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Effects of sugarcane (*Saccharum spp.*) cultivation duration on some soil physical properties in Ramu Valley of Papua New Guinea

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Abstract

*Repeated tillage operations for planting sugarcane (*Saccharum spp.*) and wheel traffic for cane harvesting and transport are known to affect the surface and sub-surface soil in Ramu sugarcane plantation of Papua New Guinea. This study examines the changes in the bulk density (SBD), penetration resistance (PR) and water infiltration (WI) parameters in cane rows and wheel tracks of a Tropofluents that have been exposed to varying durations (0, 6, 11, 16 and 22 years) of cane cultivation after being converted from grasslands. Sugarcane cultivation duration had a significant ($p < 0.05$) effect on SBD and PR in the cane rows and in wheel tracks in both surface (0-10 cm) and subsurface soils (> 10 cm depth). In response to 22 years of cane cultivation, bulk density increased by a small extent in the cane rows (2.5%), while in wheel tracks the increase was by 15%. There was a significant ($p < 0.05$) effect of converting grasslands to cane cultivation with respect to cumulative infiltration of water. Wheel tracks had 59.7, 62.8, 76.2 and 76.8% lower cumulative infiltration of water than the cane rows in the fields cultivated for 6, 11, 16 and 22 years. Sustainable soil management practices need to be explored for improving soil properties in cane rows and to alleviate compaction in wheel tracks.*
***Keywords**: Soil bulk density, soil strength, soil physical properties, sugarcane cultivation effects*

1. Introduction

Use of heavy machineries in sugarcane (*Saccharum spp.*) farming and consequent development of soil compaction and yield decline are major environmental and agronomic concerns (Braunack and Peaty, 1999; Batey, 2009). Ramu sugarcane plantation is the only commercial cane and sugar producing unit in Papua New Guinea. Over the last three decades of cane cultivation, the intensity of machinery use increased in parallel with the expansion of land under cane. Due to continuous mono-cropping and use of heavy machinery during the years of cane cultivation, soils have become susceptible to soil degradation (Hartemink, 1998). Now in several blocks ecological symptoms of soil degradation and compaction are noticed. In-field water stagnation and larger than the normal run-off volumes are observed in the fields subjected to 3-4 crop cycles, compared to recently cultivated fields. Apart from these problems, management is facing the threat of yield decline in these fields due to compaction (Bangita, 2010) which could be of the magnitude of 20-21% reported at Australia and Cuba (Bell *et al*., 2007; Perez *et al*., 2010). However, yield decline could also be due to depletion of soil fertility and acidification (Hartemink, 2001) and difficult to single out any one cause of soil degradation. An assessment of soil chemical degradation and compaction was first made in the Ramu sugar plantation by Hartemink (1998). However, there is lack of information on the rate of degradative processes in the sugarcane cropping system of tropical Papua New Guinea. We hypothesize that with the increase in the duration of sugarcane cultivation after conversion from grasslands, there is a progressive increase in soil compaction in wheel tracks and cane rows. Due to compaction, SBD, soil strength or PR, and WI are being affected and resulting in soil degradation. Repeated wheel passes leads to deformation of soil surface, as well as brings changes to soil volume and structural changes (Arvidson and Ristic, 1996; Hakansson and Reeder, 1994). Compacted soils show lower rates of WI and drainage from the compacted layer; availability of nutrients and exchange of gases slows down causing aeration-related problems (Kulli *et al*., 2003). Therefore, the present investigation was undertaken with the specific objective of identifying and quantifying the soil compaction under different cane production time-scales after conversion from the grasslands. The study was also directed at characterizing soil compaction attributes, if any, at different soil depths. Information on in-field spatial distribution of soil compaction and the time-scale involved for its genesis is vital for development of sustainable management practices.

