed hard layers in Andigama series of which bulk density was greater than 1.5 g/cm^3 and adversely affected coconut root growth (Vidhana Arachchi et al., 2000). In accordance with changes in bulk density, the SPR increased, while total air-filled porosity decreased significantly ($p < 0.05$) due to subsoil compaction (Table 1). Results also showed that total available water and volume of micropores increased significantly ($p < 0.05$) with clay content of soil. However, total available water fraction was reduced significantly ($p < 0.05$) by soil compaction (Table 1). Soil compaction often alters soil properties, resulting changes in plant available water (Gomez et al., 2002). Subsoil compaction reduced both water and nutrient use efficiencies of wheat grown in sandy clay loam soil by 38% in first year and 9% in the second year (Ishaq et al., 2001). Tillage practices used during land preparation for crop production could also induce soil compaction due to heavy load of vehicles which result in breaking of soil structure and reducing macropores volume (Tsimba et al., 1999; Defossez et al., 2003). Highly compacted coconut soils also showed that a reduction of macropores could result in a reduction of aeration capacity (Table 1).

Soils exhibited a distinct change in water retention characteristics when the natural structure is destroyed by compaction of soil at a water content corresponding to the sticky limit (Galvez and Barahona, 2005). Therefore, appropriate management practices are required to alleviate soil compaction and increase soil water content. The soil compaction adversely affected soil water absorption by coconut roots and SPR less than 250 N/cm^2 was favorable for soil water absorption by coconut roots (Vidhana Arachchi et al., 1999). Therefore, two soil series, namely Andigama and Madampe series from low productive lands (bulk density $>$ 1.5 g/cm^3; SPR $>$ 250 N/cm^2) and high productive lands (bulk density $<$ 1.5 g/cm^3; SPR $<$ 250 N/cm^2) respectively were selected to evaluate the effect of deep ploughing on the soil water status.

3.2. Effect of deep ploughing on soil water status

3.2.1. Andigama soil series

Soil physical properties of Andigama series clearly indicated that its high soil compaction was a critical constraint, which adversely affected the total available water fraction in the soil profile (Table 1) specially compared to that of Madame soil series. Stenitzer and Murer (2003) also noted that soil compaction limits the soil water absorption from the root zone of maize (*Zea mays* L.) resulting in a yield reduction. Therefore, deep ploughing of

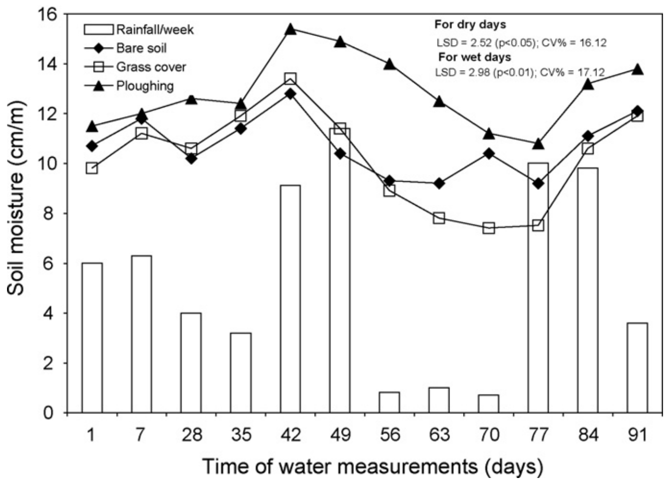

Fig. 1. Effect of deep ploughing, grass cover and bare soil on soil water status in highly compacted Andigama series.

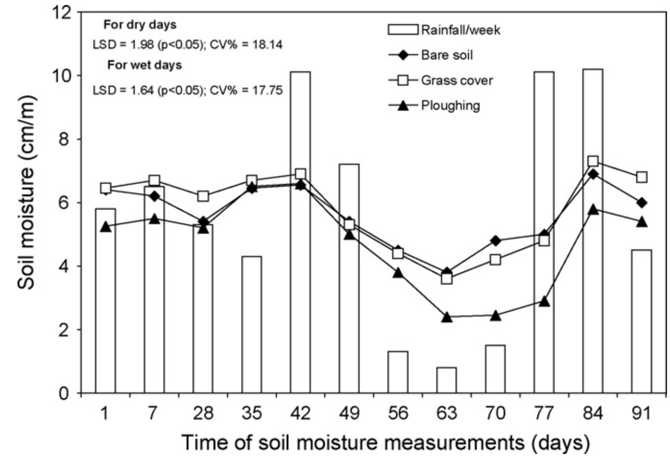

Fig. 2. Effect of deep ploughing, grass cover and bare soil on soil water status in less compacted Madampe series.

