Assessment of Soil Compaction Levels by Farm Machinery in Cultivated Fields of Elfam Farm

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ABSTRACT
Soil compaction is one of the major threats to soil quality. The increasing soil degradation due to soil compaction may be linked to the increase in weight of agricultural machinery, in the more intense use of machinery even under unfavorable soil conditions and in addition to poor crop rotation. Increased demand for food, with increasing population and limiting land has put a lot of pressure on land to increase output per unit area through mechanization. The objective of the research was to assess the level of soil compaction in cultivated fields. The research experiment was done in Elfam farm in Moiben Sub County of Uasin Gishu County, Kenya. The soils type is classified as Ferralsols with sandy loam texture. A four wheeled 70 kN tractor was used in the experiments. The experiment was conducted at three levels of normal loads of 26 kN, 30 kN and 34 k, and four levels of number of passes 1,5,10 and 15 all with three replications. The field bulk density was determined at varying levels of loading and number of passes using sand replacement method. The data was analyzed using statistical software for analysis of variance (ANOVA) at 95% confidence level and $p < 0.05$. From the results, the highest bulk density at 34 kN and 15 passes was 1513 kg/m^3 on the top soil. The lowest bulk density was 1116 kg/m^3 on the subsoil layer below 45cm at 26 kN and one pass. During the test period the moisture content average was 25%. The findings indicated that there was an increase in bulk density with the increase of loading and number of passes. The increased loading and number of passes was particularly found to affect the soil layer above 45cm. The relative compaction from the test results indicates that the soil was 95.5% compacted. Bulk density model was proposed with coefficient of determination (R^2) of 0.8822.

Keywords
Number of passes, loading, bulk density, penetration resistance, soil sampling

1. INTRODUCTION
Soil compaction is an environmental problem [1]. It is one of the causes of increased soil erosion and flooding [2]. In addition, it also affects availability of nutrients and pesticide leaching to the groundwater [3].

Due to serious effects of Soil compaction on soil quality, there have been efforts to ameliorate compacted subsoil by mechanical deep-loosening but it is very expensive and often fails [4] and [5]. The increasing soil degradation due to soil compaction may be linked to the increase in weight of agricultural machinery [6], in the more intense use of machinery even under unfavorable soil conditions and in addition to poor crop rotation.

The consequences of soil compaction are decreased root growth and plant development, leading to a reduction in crop yield [7]. Soil compaction also depends on the type of soil, texture, topography and moisture [8]. Subsoil compaction may persist for a very long time and is hence a threat to the long-term productivity of the soil [9].

The increased energy requirement also negatively influences the farmer's budget: the costs for fuel are high compared with the income from yield, and therefore, it is very important to note that the costs for tillage must be minimized in order to optimize the profit. The amount of energy consumption in tillage (especially in primary tillage) is quite high compared with other farming operations. It is contributing to the persistence of food insecurity due to reduced yields per unit area. Most large scale farmers use heavy machinery and equipment. The manner in which machinery are operated in the fields is haphazard and the operations go beyond the onset of the rainy season. Mechanization of field operations is developed with a full focus on economic profitability. As the hired contractors carry out the various farm operations there is no attention of preventing damage to the soil quality as the contractors are focused on output e.g. in terms of acreage ploughed rather than the soil's quality as a growing medium for crop [8].

The risk of undesirable changes in soil structure can be minimized by limiting the mechanically-applied stress to below a threshold stress [10], termed the pre-compression stress. While the concept of pre-compression stress as a threshold between reversible and irreversible strain is widely used, it has been scarcely tested in combination with wheeling experiments in the field. The impact of agricultural machinery on soil properties may be simulated by means of soil compaction models, which are an important tool for developing strategies for prevention of soil compaction.

Soil compaction of the agricultural soil is a global concern to engineers, soil scientists and farmers due to use of large and heavy farm vehicles. It is a major threat to intensification of crop production due to adverse effects associated with it. There is a decrease in crop yield and increase in management costs in areas where soil compaction is prevalent (Table 2). It also has a negative effect on the environment for example soil erosion, leaching of nutrients, pollution of water bodies and greenhouse gases production.