2. Methods

2.1 Site Description and Site Selection

A total of 8 cane fields from Ramu sugarcane plantations (established since 1978) owned by the Ramu-Agri-Industries Limited (RAIL) were identified using the historical sugar cane production records and the detailed soil maps (1: 10,000 and 1:

25,000) of the plantation. Fields which were located within one mapping unit i.e., Fluvisol were sorted by different sugarcane farming time scales. Some of the fields were brought under cane recently, while some have been cultivated for more than 22 years. For this study, two fields each were selected to represent cultivation durations of 0, 6, 11, 16 and 22 years under sugar cane cultivation. The main criteria for selection of these fields were the similarities in the inherent characteristics and proximities to each other. Each field selected for the study ranged between 10 and 20 ha. Additionally, two adjoining natural grasslands were sampled to compare the effects of sugarcane cultivation (0 yr). The grasslands were dominated by two native grass species *Imperata cylindrica* and *Themeda triandra* with a few sparse standing trees. Natural grass lands used for sampling were less than 75 m from the cultivated cane fields. Soil sampling and *in situ* soil physical measurements at each of the ten sites (5 cultivation durations X 2 fields), four pits (replications) were dug (total 40 pits) in the September 2008. In the cane fields, pits were excavated such that pits were across the cane rows and inter-rows. In each profile, soil core samples were collected from different depths (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm) in zones representing cane row and wheel traffic using a stainless steel core cutter (180 cm^3) for soil bulk density measurement (N = 600). For each soil depth, three cores were collected in a sealable plastic bag and immediately transported to laboratory. In the laboratory, core cutters and the contents were weighed for wet weight (g), and then oven dried at 105 ^{0}C and reweighed (g) (Blake and Hartge, 1986).

Volumetric water content (m^3/m^3) was also calculated from the information on gravimetric moisture content and bulk density. Sampling was always done 24 h after a rain event and there were no significant ($p < 0.05$) differences in the moisture content at field capacity (Figure 1). Soil penetration resistances of soil horizons in cane fields (in both cane row and traffic zone) and natural grassland were determined with a cone penetrometer (30^0; 1.2 cm^2 Dickey John Corporation, USA). Infiltration rates were determined for the soil surface near each pit (N = 78) by the double ring infiltrometer method (Bertrand, 1965) and measurements were recorded for 60 minutes after starting the test.

In situ appraisal of soil physical properties (SBD, PR, WI and soil volumetric water content) for different cultivation years and soil depths (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm) were statistically analyzed for two- way analysis of variance (ANOVA) in Genstat Discovery Edition 3. Infiltration rates and cumulative infiltration data was subjected to one way ANOVA as the test was conducted only to the soil surface at 95% confidence level (p = 0.05). Correlation and regression analysis was conducted between PR and SBD.

3. Results

3.1 Effects of Cane Cultivation and Wheel Traffic on Soil Bulk Density

Sugarcane cultivation duration had a significant ($p < 0.05$) effect on soil bulk density (SBD) in cane rows and in the wheel tracks (Table 1). SBD measured in the cane rows showed a slight decrease after first cane production cycle, later the values showed increasing trend and after four cane production cycles (22 yr) it was maximum. Such a trend was noticed in top soil layers, up to 0-30 cm depth; below these layers, the SBD remained greater than that noticed in sub-surface horizons (30-50 cm) of grasslands. Compared to the cane rows, the wheel tracks recorded much higher SBD values (Table 1). On an average, the traffic zone had higher SBD values than the cane rows by 17, 8, 8, 6, and 5% in the soil depths of 0-10, 11-20, 21-30, and 31-40 and 41-50 cm, respectively. These findings indicated that an increase in SBD or compaction process is mostly restricted to top soils (0-30 cm).

3.2 Effects of Cane Cultivation and Wheel Traffic on Soil Penetration Resistance

Cane rows in the fields cultivated for 22 yr registered significantly ($p < 0.05$) higher soil penetration resistance (PR) values compared to the grasslands (Table 2). General trends in temporal and spatial in-field variations of PR were similar to that of soil bulk density. Much of the decrease in PR of the cane rows in the fields of different cultivation periods was at depths 0-10, 11-20 and 21-30 cm, without altering PR in the soil layers beneath. In the wheel tracks of fields cultivated for 11 yr, PR values were significantly greater than those of grasslands at all depths indicating an increase in the soil strength. Due to wheel traffic, marked increase in PR was noticed in surface soils up to 30 cm, while, there was marginal increase in sub-soil (30-50 cm) strength due to duration of cane cultivation.

