IMPACT OF MECHANIZED LOGGING OPERATIONS ON WET AND DRY SOILS OF SAO HILL FOREST PLANTATIONS, TANZANIA

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Abstract

Mechanization of timber harvesting operations in Tanzania involves use of machinery such as feller bunchers, skidders and tractors which are generally heavy in weight ranging from 12 to 16 tones in unloaded state. The movements of these machines induce soil compaction owing to the exerted normal pressure, vibrations and shear stress. But little literature has quantified such phenomena in Tanzania. This paper reports results of soil disturbance caused by timber harvesting machinery in Sao Hill Forest Plantation in wet and dry seasons. Soil characteristics were recorded two years after the plots were harvested using both visual classification and soil strength measurements. The results indicate that bulk densities of the upper 20 cm of soil on a plot logged in wet season increased by an average of 60.5% to 1.61 g/cm^3 while for a plot harvested in dry season the increase was 28.7% to 1.28 g/cm^3 compared to those of adjacent undisturbed soils. Porosity of the soil reduced by 31.5% and 14.3% for the area harvested in wet and dry seasons respectively. In the top 35 cm of soil depth, the soil penetration resistance increased by 192% and 112% for the area harvested in wet and dry season respectively. The penetration resistances for both areas exceeded the USDA allowable limits. In addition, the results indicate that logging in wet season can lead to restricted root growth (1.61g/cm^3) while logging in dry season may only affect root growth (1.21 g/cm^3). Compaction is a concern on Sao Hill forest soils especially where fully mechanized logging occurs during moist antecedent soil conditions. Compaction can be minimized by logging during dry soil conditions.

Key words: Soil penetration resistance; USDA forest soil compaction standard; growth limiting bulky density

Introduction

In forest operations, the use of ground-based heavy machinery for harvesting is common practices around the world (Najafi and Solgi, 2010).These machines are usually associated with the increase in size, power and weights that generally amounts up to 12-16 tones in unloaded state (Ampoorter *et al.* 2007). This may cause soil degradation in forestry ecosystems as the passes of harvesting machines modify important soil structure characteristics which leads to soil compaction (Mickineci *et al.* 2007).

Soil compaction decreases total porosity, water and air infiltration and increases soil bulky density and soil strength as documented by Naghdi *et al.* (2007) and Zhang *et al.* (2006). Root responses to compaction may be complex owing to the numerous ways in which compaction can modify the physical properties of soil (Naghdi *et al.* 2007). These physical changes can inhibit root elongation, impede soil drainage and slow the exchange of nutrients needed for plant growth (Siegel-Issen, *et al.* 2005). Further deterioration in site productivity may occur from surface soil displacement during logging and accelerated surface erosion because of increased overland flow on skid trails (Megahan *et al.* 1972). Much work has been done to determine levels of soil compaction that are critical to plant growth (Hatchell 1970). Some researchers have noted a relationship between poor survival and growth of tree seedlings and soil compaction and soil texture which can be used to relate the bulky density to growth of forest and range plants (Daddow and Warrington 1983).

Effect of soil compaction on tree growth

Various research studies have shown the detrimental effects of soil compaction on the establishment and growth of forest and range plants (Greacen and Sands 1980, Wert and Thomas 1981). The effects of soil compaction on plant growth are a complex interaction between many soil and plant properties, but for many situations there appears to be an upper limit or threshold soil bulk density value where resistance to root penetration is so high that plant root growth is essentially stopped (O'connell 1975). This threshold bulk density will be referred to as "growth-limiting" bulk density (GLBD). GLBD is influenced by many soil properties but for most cases, soil texture appears to be the most important property determining the GLBD of a soil (O'Connell 1975).

A soil's GLBD is strongly influenced by soil texture because this property has a major effect on the average pore size and mechanical resistance of a compacted soil. The relationship was used by Daddow and Warrington (1983) to develop and locate growth limiting isodensity lines on the USDA soil textural triangle. These isodensity lines represent equal GLBD values and are used to estimate the GLBD of a soil. Such lines are useful in estimating the effect of soil compaction on tree/plant growth.

This technology of using feller bunchers, cable and grapple skidders has been introduced and is being used at Sao Hill and Tanganyika Wattle Company plantations by the Mufindi Paper Mills company. These machines being a new technology in timber harvesting operations in Tanzania, call for studies to

This study was designed to comprehend the degree, extent and effects of soil compaction in Sao Hill Forest plantation where the technology of feller bunchers, cable and grapple skidders has been introduced and being used but not well known to what extent these machines are causing soil disturbances in dry and wet seasons. Another objective was to assess tree response to soil compaction according to USDA Soil quality standard for compaction and affected area extent (USDA Forest Service 2003).

