Journal Pre-proof

Exploring the sensitivity of visual soil evaluation to traffic-induced soil compaction

J.P. Emmet-Booth, N.M. Holden, O. Fenton, G. Bondi, P.D. Forristal

PII: S2352-0094(19)30242-1

DOI: https://doi.org/10.1016/j.geodrs.2019.e00243

Reference: GEODRS 243

To appear in: *Geoderma Regional*

Received date: 22 August 2018

Revised date: 1 October 2019

Accepted date: 14 October 2019

Please cite this article as: J.P. Emmet-Booth, N.M. Holden, O. Fenton, et al., Exploring the sensitivity of visual soil evaluation to traffic-induced soil compaction, *Geoderma Regional*(2019), https://doi.org/10.1016/j.geodrs.2019.e00243

Exploring the sensitivity of visual soil evaluation to traffic-induced soil compaction

J.P. Emmet-Booth[a], N.M. Holden[a], O. Fenton[b], G. Bondi[b], P.D. Forristal[c,*]

dermot.forristal@teagasc.ie

[a]UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4, Ireland

[b]Teagasc Environment Research Centre, Johnstown Castle, Co. Wexford, Ireland

[c]Crop Science Department, Teagasc Oak Park, Carlow, Co. Carlow, Ireland

[*]Corresponding author.

Abstract

Visual Soil Evaluation (VSE) techniques are useful for assessing the impact of land management, particularly the identification and remediation of soil compaction. Despite an increasing body of VSE research, comparatively few studies have explored the sensitivity of VSE for capturing experimentally imposed compaction to estimate sensitivity and limit of detection. The aim of this research was to examine the ability of VSE techniques to indicate soil structure at different soil profile depths and to measure the associated soil productive function (yield) response to imposed compaction. A two-year experiment was conducted on sites with loam and sandy soils. Varying levels of wheeled traffic were imposed on plots in a randomised block design, prior to sowing winter barley (*Hordeum vulgare* L.). Quantitative crop and soil measurements were taken throughout the season in conjunction with VSE techniques, which assessed to 25 cm (VESS), 40 cm (Double Spade) and 80 cm (SubVESS) depth. Graduated changes were observed by soil and some crop quantitative measurements as traffic treatment varied. VESS and Double Spade successfully identified a graduated treatment effect at all sites to 40 cm depth, although diagnosis translated into a functional (yield) response for the loam but not the sandy soil. Correlation between VESS *Sq* scores and crop yield were found. SubVESS gave mixed signals and indicated impacts lower in the profile in certain instances. These impacts were not captured by quantitative soil measurements. This work highlights the capacity for VSE techniques to indicate soil structure damage, which may cause a crop yield response, therefore allowing appropriate soil management strategies to be used before yield penalties occur.

Keywords: soil quality, soil structure, soil compaction, visual soil evaluation, VESS

1. Introduction

Visual Soil Evaluation (VSE) techniques are procedures for visually assessing soil quality with emphasis on soil structural quality (Mueller et al., 2013). Their utility is well established for research (Cherubin et al. 2019; Sasal et al., 2017; Pulido Moncada et al., 2014; Munkholm et al., 2013), soil management (Ball et al., 2017; McKenzie, 2013) and increasingly, knowledge transfer (Ball et al., 2018) due to procedures being suitable for a range of stakeholders (van Leeuwen et al. 2018). Multiple techniques exist, varying in objective and methodology (Emmet-Booth et al., 2016), and can be loosely categorised by their depth of assessment (Ball et al., 2017) and the assessment approach taken, i.e. profile description, or assessment of sample blocks extracted by spade (Boizard et al., 2005).

Examples of profile methods include Le Profil Cultural (Hénin et al., 1960; Manichon, 1987), SOILpak (McKEnzie et al., 1998) and SubVESS (Ball et al. 2015a), all of which require the mechanical excavation of soil pits and assessment of a profile face using traditional principles of soil classification (Emmet-Booth et al., 2016). Le Profile Cultural centres on the assessment of aggregates, their morphology and spatial arrangement with results described by symbols (Peigné *et al.*, 2013). SOILpak examines aspects of structural stability as well as structural form (Kay, 1990) and includes a numeric scoring system for aggregation (McKenzie, 1998). SubVESS also employs a scoring system and requires the assessment and scoring of individual properties with emphasis on identifying restrictive layers (Ball et al., 2015a). Two commonly used spade procedures include the VSA (Shepherd, 2009) and VESS (Guimarães et al., 2011) methods (Ball et al., 2017). VSA requires the individual assessment and numeric scoring of multiple soil properties including soil structure which is assessed by visually estimating aggregate size distribution following a drop-test on a sample block, typically extracted to ≈ 20 cm depth (Shepherd, 2009). VESS, perhaps the simplest and quickest technique (Guimarães et al., 2013; Pulido Moncada et al., 2014) requires the extraction of a sample block to 25 cm depth and following manual break-up, soil properties are assessed concurrently leading to an overall numeric score (Ball et al., 2007).