3.3 Effects of Cane Cultivation and Wheel Traffic on Soil Permeability

Significant differences ($p < 0.05$) were observed in the infiltration rates and cumulative water intake of the cane fields due to cultivation period (Table 3). Cane rows of the fields cultivated for 6, 11 and 16 years showed significantly ($p < 0.05$) higher cumulative water infiltration than those of the grasslands albeit, those cultivated for 22 yr registered slightly lower cumulative infiltration. Cane rows in fields subjected to cane production for 6, 11 and 16 yr had the cumulative water infiltration of 151, 97 and 27% greater than the grasslands, respectively. However, in the cane rows cultivated for 22 yr the cumulative infiltration was 16.2% lower than the grasslands. In the wheel tracks, cumulative water infiltration was markedly lower in the cane fields

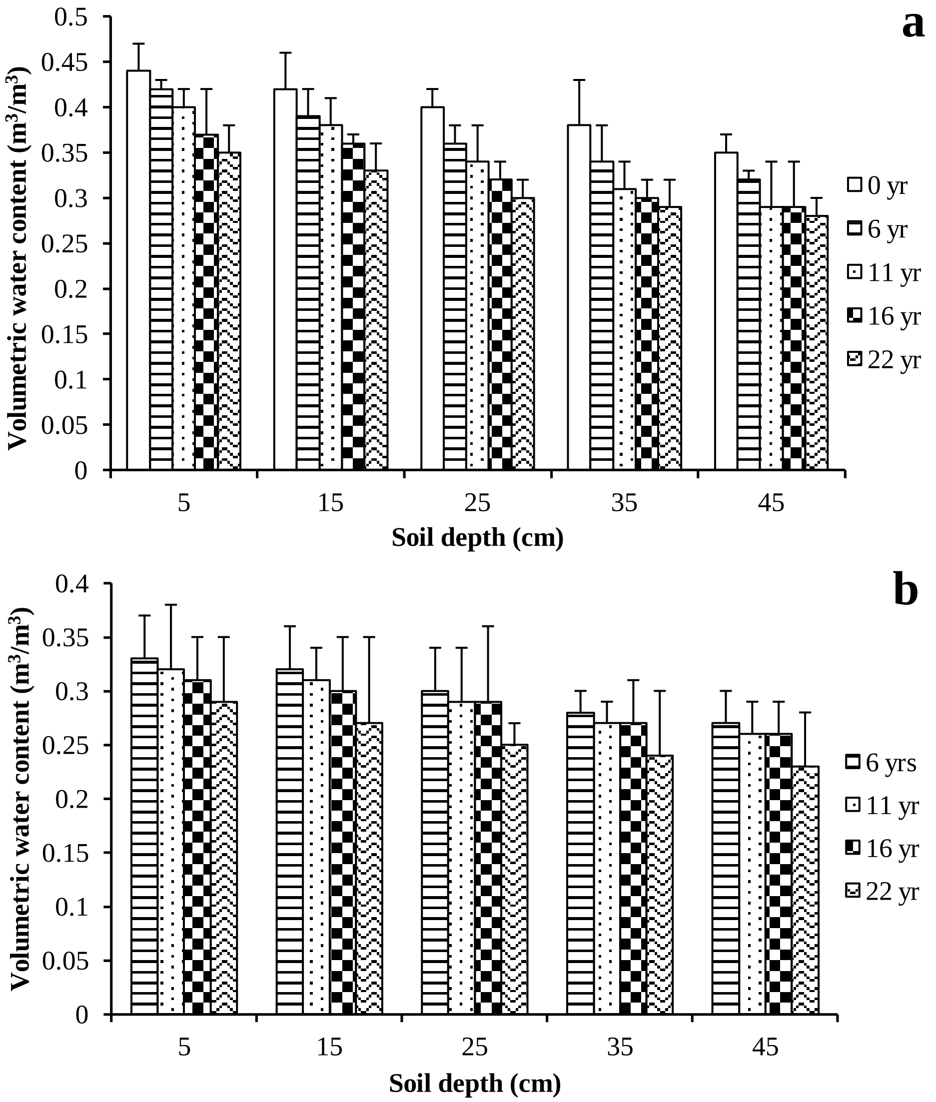

Figure 1. Effect of cane cultivation period and soil depth on the volumetric water content (m^3/m^3) of the soil in a) cane rows and b) wheel tracks. Error bars represent SEM ($p > 0.05$).

Table 1. Effect of cane cultivation period and soil depth on the SBD (g/cm^3) in cane rows and wheel tracks.

Sugarcane cultivation period	Soil depth 0-10	10-20	20-30	30-40	40-50	Mean
			Cane row			
Grassland	1.24(0.11)	1.32(0.07)	1.37(0.08)	1.43(0.06)	1.45(0.04)	1.36^{a}
6 years	1.20(0.09)	1.25(0.13)	1.33(0.12)	1.44(0.07)	1.46(0.06)	1.34^{bc}
11 years	1.22(0.15)	1.27(0.15)	1.36(0.10)	1.44(0.08)	1.47(0.07)	1.35^{b}
16 years	1.23(0.17)	1.29(0.11)	1.40(0.13)	1.45(0.04)	1.48(0.07)	1.37^{ab}
22 years	1.26(0.12)	1.34(0.13)	1.41(0.10)	1.45(0.09)	1.51(0.03)	1.39^{a}