It has been accelerated by the use of large and heavy machinery and equipment under unfavorable soil conditions. The farming community is solely driven by profitability and without any thought of preserving the soil for tomorrow. Farming community also believed that sub-soiling once in a while will be able to address the issue once their unit production has gone down eroding their profit margins [12]. There is also another school of thought that as long as you are not using a disc or a mould board plough no soil compaction will occur, as such they have resorted to using spring-tined chisel plough mostly which require a lot of power. Soil compaction which is a physical form of soil degradation is a subject that is attracting increasing concern worldwide. Not much have been done in Kenya to study, documented and recommendation made on the impact of soil compaction due to the use of heavy farm machinery though it is one of the main threats to soil that contributes to the soil degradation. The main objective of this research study was to assess the extent of compaction by farm machinery in cultivated fields of Elfarm.

2. MATERIALS AND METHODS

2.1 Study Area

There are several large scale farms in Moiben division with fully mechanized wheat and maize production. Elfam is one of the several large scale farms in the division with 1012 ha of land. Elfam farm is in Moiben sub County of Uasin Gishu County. It lies to the North East of Eldoret town. It is about 20 km from the Eldoret town along the Eldoret – Iten road. The farm office has the coordinates 0°35'38.5"N and 35°22'15.7"E and the experimental plot has the coordinates 0°35'26.8"N and 35°22'52.8"E. The altitude is 2200 m above sea level. The prevailing rainfall ranges between 900-1100 mm per annum and the soils type is classified as Ferralsols with sandy loam texture[12]. The arable land is 607 hectares of which the area under maize is 364 hectares while the remaining is used for wheat growing, barley and *Boma Rhodes* grass for dairy animals (Table 3). The farm operations are fully mechanized from land preparation, harvesting and post-harvest. The machinery sizes vary from 45 hp to 180 hp. The combine harvesters are large with grain tank capacity of up to 6 tons with a choice of wheat or corn harvesting heads. (Elfam reports, 2014)

2.2 Machinery and Equipment

During the field tests the machinery, tools and equipment used were a 70 kN four wheel tractors, 60 kN and 120 kN capacity trailer, Dynamic Cone penetrometer (DCP), Sand replacement method equipment, basic soil excavation tools e.g. mattock, spade, chisel, mason hammer and Soil sample collection bags. The samples collected were taken to the Ministry of Transport and Infrastructure Materials Testing and Research Department laboratory (Eldoret) for the determination of moisture content, standard proctor tests and sieve analysis of the soil.

2.2.1 Tractor data

The weight of the tractor and equipment used was as per manufacturer's specification. The tyre pressure was kept at the recommended inflation of 124.2kPa by the manufacturer. The weight on the big rear wheel of the tractor is 65% of the total weight of the tractor ($W_{tractor}$) the weight transfer from the trailer to the tractor rear wheel is 15% of the total weight of the trailer and the load (W_{TL}). Therefore the normal force on the rear (F_r) tyres is given by the total as indicated in the John Deere operator's manual for 6605 of 2001.

2.3 Experimental Procedure

The experimental plot was chosen such that it was fairly flat and measured 400 m long by 48 m wide. It was then divided into three strips of 400 m long by 16 m wide (Figure 7).

Step 1: The plot was harrowed using a heavy spring tinned harrow then followed by a heavy disc harrow. Final harrowing and raking was done in readiness for planting.

Step 2: Each strip was divided into four sections of 100 m long and 16 m wide

Step 3: Plot L_1 was subjected to a loading of 26 kN by running the tractor at a speed of 7.5 km / hr once

Step 4: The data was randomly taken at the centre of the tyre mark. A set of three replicates were taken at depths of 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm.

Step 5: Step 3 was repeated by operating the tractor through the same tyre mark with the same load of 26 kN four times to make the number of passes to five. Step 4 was then repeated. The same procedure was repeated for 10 and 15 passes on the same plot with the same load

Step 6: On the second plot L_2 steps 3, 4, and 5 were repeated but with 30 kN load.

Step 7: On the third plot L_3 steps 3, 4, and 5 were repeated but with 34 kN load

2.5 Soil Sampling

Random soil sampling was done for use in the standard Proctor test (ASTM D698/ AASHTO T99) at materials laboratory in Eldoret using the standard sampling procedure (ASTM D4700) from experimental plots (Figure 1) at the following depths 0-30 cm and 30-60 cm

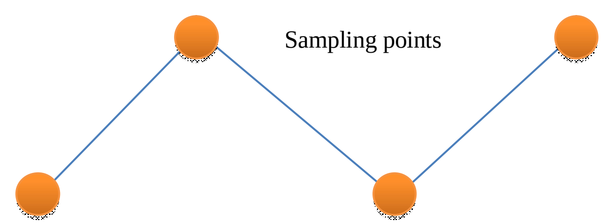

Figure 1: Sampling points design

2.6 Determination of the Effects of Load and Passes on Bulk Density

The field bulk density *(in situ)* was determined using sand cone replacement method (ASTM 1556) at the following depths 0-15 cm, 15-30 cm 30-45 cm and 45- 60 cm at random [9].