Andigama series could be useful to enhance total available water fraction of the soil profile. The effects of the native characters and deep ploughing of Andigama soil series on soil water status up to 1 m depth during the rainy and dry periods are shown in Fig. 1.

During the rainy period, soils of Andigama series (bare soil) had a lower capacity to intercept much water compared to that of grass cover, and this could be due to low infiltration and high runoff water. However when soil was deeply ploughed, soil water content of Andigama series significantly ($p < 0.01$) increased compared to bare soils and live grass-covered soils. Deep ploughing resulted in loosing compacted hard layers, which enhanced soil water infiltration into sub-horizons (Contreras, 2003).

Soil water losses through transpiration and evaporation during the dry period could explain the significantly ($p < 0.05$) decrease of water in soil with grass cover, compared to other treatments. Amount of water conserved in ploughed Andigama series soils with respect to bare soils and grass-covered treatments during the severe dry period (from 56 to 77 days) was 10.4 and 16.9 cm/m respectively (Fig. 1). In addition, deep ploughing of compacted soil significantly ($p < 0.05$) conserved more water compared to other treatments due to storage of more water in its profile during the rainy season (Fig. 1). Chaudhary et al. (1985) reported that deep ploughing of highly compacted soil induced deeper and greater rooting and increased profile water use, compared with conventional tillage. Moreover, subsoiling, moldboard ploughing and deep digging increased sorghum plant height by 30–35 cm and yielded 80–100% more stover and 70–350% more grain than the conventional tillage.

3.2.2. Madampe series

The changes of soil water status as affected by deep ploughing of Madampe series (less compacted soils) during the rainy and dry periods are shown in Fig. 2. Conserved soil water during the rainy season after deep ploughing of Madampe series was not significantly higher than for the bare soil and grass-covered soils. It appeared that during the process of deep ploughing in Madampe series, their naturally developed pore structure could be destroyed, thereby leading to lower retention of soil water retention in the rainy season, specially due to deep percolation losses. Connolly et al. (1997) also reported that ploughing of less compacted soils increased infiltration of water to deep layers, which enhanced deep percolation and therefore reduced conserved soil water. Not only deep percolation losses in rainy season, but high evaporation losses in dry period could also explain the low soil water conservation in Madampe series (Fig. 2). Amount of water reduction in ploughed Madampe series soils with respect to bare soil and grass-covered treatments during the severe dry period (from 56 to 77 days) was 6.55 and 5.45 cm/m respectively (Fig. 2). Also deep ploughing conserved high volume of soil water with subsequent damage of the soil structure, that could also induce high soil water evaporation (Stenitzer and Murer, 2003; Yavuzcan et al., 2005). Even though farmers prefer deep ploughing, Chatterton and Chatterton (1996) explained that it is a wasteful and costly operation and there was no significant benefit on the yields of barley and wheat with deep ploughing of light-textured soil to depths between 15 and 30 cm. Soil water content during rainy periods for the grass-cover treatment was higher than for the bare soil treatment due to soil water infiltration but during the dry period it was lower due to transpiration compared to bare soil (Fig. 2). Complementary to the adverse effect of deep ploughing in light-textured soil, Yavuzcan et al. (2005) also reported that deep ploughing in typical Bavarian soil (Regosol) in Germany, further increased soil compaction resulting in increased bulk density, soil strength and decreased porosity and saturated hydraulic conductivity.

3.3. Soil response near the root zone of coconut in Andigama series

Overall results suggested that deep ploughing in highly compacted soils is useful and important to enhance the soil water status compared to less compacted soils. However, deep ploughing within 1.75 m radius around the base of coconut palms grown in both highly and less compacted soil could adversely affect the soil water status near the effective root zone. Therefore, the effect of deep ploughing on soil water status up to 1 m depth near the root zone of coconut palm grown in Andigama and Madampe series was also evaluated and those results are shown in Fig. 3. Soil water retention in Andigama series with respect to every treatment was significantly ($p < 0.001$) higher than in Madampe series. However, coconut roots were unable to penetrate long distance throughout Andigama soil profile due to its high compaction, resulting in low water absorption by coconut roots. In contrast, coconut roots in Madampe series were easily able to penetrate through the soil profile due to its low compaction and could absorb soil water from deeper layers (Vidhana Arachchi et al., 1999). Deep ploughing near the effective root zone of coconut in low compacted Madampe series greatly promoted water losses (Fig. 3) and that could adversely affect the coconut production. However, deep ploughing, even near the effective root zone of coconut in highly compacted