Mean	1.23^{e}	1.29^{d}	1.37^{c}	1.44^{b}	1.47^{a}	
			Wheel tracks			
Grassland	-	-	-	-	-	-
6 years	1.39(0.08)	1.41(0.11)	1.49(0.04)	1.53(0.07)	1.54(0.10)	1.47^{c}
11 years	1.44(0.10)	1.45(0.12)	1.50(0.06)	1.54(0.09)	1.55(0.12)	1.50^{bc}
16 years	1.46(0.05)	1.48(0.06)	1.54(0.09)	1.56(0.14)	1.58(0.11)	1.52^{ab}
22 years	1.48(0.09)	1.50(0.05)	1.57(0.13)	1.58(0.09)	1.60(0.13)	1.55^{a}
Mean	1.44^{c}	1.46^{c}	1.53^{b}	1.56^{a}	1.57^{a}	

Mean and SEM in parentheses. Different superscripts differ significantly ($p < 0.05$).

Table 2. Effect of cane cultivation period and soil depth on the PR (MPa) of soil in cane rows and wheel tracks.

Sugarcane cultivation period	Soil depth					
	0-10	10-20	20-30	30-40	40-50	Mean
			Cane row			
Grassland	0.83(0.05)	1.24(0.07)	1.72(0.11)	2.07(0.08)	2.20(0.06)	1.61[a]
6 years	0.50(0.02)	0.83(0.05)	1.07(0.05)	2.10(0.07)	2.25(0.05)	1.35[cd]
11 years	0.55(0.04)	0.82(0.06)	1.10(0.04)	2.10(0.08)	2.25(0.07)	1.36[c]
16 years	0.65(0.01)	0.92(0.10)	1.20(0.05)	2.15(0.05)	2.31(0.06)	1.45[b]
22 years	0.88(0.06)	1.35(0.09)	1.80(0.04)	2.15(0.07)	2.33(0.04)	1.70[a]
Mean	0.68[d]	1.03[c]	1.38[b]	2.11[a]	2.27[a]	
			Wheel tracks			
Grassland	-	-	-	-	-	-
6 years	1.00(0.01)	1.30(0.04)	1.71(0.04)	2.13(0.07)	2.24(0.07)	1.68[b]
11 years	1.20(0.09)	1.40(0.07)	1.83(0.05)	2.14(0.10)	2.27(0.05)	1.77[ab]
16 years	1.28(0.05)	1.50(0.06)	1.87(0.04)	2.14(0.08)	2.32(0.09)	1.82[a]
22 years	1.35(0.07)	1.56(0.05)	1.94(0.06)	2.16(0.03)	2.33(0.05)	1.86[a]
Mean	1.21[c]	1.44[c]	1.83[b]	2.14[a]	2.29[a]	

Mean and SEM in parentheses. Different superscripts differ significantly ($p < 0.05$).