2.6.1 Determination of dry bulk density of sand to be used.

The sand mass in grams (g) was obtained by weighing and using the known volume of the calibrating container in cm^3. The bulk density of sand was calculated as follows:-

$$\rho_1 = \frac{M_1}{V_1}\ g/cm^3 \qquad \text{Eqn (3.5)}$$

Where ρ_1 is the dry density of sand in g/cm^3, M_1 is the mass of sand (g) and V_1 is the volume of sand in cm^3

The above calibration process was used to calibrate dry and clean sand to be used in the field. For every test two sets of calibrated sand was packed in a 3000 g marked container and 6000 g container. Each container had a unique identification label on it.

2.6.2 Volume of the test hole (V)

In the field the identified test point was leveled until the base plate fitted flat on top (Figure 15). The base plate was then secured using hooks hammered to the ground. The cylinder was then placed on the base plate. The sand in the 3000 g marked container was used to determine the mass of sand in the funnel and base (M_7). After removing the cylinder the test hole was excavated up to a depth of 15 cm (Figure 15). The soil from the test holes were packed in polythene bags sealed and labeled. The sand in the 6000 g marked container was then used to determine the mass of sand used to fill the test hole (M_6). The remaining sand in the cylinder was carefully returned to their specific container. The container was then weighed with the remaining sand. M_6 and M_7 were obtained by subtracting the remaining weights from their respective initial weights of the calibrated clean sand.
The volume of the test hole where soil had been scooped was then determined using the equation 3.6.

$$V = \frac{M_5 - M_7}{\rho_1} \ cm^3 \qquad \text{Eqn (3.6)}$$

Where ρ_1 is the dry density of sand in g/cm3, M_6 is the mass of sand (g) used to fill the test hole and M_7 is the mass of sand in the funnel and base (g)

2.6.3 Moisture content determination of the scoped material (ASTM 2216).

The scooped material from the test hole was packed in a sealed polythene sampling bags and taken to the lab for oven drying. The moist mass M_4 was determined. After which two samples were scooped into moisture drying cans per sample. The moisture cans were each weighed M_2 in grams. After oven drying for 48 hours, weight M_3 in grams was taken. The percentage moisture content w was calculated using equation 3.7. The average percentage moisture content of the two samples was taken.

$$w = \frac{M_2 - M_3}{M_3} \times 100\,\% \qquad \text{Eqn (3.7)}$$

Where w is the moisture content of the material from the test hole in percentage, M_2 is the mass of the moisture sample in (g) and M_3 is the dry mass of moisture sample in (g)

2.6.4 Calculation of the dry mass of the material from test hole using equation 3.8

$$M_5 = \frac{M_4}{(0.01)(w+100)} \ g \qquad \text{Eqn (3.8)}$$

Where w is the moisture content of the material from the test hole in percentage, M_4 is the moist mass of the materials from the test hole in g and M_5 is the dry mass of the materials from the test hole in g

2.6.5 Calculation of the bulk density of the materials from the test using equation 3.9 below.

$$\rho_2 = \frac{M_5}{V} \ g/cm^3 \qquad \text{Eqn (3.9)}$$

Where ρ_2 is the bulk density of the material from the test hole in g/cm^3, M_5 is the dry mass of the materials from the test hole in g and V volume of the test hole in cm^3

$$\rho_2 = 100 \times \frac{M_4}{M_8} \times \frac{\rho_1}{(w+100)} \ kg/m^3 \qquad \text{Eqn(3.10)}$$

Where: $M_8 = M_6 - M_7$ which is the mass of sand in the test hole

3.0 RESULTS AND DISCUSSION

3.1 Sieve Analysis

The results of soil sieve analysis using the British Standard (B.S) sieves and samples passing through 5 mm sieve yielded 7.4 % of clay, 32.7 % of silt and 59.6 % of Sand (Table 7). The soil texture based on USDA textural soil triangle (Figure 30) was found to be sandy loam. Generally sandy loam soils have bulk density between 1400kg/m^3 and 1600kg/m^3 [9].

