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# Characterization of traffic induced compaction in controlled traffic farming (CTF) and random traffic farming (RTF) - A multivariate approach

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## Abstract

A field scale experiment was carried out in *Pukekohe* in 2020 under an annual grass crop season to characterize the subsoil compaction in controlled traffic farming (CTF) and random traffic farming systems (RTF). Soil penetration resistance (PR) measurements were taken in each field using a cone penetrometer fitted with a 100 mm$^2$ 60° top angle cone. Multivariate analysis was performed to identify penetration resistance by depth through cluster analysis and principal component analysis (PCA). Repeated measures ANOVA was performed on the penetration data using the mixed model procedure to determine the treatment effects. In RTF, the penetrometer values increased more rapidly with depth resulting in higher values being recorded from 20cm compared to CTF. In contrast, it was greater in CTF than in RTF at the subsurface (55-60cm). The differences in PR declined beyond 55cm depth at both sites. All depths showed that differences in soil PR were most apparent in the 5-40cm depth, with significant differences between CTF and RTF ($P<0.0001$). This shows that traffic management at both CTF and RTF sites caused significant changes in the 5-40cm depth. However, there were no differences in PR between CTF and RTF below 40cm and at 0-5cm depth ($P >0.05$) showing that the soil layers were homogeneous in both systems beyond 40cm depth. The propagation of subsurface compaction was identified at the deeper layer (40-60cm) in CTF systems whereas it was identified from shallower depths (25-55cm) in RTF system.

**Keywords:** Controlled traffic, Multivariate analysis, Penetration resistance, Principal component analysis, Random traffic.

## Introduction

Agricultural machinery movements in fields are the main source responsible for soil compaction (Chen & Yang, 2015). It leads to negative consequences such as the reduction in soil porosity, aeration (McHugh *et al.*, 2009), saturated hydraulic conductivity and an increase in soil resistance (Balbuena *et al.*, 2003; Valdés Abellán *et al.*, 2015). Controlled traffic farming (CTF) is considered to be a new approach to solve the soil compaction issue, in which crop areas and traffic lanes are permanently separated to provide optimal conditions for crop growth (Gasso *et al.*, 2013). Numerous studies have reported that CTF improves soil physical conditions, including reduced bulk density and penetration resistance, and increased infiltration, hydraulic conductivity, and plant available water (Alvarez & Steinbach, 2009; Chamen & Longstaff, 1995; Tullberg, 2010).

Even though different approaches are used for fast characterisation of soil compaction, a widely recognized approach is the measurement of soil penetration resistance or mechanical resistance (Marinello *et al.*, 2017). Characterization of soil compaction would be a useful measure in identifying layers with differences in levels of compaction to determine the effectiveness of CTF compared to random traffic farming (RTF). In this regard, multivariate analysis was used in this study to characterize the spatial (vertical and horizontal) compaction variability of both traffic systems to classify the attributes of traffic induced compaction. The present work focuses on characterizing the subsoil compaction during the growing period of annual grass in controlled traffic and random traffic farming systems in Pukekohe, New Zealand.

## Materials and methods

### *Experimental site*

A field experiment was conducted on two commercial scale vegetable sites located in Pukekohe (37.3187S, 174.9985E). Th fields have a sloping topography with dark reddish-brown clay-loam texture. The field was planted with annual grass during the course of study, treated with a controlled traffic farming (CTF) and a random traffic farming field, (RTF). The CTF site consisted of 3.6 ha of land with 130 established beds of 1.72m width and 260 intermediate tramlines having 0.9 m width (wheel tracks in between the beds). Tramline spacing typically occurred at approximately 1.72 m with a wheel gauge width of 3.40 m.

### *Traffic management*

Details of cultivation operations were noted for grass at CTF and RTF plots. During the annual ryegrass cycle, the CTF plot was excluded from deep ploughing machines except for a subsoiler. The tillage carried out at CTF beds consisted of a rotary hoe (175 hp), with one pass. The RTF site has an area of 3.6 ha and has been traditionally managed through random traffic farming treated with a ripper towed by John Deere tractors for land preparation with two passes. Land preparation involved deep ploughing, sub soiling and rotary hoeing at the RTF plot and the field was conventionally ploughed.