Profile methods focus on interactions between inherent soil properties and anthropogenic morphology through the profile, while spade methods, which focus on the upper profile, identify anthropogenic impacts (Emmet-Booth et al., 2016). However, in arable soils, a spade method such as VESS (which assesses to 25 cm depth) may not fully examine structural quality directly below the cultivation zone therefore, missing important features. The zone below cultivation is often referred to as the transition layer (Peigné et al., 2013) and is prone to compaction (Schjønning et al., 2002). A procedure combining both profile and spade methodology, termed the Double Spade (DS) method has been developed (Emmet-Booth et al. 2019; 2018) which aims to capture the transition layer using principles of both VESS and SubVESS. It requires evaluation of a profile to 40 cm depth without the need for mechanical soil pit excavation and therefore, is quicker than a full (to ≈ 1 m) profile method, allowing replication over wide areas.

VSE techniques can potentially explore multiple soil functions (Ball et al., 2017), though diagnosis is currently, primarily in terms of limitations to the productive function (Ball et al., 2007; Mueller et al., 2013; Ball et al., 2015a). Indeed correspondence between VSE diagnosis and crop yield has been reported (Mueller et al., 2009; Mueller et al., 2013; Abdollahi et al. 2015) notably for VESS *Sq* scores (Giarola et al., 2013; Munkholm et al., 2013). However, relationships may be site specific (Mueller et al., 2013; Abdollahi et al. 2015) potentially resulting from the interaction of multiple factors including soil texture, climate and management. VSE techniques have also been shown to successfully indicate impacts of different soil management (e.g. Guimarães et al., 2013; Askari et al., 2013; Abdollahi et al., 2015; Cherubin et al., 2017) and are even able to capture seasonal changes under specific systems (Pulido Moncada et al., 2017). However, comparatively few studies (e.g. Ball et al., 2015a; Obour et al., 2017) have explored the sensitivity of VSE techniques for capturing experimentally imposed structural degradation at prescribed levels. Therefore, the objective of this work was to explore how sensitive different VSE techniques were, in comparison with quantitative methods, to different levels of traffic-induced compaction, including levels that would impact crop yield.

2. Materials and methods

2.1. Experiment design

A two-year trial was established at the Teagasc Crop Research Centre, Oak Park, Ireland (52.8623 N, - 6.9179 W) in September 2015 at two sites of contrasting soil texture. According to WRB classification (FAO, 2015), the sites represented a Haplic Luvisol (Site 01) and Haplic Cambisol (Site 02). Site 01 consisted of a loam over sandy clay loam and Site 02, sandy loam and gravel over course sand and gravel

(Table 1). A third site (Site 03), similar to Site 01, was added for the second year. This represented a Haplic Cambisol and consisted of a loam over clay loam (Table 1).

At Sites 01 and 02, four imposed compaction treatments (Table 2) were applied to individual plots (5 m x 24 m) with four replications in a randomised block design, prior to sowing winter barley (*Hordeum vulgare* L.). At Site 03, because of space restrictions, three imposed compaction treatments were replicated four times. Traffic treatments (T) were applied following conventional ploughing (to ≈ 25 cm depth). In both years, compaction was imposed by driving specific machinery over the plots, ensuring complete coverage by the wheels. Full details of the machinery used, axle loads, tyre sizes and tyre pressures are outlined in Table 2. Machinery included a tractor with a mounted five-furrow reversible plough, a tractor with a mounted combined cultivation and sowing unit and a telescopic loader carrying ballast weight. For Year 2, a tractor towing a ballasted trailer was used instead of the telescopic loader to increase the loads applied. On completion of the traffic treatments, sowing was conducted with a tractor-mounted combined cultivation and sowing unit, which included a front press, rotary power harrow and integrated seed drill. All sites were rolled with a ring roller post sowing. Plots were divided into two sections, ensuring undamaged barley for harvesting and an area for destructive crop and soil measurements throughout the year.