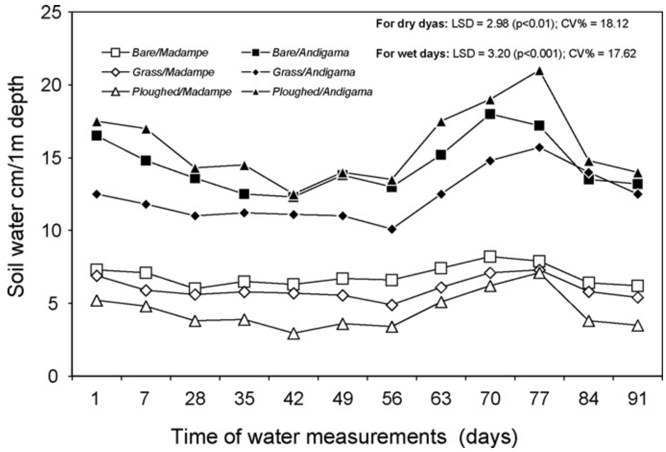

Fig. 3. Effect of deep ploughing, grass cover and bare soil on soil water status in the effective root zone of coconut palm.

Andigama series, significantly ($p < 0.001$) increased water retention than that of Madampe series (Fig. 3). Complementary to these results, Castrignano et al. (1997) reported that following deep ploughing of silty clay soils in Foggia, Southern Italy, the soil water content was lower at 20–40 cm depth and higher at 40–60 cm depth due to light-textured and compacted hard layers in soil profiles respectively. However, coconut grown in Madampe soil series gave a high yield even during the dry spell, because during dry periods, coconut roots in Madampe series could penetrate deeper layers and were able to absorb more water from deeper layers (Somasiri et al., 1994). Therefore, ploughing of less compacted soils such as Madampe series is unnecessary and a real disadvantage for coconut growers. Although live cover promoted infiltration of water into soil profiles during the rainy season, its establishment during the dry period extracted more water from the root zone (Fig. 3) probably due to transpiration. It is therefore, suggested that instead of introducing live material to the effective root zone of coconut, mulching with coconut leaves and fronds may conserve more water in the soil profile (Vidhana Arachchi, 1998). Where live cover exists in less compacted soil, light harrowing near the effective root zone around coconut palm at the time of fertilizing would be more effective to conserve soil water than deep ploughing. In contrast, deep ploughing in highly compacted soils, even near the effective root zone, promoted soil water conservation, thereby increasing coconut production.

4. Conclusions

Soil compaction restricted the available water fraction and aeration status of soil. Deep ploughing of highly compacted soils (bulk density > 1.5 g/cm^3 and penetrometer resistance > 250 N/cm^2) during the rainy and dry periods greatly enhanced soil water conservation, whereas in less compacted soils (<1.5 g/cm^3 and penetrometer resistance < 250 N/cm^2), deep ploughing had no beneficial effect on water retention in the soil profile. Moreover, on less compacted soils, deep ploughing within the root zones was not effective in increasing water retention. Therefore, application of dead mulch using coconut leaves with fronds instead of live grass cover may be effective in increasing coconut production in less compacted soils.

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References

Arif, M., Ali, M., Din, Q.M., Ali, M.A., Akram, M., 2004. Growth and yield of cotton (*Gossypium hirsutum* L.) as influenced by deep ploughing interval on sandy loam soil. Pakistan Int. J. Agric. Biol. 6 (4), 639–643.

Bell, J.P., 1987. Neutron probe practice. Report 19, 3rd ed., Institute of Hydrology, Wallingford, England, pp. 1–55.

Boone, F.R., Veen, B.W., 1994. Mechanism of crop response to soil compaction. In: Soane, B.D., Van Ouwerker, C. (Eds.), Soil Compaction in Crop Production. Elsevier Science Publishers, New York, USA, pp. 237–264.

Bradford, J.M., 1986. The penetration resistance in a soil with well-defined structural units. Soil Sci. Am. J. 44, 601–605.

Castrignano, A., Colucci, R., Giorgio, D.D., Rizzo, V., Stelluti, M., 1997. Tillage effects on plant extractable soil water in a silty clay Vertisol in Southern Italy. Soil Tillage Res. 40 (3–4), 227–237.

Chatterton, L., Chatterton, B., 1996. Sustainable Dryland Farming. Cambridge University Press, Great Britain.

Chaudhary, M.R., Gajri, P.R., Prihar, S., Khera, R., 1985. Effect of deep tillage on soil physical properties and maize yields on coarse textured soils. Soil Tillage Res. 6 (1), 31–44.

Chen, Y., Cavers, C., Tessier, S., Monero, F., Lobb, D., 2005. Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. Soil Tillage Res. 82 (2), 161–171.

Connolly, R.D., Freebairen, D.M., Bridge, B.J., 1997. Change in infiltration characteristics associated with cultivation history of soils in South-eastern Queensland. Aust. J. Soil Res. 35 (6), 1341–1358.