MATERIALS AND METHODS

Site Description

The study was conducted in four plots of compartment 1/ID/5a of Sao Hill Forest Plantation, located in Southern Highland, Tanzania. Plot pp/17.91/87 was planted in 1987 and harvested in 2009 rain season. Plot pp/30.11/87 was planted in 1987 and harvested in 2009 dry season. Plot pp/14.01/87 which has not been harvested until the time of this study and is adjacent to the plot harvested in wet season was used as its control. For similar reasons plot pp/25.26/89 was used as control for the plot harvested in dry season.

Sao Hill forest, which covers an area of about 83,000 ha at an average elevation of about 2000 m above sea level, receives a mean annual rainfall of 1000 mm falling between November and April, and has a mean annual temperature of 16 ˚C. Generally, the soils are *Hapli-Chromic Lixisols* and *Hapli-Ferric Lixisols* or *Typic Paleustults (Ultisols*). The natural vegetation of the area consists of open grasslands with scattered miombo woodland trees and shrubs dominated by *Brachystegia* and *Jurbernadia species* (Maliondo *et al.* 2005).

Data Collection

Measurements were made two years after logging operation on two plots, one disturbed in wet season and the other in dry season. For the first plot which was harvested in wet season, 10 soil cores, 5 cm in diameter and 5 cm high were taken randomly from the upper 20 cm of the surface of the plot by driving metal core rings into the ground and removing the samples intact. Similar samples were also taken from undisturbed, adjacent plot which was planted in the same year as the disturbed plot. The undisturbed plot was used for taking control measurements. The second plot was harvested in dry season and measurements were taken as for the first plot. Control measurement were take from adjacent undisturbed plot with similar characterizes to the disturbed.

Resistance to penetration in each of the disturbance classes was measured by a self-recording penetrometer equipped with a 1 cm^2 base surface cone to measure soil strength. Ten to twenty replicates of each probe at a 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 cm depth were made in each of the disturbance classes and the controls. The amount or degree of compaction was expressed by three indexes, namely the actual numerical change in bulk density, total porosity and soil strength from the value of these properties for the undisturbed site.

Bulk density was determined by drying the soil samples to a constant weight at 105 °C in an oven. The total porosity, which is similar to bulk density as a measure of compaction (Lenhard 1986) was computed from the bulk density. The effect of change in soil bulky density on tree/plant growth was assessed using the growth-limiting bulk density texture triangle (Daddow and Warrington 1983).

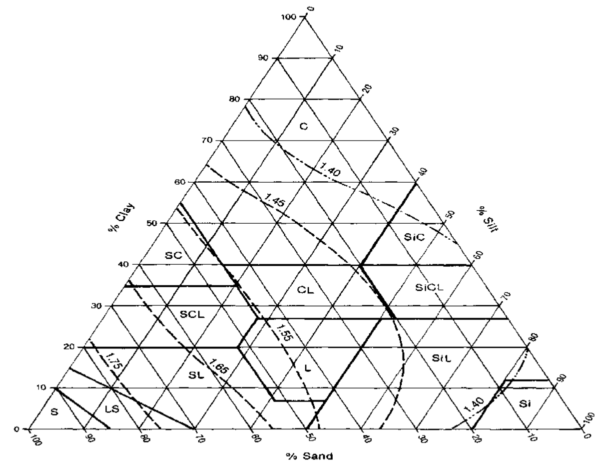


Figure 1: Growth limiting bulk density textural triangle

Statistical Analysis

The data was subjected to t-test to separate significant differences in soil strength between treatments (disturbance classes).

RESULTS AND DISCUSSION

Change of pore space and bulky density

Soil compaction from the fully mechanized timber harvesting equipment measured two years after the harvesting operations, showed that the operations conducted during wet season caused the greatest change of bulk density compared to the dry season operations. Working during wet season increased the average bulk density of soils from 1.14 to 1.61 g/cm^3 which was 67.0% greater than adjacent undisturbed soils. Bulk densities from area harvested during dry season averaged 1.21g/cm^3, which was 14.0% more than the average for undisturbed soils (Table 1).