### *Soil Penetration resistance (PR)*

Penetration resistance (PR) was measured on 26$^{th}$ June 2020 after grass establishment in both CTF and RTF fields. Measurements were made across lower, and middle transects separately at both plots at a horizontal spacing of 10m, perpendicular to the direction of cultivation. Measurements were taken along each transect at 30cm intervals (horizontal direction, *X*-coordinate) and at 1 cm depth increments to a depth of 70 cm (vertical direction, *Z*-coordinate), and the force was digitally recorded using a cone penetrometer fitted with a 100 mm$^2$ 60° top angle cone. Readings included a tramline of ≈ 0.24m width and CTF-beds of 1.72m width in the CTF system. At the RTF plot where there were neither the beds nor tramlines, the measurements were randomly taken along lower, and middle transects as undertaken at the CTF plot. On an average, fifty measurements per transect were made at each plot, resulting in 7000 measurements per plot in total. Figure 1 shows the primary sampling points used for PR at CTF and RTF plot.

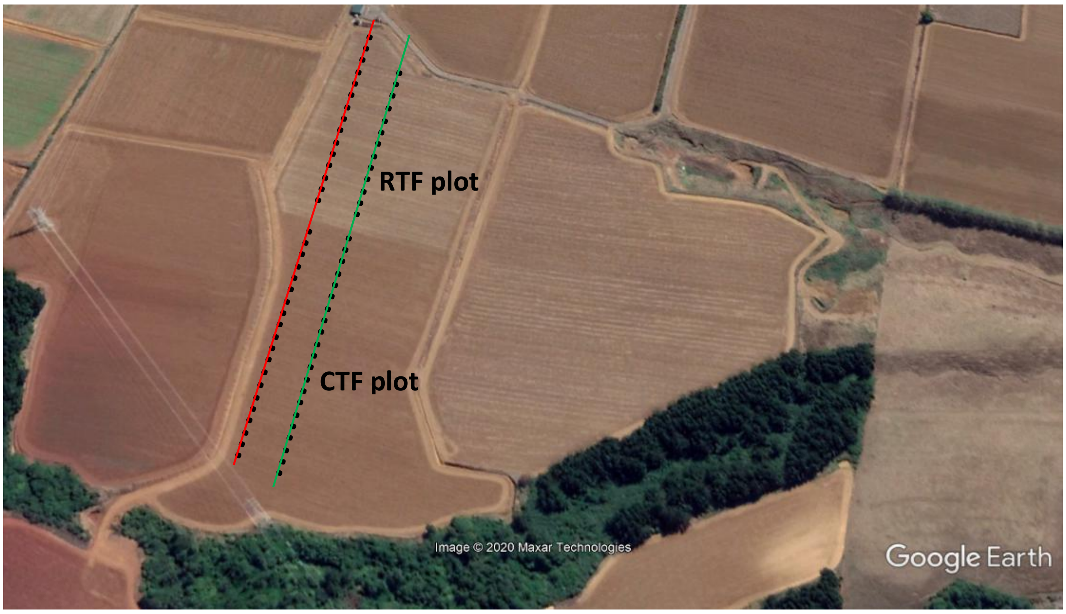


**Figure 1. Penetration measurement points at CTF and RTF plots** (37.3187S, 174.9985E). Black dots indicate PR measurement locations along lower (red), and middle (green) transects. Imagery date 3/11/2016. *Source: Adapted from Google Earth (2020).*

### *Data analysis*

Multivariate analysis was performed to identify the penetration resistance by depth through cluster analysis and principal component analysis (PCA). Clusters were formed by depth and by extent to establish the presence of layers and compact zones, using the Euclidean distance to separate the groups identified in the respective dendrograms. The measurements of penetration resistance at each depth in 5cm intervals were treated as different variables and PCA was performed to the different depths, using Varimax rotation. Repeated measures ANOVA was performed on the penetration data using the mixed model procedure of SAS software (SAS Institute 9.4). Traffic treatments were considered as the fixed effect, replication as the random effect, and soil depth as the repeated measure variable.

## Results

### *Cluster analysis*

The cluster analysis for CTF by depth presented three distinct groups (Figure 2A), where groups I and 2 were identified at depth 0-40 and 40-60cm with lower values of PR. In RTF system, the cluster analysis identified three groups (Figure 2B) which shows lower values of PR at depths between 0-25cm (group 1) with the highest values at depths between 25-60cm (group 2). This suggests a process of soil hardening at the shallow depths in RTF system. At depth 60-70cm where the PR tended to decline in both CTF and RTF systems where the PR values were lower than the second layer, but above the top layer (Group 3).