3.1.1 Standard Proctor Test

The average maximum dry density (MDD) of the soil was found to be 1376 kg/m^3 and at an average optimum moisture content (OMC) of 29 %

3.2.1 Effect of the number of passes on bulk density for selected loads on a 0-15 cm soil layer

The results of the varying number of passes for the selected loading of 26 kN, 30kN and 34 kN were plotted against their respective bulk density for every soil layer. In figure 2 the plotted results indicates that loading has an effect on the bulk density as well as the number of passes. The increase in bulk density between a single pass and 5 passes is 5.5% for the lowest loading of 26 kN. The highest increase in bulk density is between the first and 5 passes for all the three levels of loading of 26 kN, 30 kN and 34 kN. The results show that there is an increase in bulk density with the increase in the number of passes. The change in bulk density between the first pass and 5 passes with the change in loading levels of 26, 30 and 34 kN is 5.5, 6.6 and 5.3 % respectively. The impact of number passes is felt between the first pass and five passes in all the treatments. This clearly confirms that bulk density is affected by change in loading as well as the change in the number of passes.

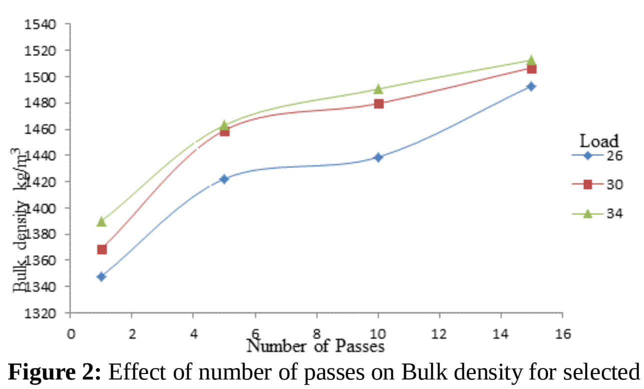

Figure 2: Effect of number of passes on Bulk density for selected loads for 0-15cm

3.2.2 Effect of the number of passes on bulk density for selected depths

The top soil layer has the highest bulk density and increases with increasing number of passes. The increase in bulk density between a single pass and 15 passes in the top layer is 10.8%. The second soil layer is less affected as the decrease in bulk density between first and the second layers for 1,5,10 and 15 passes are 9.9%, 10.7%, 9.7% and 6.8% respectively. From this result the top layer has the lowest bulk density of 1348 kg/m^3 and the highest is 1493 kg/m^3. The 15-30 cm, 30-45cm and 45-60 cm are less affected though there is an increase in bulk density with corresponding change in the number of passes (Figure 3). [3] studied the effects of compaction on pore size distribution of a soil aggregate at zero, three and five number of passes. He concluded that soil compaction decreases the pore sizes with increase in the number of passes. This implies that there is a decrease in volume and an increase in bulk density of the soil. The same trend happened with the loading level of 30 kN and 34kN though with higher bulk density. There is also a general decrease in bulk density with increase in depth for the selected levels of loading. The increase in bulk density means the soil cannot allow water penetration and at the same time roots will not penetrate deeper. Due to high bulk density increase in surface runoff will results and poor yields [16] in his study established that soil compaction affects the length of crop roots and yield of corn under irrigation.

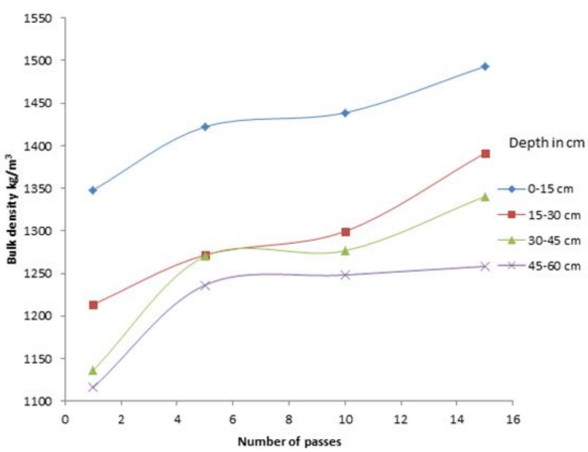

Figure 3: Effect of number of passes on Bulk density for selected depths for a loading of 26kN