2.2 Crop management

The winter barley variety KWS Cassia was sown at a target seed rate of 350 seeds per m^2 on 2nd October in Year 1 and 4th October in Year 2. Except for imposed pre-sowing compaction treatments, crops were managed conventionally. Potassium (K) and Phosphorus (P) were applied according to soil analysis, while a total of 180 kg of Nitrogen (N) was used over two applications in Spring. Herbicide (Isoproturon and

Diflufenican) was applied in Autumn for weed control and fungicide (Priothioconazole and Epoxyconizole based products) at crop growth stage (Zadoks et al., 1974) 30 and 37. A growth regulator (Chloroethylphosphonic Acid) was applied at growth stage 37.

2.3 Visual soil evaluation

VSE was conducted annually to three soil depths across all soil types, using the VESS (Guimarães et al., 2011), DS (Emmet-Booth et al., 2018) and SubVESS (Ball et al., 2015a) methods, examining to ≈ 25, 40 and 80 cm depths respectively.

VESS required the visual and tactile assessment of soil layers within a block of topsoil (0 to 25 cm), which was extracted by spade. Soil properties including aggregate size, shape, rupture resistance, visible porosity, rooting and redox morphology were considered. Evaluation was made with reference to the VESS score sheet (Guimarães et al., 2011) with application of structural quality (*Sq*) scores between 1 (good) and 5 (poor) per soil layer. The summation of layers scores multiplied by their corresponding depths as a proportion of the block depth gave overall soil block scores. *Sq* scores of ≤ 2, > 2 to ≤ 3 and > 3 were classified as good, moderate and poor structural quality respectively (Ball et al., 2007). VESS assessments were conducted in April and post-harvest and repeated three times per plot, per assessment.

DS followed VESS deployment, requiring the enlargement of the spade-sized pits created for VESS to 40 cm depth, with three assessments carried out per plot once per season; post-harvest. On an undisturbed side of the soil pit, structural layers were determined according to penetration resistance by inserting a trowel, and their position was recorded. Assessment was conducted on each layer and required the separate scoring of: (a) perceived penetration resistance; (b) redox morphology; (c) aggregate/fragment size; (d) aggregate/fragment shape; (e) intra-aggregate porosity; (f) perceived rupture resistance and (g) rooting. Using a similar scoring system to VESS, scores from 1 (good) to 5 (poor) were assigned for each property, with the sum of the property scores divided by the number of properties (7) giving layer scores. The sum of layer scores multiplied by their corresponding layer depths, divided by the total depth gave overall scores.

SubVESS required the mechanical excavation of soil pits to 1 m depth, however assessment was limited to 80 cm with just one assessment conducted per plot post-harvest. Varying structural layers from 20 cm downwards were identified by probing with a trowel and marked with plastic tags and their depths recorded. Each layer was evaluated with reference to the SubVESS score sheet (Ball et al., 2015b) by considering: (a) redox morphology; (b) soil strength; (c) porosity; (d) rooting and (e) aggregation, assigning scores to each as well as an overall layer *Ssq* score. To combine soil profile evaluations for individual replicates according to each treatment, the most frequently occurring structural layers were identified and their mean depths and corresponding *Ssq* scores were calculated for each treatment, per site. In addition, overall profile *Ssq* scores were also calculated by combining layer scores as for VESS. According to Ball et al. (2015a), *Ssq* scores of ≤ 3, >3 to ≤ 4 and > 4 were classified as good, moderate and poor structural quality respectively.

2.4 Crop measurements

Establishment counts were conducted each November using twelve 25 x 50 cm quadrates per plot. Pre-harvest head counts were conducted in July (≤ 10 days before harvest) using four 25 x 50 cm quadrats with the contained crop hand-harvested for harvest index and associated moisture content determination. For plot harvesting, a 2.75 m wide strip was harvested down the centre of each plot using a modified Deutz Fahr 33.70 combine fitted with a pneumatic grain delivery system and Harvestmaster automated weighing system which gave a total plot yield value. Crop moisture, thousand grain weight (TGW) and specific weight (*hl* weight) were determined from samples taken during plot harvesting.