Table 3. WIR (mm/min) and CI (mm) of soils in relation to cane cultivation duration at 1 (initial) and 60 (steady state) min.

Sugar-cane cultiva-tion period	Infiltration rate at 1 min (Initial) mm/hr		Infiltration rate at 60 min (steady state) mm/hr		Cumulative infiltration (mm)		Cumulative infiltration in wheel tracks as a percentage of cane
	Cane row	Wheel track	Cane row	Wheel track	Cane row	Wheel track	
0 years	26(4.8)[b]		0.28(0.04)[a]		69.7(5.2)[b]		-
6 years	69(5.3)[a]	28(3.8)[a]	0.25(0.03)[a]	0.17(0.02)[a]	175.2(3.8)[a]	70.5(5.1)[a]	59.7
11 years	41(4.9)[b]	6(2.1)[b]	0.24(0.01)[b]	0.13(0.02)[b]	137.1(4.1)[a]	51.4(4.5)[a]	62.8
16 years	26(4.2)[b]	3(1.2)[b]	0.24(0.03)[b]	0.13(0.01)[b]	88.4(4.8)[b]	21.0(3.6)[b]	76.2
22 years	24(3.8)[b]	2(0.4)[b]	0.15(0.02)[b]	0.06(0.01)[b]	58.4(2.7)[b]	13.5(2.0)[b]	76.8

Mean and SEM in parentheses. Different superscripts differ significantly ($p < 0.05$).

from different cane production durations, except in the fields brought under cultivation very recently (6 yr). Wheel tracks had 76.8% lower cumulative infiltrations than the cane rows in the fields cultivated for 22 yr. The major difference in infiltration rates of the cane rows and the wheel tracks was in the initial infiltration rates (recorded in the first 1 minute) (Table 3). Infiltration rates in the initial 1 minute were almost three-times greater than that of grassland in cane rows during the first cane cycle. The infiltration rates decreased with cane production duration and after four cane production cycles it was comparable with that of natural grasslands. However, in wheel tracks dramatic drop of infiltration rate by almost 13-times to 2 mm/min was noticed due to 22 yr of cane production. Cane cultivation and field traffic influenced the steady state infiltration rates (Table 3). Steady state infiltration rates were significantly ($p < 0.05$) reduced in both the cane rows and wheel tracks after cultivation for more than 6 yr.