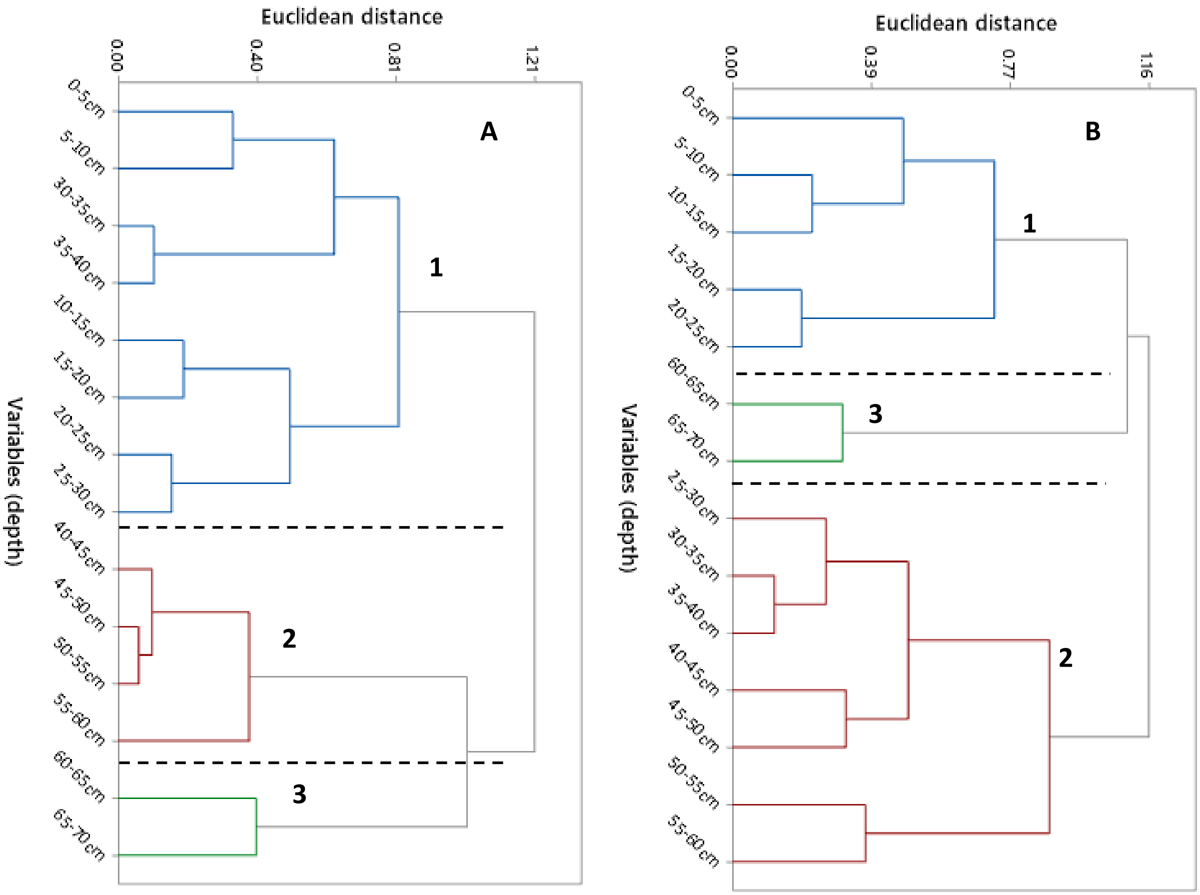


**Figure 2. Clustering dendrograms at different depths at CTF (A) and RTF (B)**

### *Principle component analysis (PCA)*

The PCA corresponds with cluster analysis, which relates the coefficients from the first three components, with eigenvalues > 1.0 and account for over 70% of the total variance in both CTF and RTF (Table 1 & 2). Each principal component (PC) is directly related to a soil layer which provides a clear performance of PR in three layers as identified in the cluster analysis. Communality values close to 1.0, for the PR at different depths explains the representative components analysed for this study. In CTF system, PC1 represents about 31.9% of the total variance and is related to surface layer at 0-40 cm depth, PC2 constitutes 28.6% of the total variance which confirms the presence of a layer at 40-60cm. PC3 represents 13.2% of the total variance and represented mainly by the soil layer >60cm. The coefficients of PC3 show negative correlation confirming the reduction in PR at depth >60cm (Table 1).