Harvesting timber with heavy equipment during wet season reduced the average pore space of soil to 39%, a loss of about one-third of the macro porosity of undisturbed soil (57%). Pore spaces of the area harvested in dry season averaged 52%, which was 11 percentage points below that of undisturbed soil. An increase in bulk density and loss of pore space reduces the percolation rate of compacted soils (Sands *et al.* 1979; and Burger *et al.* 1984). A reduced percolation rate causes a substantially lower infiltration rate and larger amounts of surface run-off (Kamaruzaman *et al.* 1986). In addition, most compacted soil in areas logged in wet season occurs in bare track ruts which serve to channel run-off water (Dyrness 1965).

Table 1: Main effects of fully mechanized timber harvesting operations on some selected soil physical properties

Disturbance class	Plot	Bulky density	Total porosity %	Change of Bulk density %	Change of porosity %	Change of Soil Resistance (N/cm^3) in 0-15 cm depth
wet season	Control	1.14	57.0	60.5	31.5	189.3
	Harvested	1.61	39			
dry season	Control	0.99	63	28.7	14.3	97.2
	Harvested	1.28	52			

A loss in macropores generally leads to a reduction in saturated hydraulic conductivity (Gent *et al.* 1983 and Fritton *et al.* 1986). These changes in saturated hydraulic conductivity may affect plant growth because this factor determines the rate at which excessive moisture can leave the soil system and how rapidly water, required for plant growth, can move through the soil system.

Change of Soil strength Characteristics

Analysis of soil penetration resistances, from sample locations, using t-test, showed that machine traffic increased soil compaction significantly (α =0.01). The effect was more pronounced when logging was done in wet season. For the plot which was disturbed in wet season, the soil penetration resistance increase ranged between 89.3 and 195.8 N/cm^2 while for the plot which was harvested in dry season the change of soil penetration resistance was between 47.5 and 108.6 N/cm^2 for the top 35 cm of the soil (Table 2).

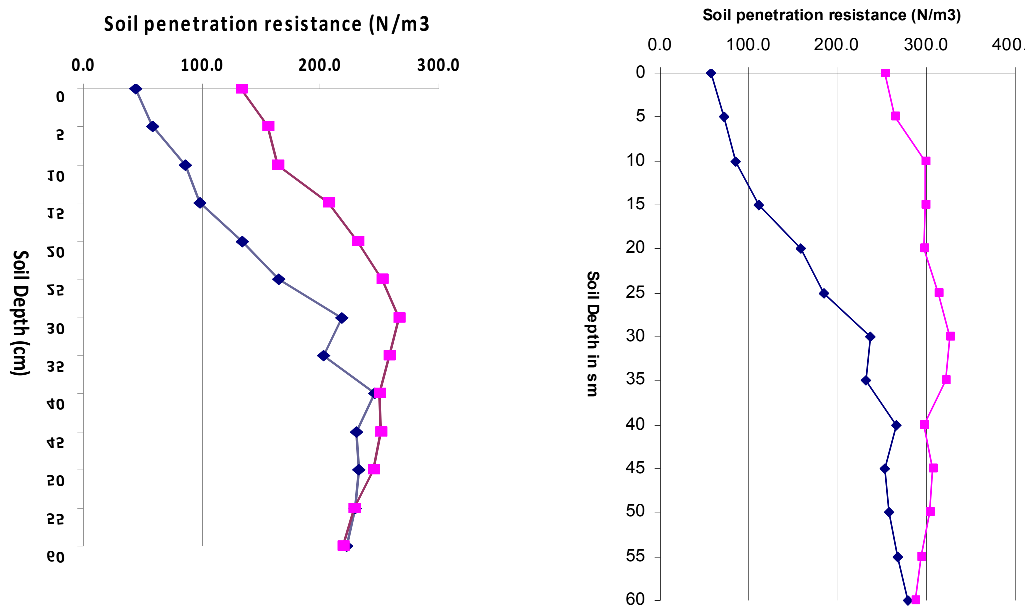
For the plot harvested in dry season increase in soil strength occurred to the depth of 50 cm, while for that which was harvested in wet season the strength was affected beyond 60 cm depth. However, when increase in soil penetration resistance was compared to the control plots adjacent to the harvested plot, the change was significant (α=0.05) only to the depth of 35 cm. This implies that, although machine traffic cause more soil compaction during wet season than in dry season, the soil layer affected significantly is the same (0-35 cm deep).