Contreras, S.M., 2003. Analysis of the effects of plowed hardpan on sub-soil stored water use in sugarcane. ICRS Progress Report, Final Report of the Visiting Research Fellows, International Center for Agricultural Sciences (JIRCAS), Okinawa Subtropical station 11, pp. 37–50.

Defossez, P., Richard, G., Boizard, H., O' Sullivan, M.F.C., 2003. Modeling change in soil compaction due to agricultural traffic as function of soil water content. Geoderma 116, 89–105.

Fuller, K., 1999. Bolstering the soil environment-site preparation. Paper presented at the 42nd Annual IDFTA Conference, December 20–24, Hamilton, Ontario, Canada.

Galvez, J.F., Barahona, E., 2005. Changes in soil water retention due to soil kneading. Agric. Water Manage. 76 (1), 53–61.

Gerad, C.J., Sexton, P., Shaw, G., 1982. Physical factors influencing soil strength and root growth. Agron. J. 74, 875–879.

Gomez, G.A., Singer, M.J., Power, R.F., Horwath, W.R., 2002. Soil compaction effects on water status of ponderosa pine assessed through C^{13}/C^{12} composition. Tree Physiol. 22, 459–467.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82 (2), 121–145.

Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., Lal, R., 2001. Subsoil compaction effects on crops in Panjab, Pakistan. Soil Tillage Res. 59 (1–2), 57–65.

Klute, A., 1986. Water retention. Laboratory methods. In: Klute, A. (Ed.), Method of Soil Analysis, Part 1. 2nd ed., ASA Monograph 9. Am. Soc. Agron., Wisconsin, USA, pp. 425–441.

Liang, J., Zhang, J., Chan, G.Y.S., Wong, M.H., 1999. Can differences in root responses to soil drying and compaction explain differences in performance of tree growing on landfill sites? Tree Physiol. 19, 619–624.

Rawitz, E., Morin, J., Hoogmoed, W.B., Margolin, M., Etkin, H., 1983. Tillage practices for soil and water conservation in the semi-arid zone. I. Management of fallow during the rainy season preceding cotton. Soil Tillage Res. 3 (3), 211–231.

Soane, B.D., Van Ouwerkerk, C., 1994. Soil compaction problems in World Agriculture. In: Soane, B.D., Ouwerker, C., Van, (Eds.), Soil Compaction in Crop Production. Elsevier Science Publishers, New York, USA, pp. 1–21.

Somasiri, L.L.W., Nadarajah, N., Amarasiri, L., Gunathilaka, H.A., 1994. Land suitability assessment of coconut survey area in the coconut triangle. In: Panabokke, C.R., Mahindapala, R. (Eds.), Occasional Publication. The Coconut Research Institute, Sri Lanka, pp. 1–64.

Stenitzer, E., Murer, E., 2003. Impacts of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model. Soil Tillage Res. 73 (1–2), 43–56.

Sun, Y., Ma, D., Lammers, P.S., Schmittmann, O., Rose, M., 2006. On-the-go measurement of soil water content and mechanical resistance by a combined horizontal penetrometer. Soil Tillage Res. 86 (2), 209–217.

Tsimba, R., Hussein, J., Ndlovu, L.R., 1999. Relationships between depth of tillage and soil physical characteristics of sites farmed by smallhoders in Mutoko and

Chinyika in Zimbabwe. In: Kaumbutho, P.G., Simalega, T.E. (Eds.), Conservation Tillage with Animal Traction. A Resource Book of Animal Traction Network for Eastern and Southern Africa (ATNESA), Harare, Zimbabwe. p. 173.

Vidhana Arachchi, L.P., 1998. An evaluation of different mulches used in soil moisture conservation of coconut lands. Asian Pacific Coconut Community (CORD) 14 (2), 12–27.

Vidhana Arachchi, L.P., Somasiri, L.L.W., 1997. Assessment of oxygen availability in soils of different drainage classes and its effect on coconut root growth. Proc. Sri Lanka Assoc. Adv. Sci. 53 (2), 159–160.

Vidhana Arachchi, L.P., Yapa, P.A.J., Mapa, R.B., Somapala, H., 1999. Soil water extraction pattern of coconut (*Cocos nucifera* L.) in relation to soil compaction. Coconut Research Institute, Sri Lanka. Cocos 13, 66–80.

Vidhana Arachchi, L.P., Yapa, P.A.J., Mapa, R.B., Somapala, H., 2000. Soil physical properties and their effect on morphological characters of coconut (*Cocos nucifera* L.). Asian Pacific Coconut Community (CORD) 16 (1), 14–33.

Yavuzcan, H.G., Matthies, D., Auernnammer, H., 2005. Vulnerabilty of Bavarian silty loam soil to compaction under heavy wheel traffic: impacts of tillage method and soil water content. Soil Tillage Res. 84 (2), 200–215.