**Table 1. Principal Component matrix of CTF, after orthogonal rotation (varimax methods of rotation) for soil penetration resistance values of 14 depths**

| Variable | PC1 | PC2 | PC3 | Communality |
|---|---|---|---|---|
| 0-5cm | **0.518** | 0.091 | 0.402 | 0.438 |
| 5-10cm | **0.617** | 0.343 | 0.312 | 0.596 |
| 10-15cm | **0.733** | 0.340 | 0.266 | 0.724 |
| 15-20cm | **0.766** | 0.081 | -0.027 | 0.594 |
| 20-25cm | **0.861** | 0.009 | -0.137 | 0.760 |
| 25-30cm | **0.918** | 0.013 | -0.169 | 0.871 |
| 30-35cm | **0.743** | 0.363 | -0.069 | 0.689 |
| 35-40cm | **0.602** | 0.577 | -0.002 | 0.696 |
| 40-45cm | 0.324 | **0.897** | 0.004 | 0.909 |
| 45-50cm | 0.215 | **0.929** | 0.059 | 0.912 |
| 50-55cm | 0.164 | **0.953** | 0.021 | 0.936 |
| 55-60cm | -0.090 | **0.826** | -0.277 | 0.768 |
| 60-65cm | 0.074 | 0.165 | **-0.800** | 0.673 |
| 65-70cm | 0.027 | -0.008 | **-0.859** | 0.739 |
| | | | | |
| Eigen value | 6.0 | 2.4 | 1.7 | |
| % Var | 31.9 | 28.6 | 13.2 | |
| Cumulative var% | 31.9 | 60.5 | 73.7 | |

In RTF system, PC1 accounts for 32.6% of the total variance which corresponds to the depth between 25-55cm where higher values of PR were recorded. This differs from the cluster analysis, which identified the 2$^{nd}$ layer in between 25-60cm. PC2 reflects 22.2% of total variance and is related to the surface layer between 0-25cm showing lower values of PR. PC3 accounts for 16.7% of the total variance, representing the soil layer >60cm as found in CTF (Table 2). However, the coefficients show a positive correlation of the PR at this depth suggesting an increased PR in the subsequent depths.

**Table 2. Principal Component matrix of RTF, after orthogonal rotation (varimax methods of rotation) for soil penetration resistance values of 14 depths**

| Depth (cm) | PC1 | PC2 | PC3 | Communality |
|---:|---:|---:|---:|---:|
| 0-5 | 0.011 | **0.706** | -0.033 | 0.499 |
| 5-10 | 0.094 | **0.763** | -0.012 | 0.591 |
| 10-15 | 0.022 | **0.903** | 0.099 | 0.825 |
| 15-20 | 0.257 | **0.709** | -0.128 | 0.586 |
| 20-25 | **0.603** | **0.645** | -0.016 | 0.780 |
| 25-30 | **0.832** | 0.305 | 0.127 | 0.801 |
| 30-35 | **0.900** | 0.175 | -0.013 | 0.841 |
| 35-40 | **0.895** | 0.150 | -0.023 | 0.823 |
| 40-45 | **0.825** | 0.232 | -0.113 | 0.748 |
| 45-50 | **0.779** | -0.047 | 0.053 | 0.612 |
| 50-55 | **0.657** | -0.250 | 0.397 | 0.651 |
| 55-60 | 0.307 | -0.140 | **0.804** | 0.761 |
| 60-65 | -0.035 | 0.041 | **0.918** | 0.845 |
| 65-70 | -0.103 | 0.039 | **0.797** | 0.647 |
| | | | | |
| Eigen value | 5.2 | 2.7 | 2.0 | |
| % Var | 32.6 | 22.2 | 16.7 | |
| Cumulative var% | 32.6 | 54.8 | 71.5 | |

***Variance analysis***

The results of the analysis of variance showed that traffic system, soil depth, and interaction between traffic system x soil depth are highly significant ($P < 0.0001$). Mean comparison for all depths proved that differences in soil PR were most apparent in the 10-40cm depth, with significant differences between CTF and RTF ($P<0.0001$). However, there were no differences in PR between CTF and RTF below 40cm and at 0-10cm depth. ($P >0.05$). Although tramlines were not significantly different from RTF at 0-10cm, 40-45cm and 50-55cm, they were discretely separated from both plots with higher resistance between 10-40cm and over the 55 cm depth of the profile (Table 3).