4. Discussion

The most common soil physical variables used to assess soil compaction problems are BD and PR. In response to 22 yr of cane cultivation, BD increase was by a small extent of 2.5% in the cane rows, while, in wheel tracks the BD increased by 15%. Increase in BD, with the duration of cane cultivation, was more pronounced in the wheel track zones. The soil BD values increased with the depth in undisturbed grassland (0 yr), which is attributed to natural compaction processes without human, animal or machinery intervention (Batey, 2009). The lower BD of cane rows than that of grasslands in the 0-30 soil depths immediately after being brought under cane cultivation is due to the tillage operations performed to plant cane. Preparatory tillage operation performed on grasslands can loosen the soil and hence increase the porosity of the soil (Lampurlane and Cantero-Martinez, 2003). With continued tillage of cane rows, BD could increase due to decrease in soil pore volume (Horn et al. 2001). They suggested that BD is related to soil structure type and successive tillage can result in deterioration of soil structure due to homogenization and rearrangement of soil particles. In the wheel tracks repeated wheeling applies stresses exceeding the internal soil strength alongside the impacts of dynamic forces such as shearing results in complete change in the composition of pore system. A single pass of 4 Mg tractor was found to increase the BD by 0.05 g/cm^3 in the cane fields of Australia (Braunack *et al*., 2006), and this was attributed to a decrease in structural porosity (Richard *et al*., 1999). Kim *et al*. (2010) observed a decrease of macro porosity by 64% and coarse mesopores (200-1000 µm) by 75% due to an increase of BD by 10% due to compaction. Penetration resistance (PR) is widely used to characterize the soil compaction which influences the structural characteristics. Destruction of water stable aggregates, formation of platy or coherent soil structure can increase the mechanical strength of the soil to penetrometer (Celik *et al*., 2010). Repeated wheel traffic during the cane production cycles resulted in destruction of soil structure and hence the PR values gradually increased with duration of cane production. Despite gradual increase in PR values, they remained below 2 MPa in the 0-30 cm soil depths and across all production time scales, even in the wheel tracks. PR values were greater than 2 MPa in the lower soil depths (30-50 cm) and increased with traffic intensity or cane production duration, a level of soil hardness commonly used to indicate a critical threshold for root growth (Hamza and Anderson, 2005). BD was linearly related to PR of the soils and could be predicted as follows in our study; PR (MPa) = 4.50 (BD in g/cm^3) – 4.79; (R^2= 0.718**).

In the cane rows, better cumulative infiltration (CI) is expected in the initial years of cane cultivation due to formation of root channels and bio-pores (Kay, 1990). Lower CI in the cane rows of fields cultivated for 22 yr could be due to formation of surface crusts due to repeated tillage, whose effects could overcast the beneficial effects of roots in enhancing infiltration rates (IR) (Braunack *et al*., 2006). Tillage practices are expected to hasten initial IR due to increased macro-pore spaces (Coutadeur *et al*., 2002; Abrisqueta *et al*., 2006; Unger, 2009), thereby increasing infiltration in cane rows. Better root growth of sugarcane plants in cane rows resulting from fertilizer additions may have increased the number and length of continuous pores within the soil leading to better water infiltration. With the increase in cultivation period, soil structure degrades due to repeated tillage and compaction due to wheel traffic and can bring about losses in macro pore space and their continuity which can hinder water movement to soil and its redistribution in the soil profile (Pagliai *et al*., 2003; Lipiec and Hatano, 2003). Steady state IR reflects the quantity of transmission of water after reaching the complete sorption of water in the soil matrix. Possibly due to formation of sub-soil compaction, vertical transmission of water is restricted to a greater extent in wheel tracks. Decrease in steady state infiltration rates in cane rows over the extended cultivation periods may be due to formation of tillage pans below 30 cm depth. Compaction to various degrees is reported to decrease the steady state infiltration in soils (Kutilek and Nielsen, 1994; van Dijck and van Asch, 2002). Steady state infiltration can be affected by tillage and compaction mainly due to decrease in soil porosity and pore sizes (Eynard *et al*., 2004). However, in this study we were not able to characterize the dynamics of pore size distribution, and therefore it is difficult to attribute observed reduction in infiltration parameters to changes in any of the pore types.

5. Conclusions

Measurements of soil BD, PR and water infiltration rates showed significant soil quality degradation in mechanized cane production systems of Papua New Guinea. Accumulative effect of compaction was observed over sugarcane production time scales and soil depths. Further research is needed to evaluate the extent of yield loss due to compaction in wheel tracks, characterize the pore size effects of cultivation and wheel track compaction and relate them to hydrological processes in catchment scale, especially the runoff and nutrient loss. The long-term effects of continuous sugarcane cultivation show significant increase in bulk density, penetration resistance and significant reduction in water intake parameters, and served as evidence of the need for developing a management strategy that could encounter the decline in these soil quality indicators. Maximization of infiltration rate through management of traffic zone holds promise to improve soil water storage and rainwater use efficiency and minimize soil loss and run-off yields in the rain fed sugarcane cultivation in Papua New Guinea.

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