Table 3: Degree of soil compaction from harvesting equipment in relation to undisturbed control area

Plot harvested in dry season				Plot harvested in wet season			
Depth (cm)	Control area (N/cm^2)	Disturbed area (N/cm^2)	Change in Soil Strength (N/cm^2)	Depth (cm)	Control area (N/cm^2)	Disturbed area (N/cm^2)	Change in soil strength (N/cm^2)
0	43.8 (10)	132.6 (16)	88.8**	0	57.6 (10)	253.4(25)	195.8**
5	58.4 (10)	155.3 (19)	96.9**	5	72.3 (12)	265.3 (25)	192.9**
10	85.9 (9)	163.6 (19)	77.7**	10	84.3 (16)	298.4 (25)	214.0**
15	97.8 (10)	206.4 (21)	108.6**	15	111.4 (15)	299.4 (25)	188.0**
20	133.8 (10)	231.5 (19)	97.7**	20	159.0 (15)	297.9 (25)	138.9**
25	165.1 (7)	251.5 (19)	86.4**	25	184.0 (14)	314.2 (25)	130.2**
30	218.2 (12)	265.7(20)	47.5*	30	236.6 (19)	325.9 (20)	89.3**
35	203.0 (10)	257.6 (22)	54.6*	35	231.1 (14)	321.5(21)	90.5**
40	245.5 (11)	249.9 (22)	4.4 n.s	40	266.9 (12)	296.5924)	29.6 n.s
45	230.1 (12)	251.3 (19)	21.2 n.s	45	252.5 (11)	306.3 (25)	53.7 n.s
50	232.2 (12)	245.0 (20)	12.8 n.s	50	258.3 (17)	304.0 (25)	45.7 n.s
55	229.3 (12)	228.1 (21)	-1.1 n.s	55	267.0 (14)	294.1 (25)	27.1 n.s
60	222.5 (12)	219.4 (19)	-3.1 n.s	60	279.2 (16)	287.5 (25)	8.3 n.s

( ) indicates the number of observations, **Significant difference at P<0.01, *Significant Difference at P<0.05, n.s implies no significant difference

Before harvesting on these *Ultisols* soils, resistance to penetration was greater at greater soil depth on all units as shown by the control plots (Figure 2). Harvesting increased resistance to penetration on both plots but more significantly on the plot harvested during wet season (P<0.01). When compared to the existing Soil quality standard for compaction and affected area extent (UDSA Forest Service 2003), wet season equipment traffic was detrimental. The USDA compaction standard states that bulk density cannot be allowed to increase more than 15% from its natural (undisturbed) level in the top 20 cm of soil, and no more than 15% of the total area should be In the 0 to 20-cm depth, average resistance to penetration increased to 282.8 N/cm^2 from 96.9 N/cm^2 (192% increase) while the average bulky density increased by 60.5%. Average Compaction on the plot harvested in dry season increased from 83.9 to 177.8 N/cm^2 and the average bulky density increased by 28.7%. Although the plot harvested in dry season was less compacted than the plot harvested in wet season, on both plots the compaction exceeded the 15% increase limit. Also the extent of the area affected was more than 15% of the plots because sampling was based on grids laid out in the whole plot.



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Plot harvested in Wet season and its control   Plot harvested in dry season and its control

Figure 1: Valuation of penetrometer resistance with depth as affected by fully mechanized harvesting equipment for wet and dry season disturbance classes

The results of this study are very similar to others studies which investigated the effects of logging equipment traffic on forest soils. Migunga (1995) investigated the effects of tractor log skidding on the bulky density of soils in Sao hill Forest plantations and found that, after 5 passes with articulated skidder, the soil bulky density increase by 88% from 0.87 g/cm^3 to 1.53 g/cm^3. Day and Holmgren (1952) using three different levels of compactive force, found the soil to be 2.4 to 3.0 times more compacted when these forces were applied to moist soil vs. dry soil. Similarly, primary skid trails, log decks and temporary roads were about 50% more compacted during moist season equipment logging vs. dry season logging. These findings are in line with those of Hatchell *et al.* (1970), who concluded that one equipment pass under moist soil conditions was equivalent to four equipment passes under dry soil conditions.

Conclusion

With reference to the aim of this research, it must be stated that soil bulk density due to logging equipment traffic increased significantly and that the greatest soil compaction occurred due to logging in wet season. Also, degree of compaction in both wet and dry area exceeds USDA standards. The part of the disturbed plots affected by detrimental compaction was more than 15% which is not acceptable by USDA standards. The effect of soil compaction on root growth largely depends on the type of logging machinery used and soil wetness during machine use. In this study harvesting in wet season increased soil bulky density to the extent of causing restricted the root growth (1.61g/cm^3), whereas logging in dry season may only affect root growth (1.28 g/cm^3).

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