**Table 3. Comparison of mean soil penetration resistance across CTF, RTF and in tramlines at different depths**

| Depth (cm) | Penetration resistance (MPa) | | | | | |
|---|---|---|---|---|---|---|
| | CTF | | RTF | | Tramline | |
| 0-5 | 0.05 ± 0.004 | *AB a* | 0.06 ± 0.01 | *AB a* | 0.153 ± 0.04 | *A a* |
| 5-10 | 0.122 ± 0.008 | *B a* | 0.228 ± 0.01 | *AB b* | 0.352 ± 0.09 | *A b* |
| 10-15 | 0.184 ± 0.01 | *C b* | 0.361 ± 0.02 | *B c* | 0.524 ± 0.13 | *A c* |
| 15-20 | 0.241 ± 0.01 | *C b* | 0.502 ± 0.04 | *B d* | 0.859 ± 0.21 | *A d* |
| 20-25 | 0.296 ± 0.02 | *C b* | 0.589 ± 0.04 | *B d* | 0.855 ± 0.21 | *A d* |
| 25-30 | 0.360 ± 0.02 | *C b* | 0.633 ± 0.05 | *B d* | 0.799 ± 0.19 | *A d* |
| 30-35 | 0.435 ± 0.03 | *C b* | 0.619 ± 0.04 | *B d* | 0.773 ± 0.19 | *A d* |
| 35-40 | 0.525 ± 0.03 | *C b* | 0.653± 0.04 | *B d* | 0.816 ± 0.2 | *A d* |
| 40-45 | 0.645 ± 0.04 | *B c* | 0.710 ± 0.03 | *AB d* | 0.837 ± 0.2 | *A d* |
| 45-50 | 0.761 ± 0.04 | *BC d* | 0.785 ± 0.04 | *B d* | 0.948 ± 0.23 | *A d* |
| 50-55 | 0.850 ± 0.05 | *A d* | 0.786 ±0.04 | *A d* | 0.882 ± 0.21 | *A d* |
| 55-60 | 0.823 ± 0.06 | *A d* | 0.671± 0.05 | *B e* | 0.931 ± 0.23 | *A d* |
| 60-65 | 0.637 ± 0.07 | *B e* | 0.592 ± 0.05 | *B e* | 0.855 ± 0.21 | *A d* |
| 65-70 | 0.500 ± 0.05 | *B f* | 0.537 ± 0.06 | *B e* | 0.757 ± 0.18 | *A d* |

Data are mean ± standard error of 51, 46 and 17 replicates from CTF, RTF and tramlines respectively. Values followed by different small alphabet letters within a column for each PR are significantly different between adjacent depths at $P < 0.05$. Values followed by different capital alphabet letters within a row for each PR are significantly different among traffic treatments at $P < 0.05$. Note: CTF-controlled traffic farm and RTF-random traffic farm.

## Discussion

In RTF, the penetrometer values increased more rapidly with depth resulting in higher values being recorded from 20cm compared to CTF. This reveals that RTF had a significant effect on penetration resistance on soil strength. The first layer (0-40cm) was found in CTF system with PR values ranging from 0.049-0.525 MPa depicts the effects of tillage and machinery traffic had little effect as heavy machineries were not used. The only tillage implement used on the CTF beds was a rotary hoe to manage preceding potato residue and the effect of it was detected only at 40-60cm as identified by PR values in the range 0.645-0.823 MPa in the 2nd layer (Figure 2).