3.2.3 Effect of loading on bulk density for selected number of passes

The bulk density for a single pass displays a linear relationship (Figure 4) and has the lowest bulk density ranging from 1348 kg/m^3 to 1390 kg/m^3 because it was ploughed and harrowed in preparation for planting, hence had no effects of the previous farm operations. The above relationships show that loading affects bulk density and increases with the increase in loading. The change in bulk density for a loading level of 26 kN from one pass to five passes is 5.5% as indicated in table 9. The results clearly indicates that with a single pass the soil is far much less compacted or affected as compared to subsequent repeated number of passes.

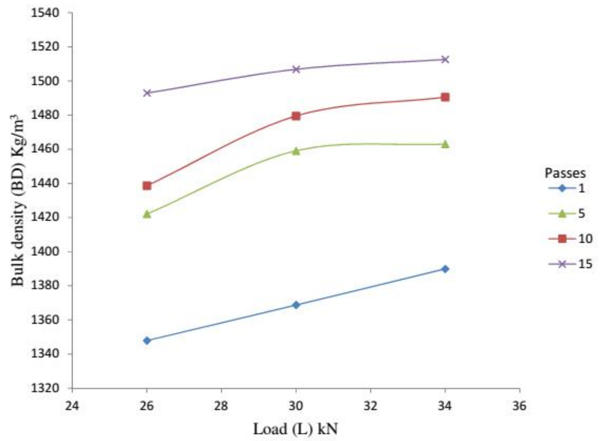

Figure 4: Effect of loading on bulk density for selected number of passes for 0-15cm layer

3.4.1 Analysis of variance for Bulk density

The multiple regression analysis of variance for bulk density was done using stepwise method (Minitab software), at 99% confidence interval and the P-value of $\alpha = 0.01$. The results are displayed on the ANOVA table. The load, number of passes and depth are all significant at 1% and 99% confidence level

3.4.2 Bulk density regression analysis model equation

Regression Equation for predicting the bulk density at a given depth, loads and number of passes was developed using Minitab software by stepwise method and the final equation is given by equation 4.1.

$$BD= 1094.6 + 9.02\ L - 4.099\ D + 12. \quad \text{Eqn (4.1)}$$

Where BD - Bulk density (kg/m^3), D - Depth (cm), L - Load (kN) and P – Passes

Using Principal component analysis(PCA) method in excel it was established that in equation 4.1 the final bulk density consist of 0.48 proportion of loading, 0.25 proportion number of passes and finally 0.25 proportion of depth(Table 1). The results show that the loading has the highest impact on the bulk density and contributes 48.3% to soil compaction while the number of passes and depth contribute 25% each. This confirms that axle load is the main cause of sub soil compaction as compared to the number of passes.

Table 1: Principal component analysis for bulk density

	L	D	P	BD
Variance	1.93	1.00	1.00	0.07
Proportion	0.48	0.25	0.25	0.02
Cumulative Proportion	48.3%	73.3%	98.3%	100.0%

The model regression equation was used to predict bulk density and compared graphically with the measured results of bulk density (Figure 5). The coefficient of determination R^2 is 0.8822 for linear correlation. If the intercept is selected to pass the origin (x=0, y=0) the coefficient of determination R^2 drops to 0.8624.

The best line therefore is the one with the intercept of 1912.5 returns the highest R^2 of 0.8822. The results display a second degree polynomial relationship between the observed and predicted results.

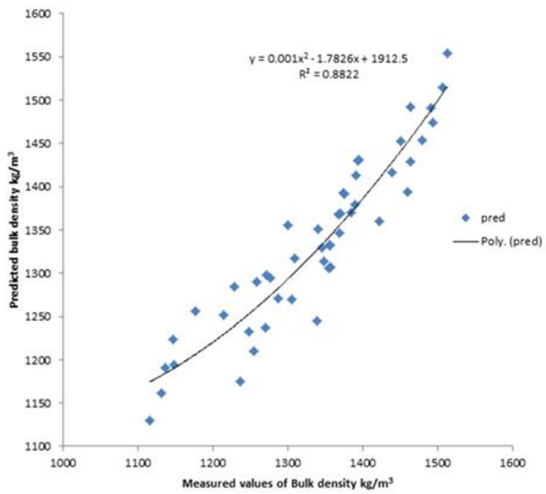

Figure 5: The relationship of measured results of bulk density against the predicted bulk density by equation 4.1