However, the 1st layer identified from RTF system was at 0-25cm system and it reveals the repeated traffic movement that resulted in greater increases in PR of 0.059 – 0.589 MPa. The 2nd layer found in between 25-60cm deep demonstrates increased traffic intensity and soil manipulation in terms of its higher PR values of 0.633 – 0.786 MPa. This was because the RTF received three tillage operations during the study period which caused the increasing PR within the 2nd layer as pre-existing random traffic patterns in the RTF site would have propagated compaction below the plough layer, which could still exist as subsurface compaction (Alakukku, 1996; Strudley *et al.*, 2008). This is because when pressure is exerted on the soil surface, it is transmitted to subsurface layers, dissipating its effect at 0.50 m depth, influenced by soil texture and moisture content (Soane *et al.*, 1980). This is evidenced in this study by the positive coefficients of PC1 and PC2 for the 1st and 2nd layer respectively, showing a continuity between adjacent depths in in both traffic management systems (Stelluti *et al.*, 1998). The highest penetration resistance of 0.85 and 0.78 Mpa were recorded at 55cm in both CTF and RTF sites respectively. Soil PR was always greater in RTF than in CTF up to 45cm and became negligible at 50cm depth. It was greater in CTF than in RTF at the subsurface (55-60cm). The differences in PR declined beyond depth 55cm at both sites (Figure 2).

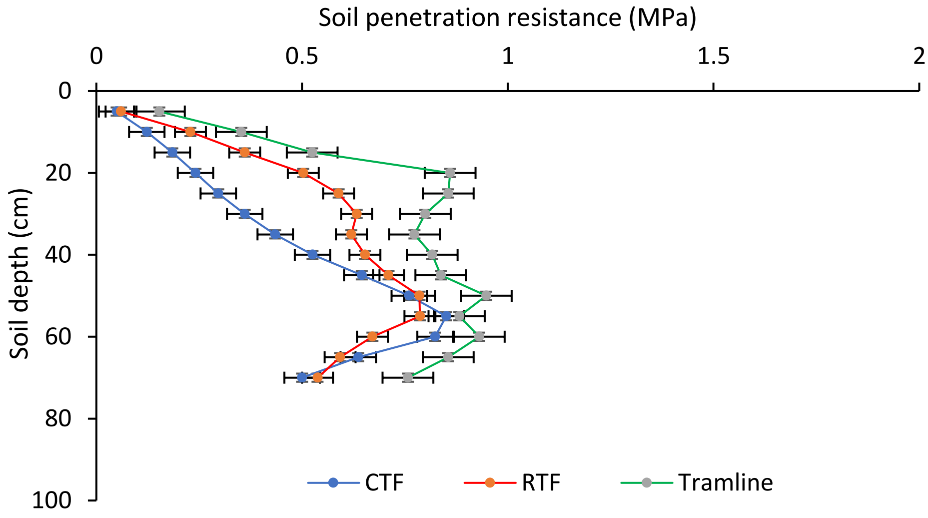


**Figure 2. Effect CTF and RTF on soil penetration resistance (PR) at 0–70 cm depth under annual grass in *Pukekohe.* Each data point is an average of 51 measurements for CTF and 46 measurements for RTF and 17 measurements for tramlines. CTF represents controlled traffic farming and RTF represents random traffic farming. Bars show the standard error between average values.**

The reduction in PR at both sites (0.37-0.5 in CTF and 0.671-0.537 in RTF) at depths greater than 60cm demonstrates the major reconsolidation occurs in agricultural soils after being subjected to external forces and climatic factors. In general, the PR values recorded in both traffic management systems do not seem to be harmful for crop growth conditions as evidenced by soil PR <2MPa which is a reference value above which root growth is increasingly restricted (Whiteley *et al.*, 1981). Lower soil PR values recorded at both CTF, and RTF sites resulted in non-significant differences in soil resistance in the upper 0-5cm depth. Less movement of machineries and soil loosening may have formed macropores at this depth by tillage in CTF. Furthermore, one of the tillage operations received by the RTF site was ripping that would also have reduced soil resistance in the 0-5cm depth.

## Conclusions

- Based on cluster analysis and principal component analysis three soil layers were identified in CTF and RTF system. The top layer exists at 0-40cm, the middle layer at 40-60am and the 3rd layer beyond 60cm in CTF site. RTF exhibited the top layer at the depth of 0-25cm, the middle layer at 25-60cm and the 3rd layer at depth >60cm.

- The traffic management at both CTF and RTF sits caused significant changes in the 5-40cm depth with their significantly lower soil strength in CTF compared to RTF system. The propagation of subsurface compaction was identified at the deeper layer (40-60cm) in CTF systems whereas it was identified from shallower depths (25-55cm) in RTF system. The soil layers were homogeneous in both systems in terms of soil strength beyond 40cm depth.

- Soil PR values do not seem to be detrimental for root growth as they did not exceed 2 MPa in any of the traffic system.

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