3.4.3 Bulk density for 30-45cm with a fitted line

The results of soil layer 30-45cm displayed graphically displays a second degree polynomial relationship with the coefficient of determination of 0.8985 and 0.9243 for 26kN and 30kN test results (Figure 6)

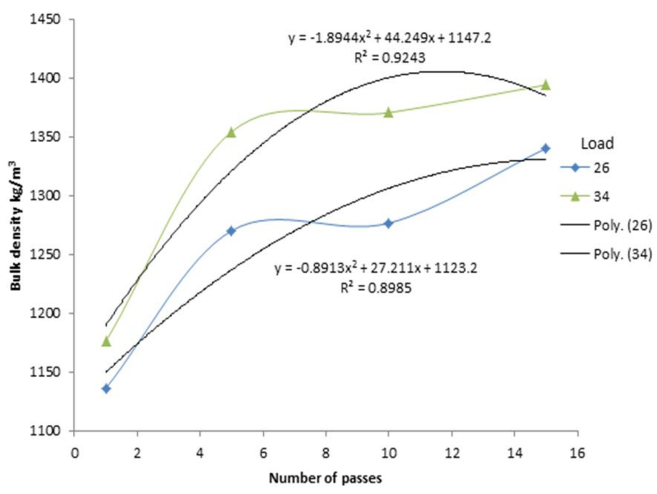

Figure 6: Fitted lines to measured results of bulk density for 26 kN and 34 kN

5. CONCLUSIONS

The maximum dry density (MDD) was 1376 kg/m3.Observed bulk density 1116 to 1513 kg/m3 and the Relative compaction was 81.1% to 110%

i. The effect of loading on bulk density on the top soil layer was high and it decreased with the increase in depth.
ii. Bulk density increased with the increase in the number of passes
iii. The increase in loading has more effect on the lower layers of the soil than the number of passes.
iv. The coefficients of determination (R2) for bulk density was found to be of 0.8822.

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Table 2 Average yield in tons per hectare for the last 7 years

Crop	Year						
	2008	2009	2010	2011	2012	2013	2014
Wheat (tons/ha)	3.3	4.0	3.8	0	3.3	0	0
Maize (tons/ha)	0	0	0	5.0	0	5.3	5.6

(Source: Elfam reports, 2014)

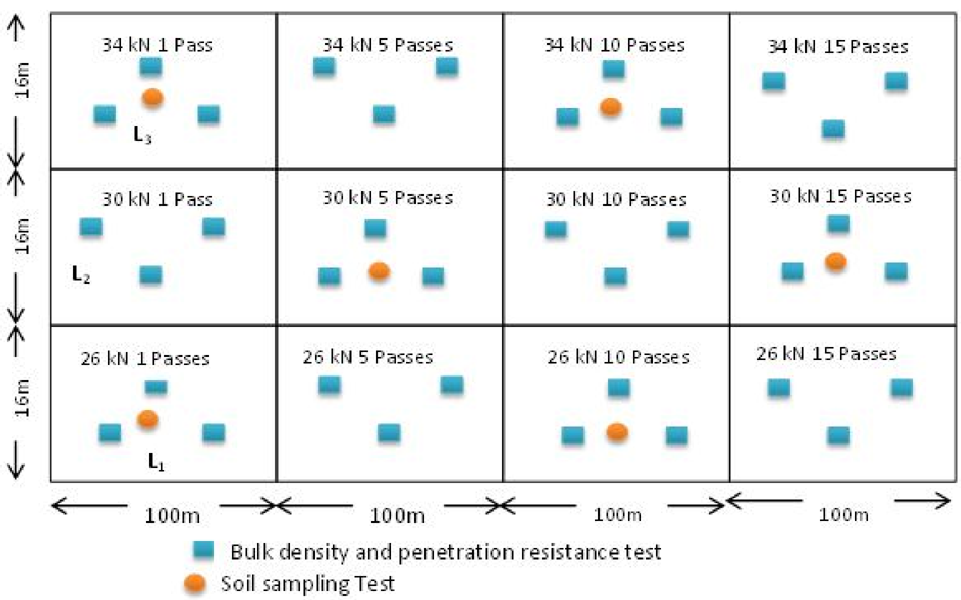

Figure 7: Experimental plots layout