2.5 Quantitative soil measurements

Cone penetration resistance was measured at 1 cm intervals to 80 cm depth (Eijkelkamp Penetrologger with a 1 cm^2 x 60^o cone) and shear resistance at 5 and 15 cm depth (Pilcon Hand Vane with a 1.9 cm vane) at ten points per plot in April and post-harvest during VSE deployment. As well as observing complete overall values, mean penetration resistance values were calculated for 10 cm increments, centred at 10 cm to 70 cm depth (incremental penetration resistance). Intact soil cores (Ø 5 cm x h 5 cm) were taken vertically within soil pits at 5 to 10 and 15 to 20 cm depth following VESS deployment in April and at additional depths of 25 to 30 and 35 to 40 cm following post-harvest VESS and DS deployment. Bulk density (ρ_b) and total porosity (TP) were determined from cores according to Grossman and Reinach (2002) and Flint and Flint (2002). Additionally, ρ_b was determined (Grossman and Reinach, 2002) from core (Ø 5 cm x h 5 cm) samples taken horizontally within SubVESS soil pits at 10 cm increments from 20 to 60 cm depth in three vertical lines across profile faces. In all cases, the > 2 mm fraction was isolated by wet sieving and $\rho_{b\,<\,2mm}$ was calculated, though described henceforth as ρ_b.

2.6 Data analysis

Arithmetic mean values for each measurement were calculated per plot and analysis was conducted using R Studio 3.4.4. (R Core Team, 2018). When exploring treatment effects, quantitative soil and crop measurements were normally distributed allowing the use of a parametric test (ANOVA), while VSE scores required the use a non-parametric equivalent (Friedman). In each case, the randomised block design was accounted for within equations. Relationships were explored using Spearman's rank correlation.

3. Results and Discussion

3.1 Crop response to traffic treatment

The traffic treatment generated a significant crop response on the loamy soils (Sites 1 and 3) following only one year of treatment (Tables 3 and 4). A 22.4 and 19.7 % reduction in yield was observed between T1 and T4 at Sites 01 and 03 respectively in Year 2. Visual differences in crop growth were notably evident at Site 03 during the season (Fig. 1). No significant yield response was found on the sandy soil (Site 02), despite two years of treatment. At Site 03, a significant reduction in specific grain weight may have contributed to the yield reduction (Table 4). The absence of a yield response to treatment on the sandy soil was surprising. Though occasionally difficult to detect, sandy soils are as prone to compaction as other textures (Batey and McKenzie, 2006). However, Arvidsson and Håkansson (1996) reported increased yield reductions with increased clay content, with on average, 10 to 20 % reductions observed on clay loam soils and < 10 % on sandy soils following a repeated compaction treatment. In this case, the duration of the experiment or traffic treatments may have been insufficient to generate significant yield-affecting compaction on the sandy soil.

3.2 Soil structure response to traffic treatment - quantitative soil measurements

Quantitative soil measurements indicated a significant soil structural response to traffic treatment at all sites in both years, including the sandy soil, though to a lesser extent than the loamy soils (Tables 5 and 6). Properties including $\rho_{b,}$ TP, shear resistance and incremental mean penetration resistance (Figs. 2 and 3) showed progressive change with treatments. Despite $\rho_{b\ 35\text{-}40\ cm}$ showing significant difference at Site 02, significant effects were generally observed to 20 cm at both Sites 01 and 02 in Year 1 (Table 5) and to 30, 20 and 50 cm depth for Sites 1, 2 and 3 respectively in Year 2 (Table 6). Apart from the mentioned anomaly at Site 2 in Year 1, ρ_b, and TP at 25 to 30 and 35 to 40 cm depth, showed no significant difference in either year (data not shown). The greater depth of compaction suggested by PR measurements (Figs. 2 and 3) at Site 01 and the greater number of measurements that showed significant impact in the second year at Site 01 and less so at Site 02 (Tables 5 and 6) may indicate the potentially cumulative nature of compaction (Gameda et al., 1984) and progressive impact of the treatment. Post-harvest measurement of PR at Site 02 was greatly restricted due to encountering stones at ~ 30 cm depth (Fig. 2). This was more easily measured in April in Year 1 and in Year 2 perhaps due to greater soil moisture content ($\theta_{15\text{-}20\ cm} \approx 0.2$, compared to ≈ 0.1) allowing smaller stones to move. Mean horizontal ρ_b values obtained from SubVESS soil pits showed very limited treatment effect. Difference was only observed at 20 cm depth at Site 1 (P = < 0.01) in Year 2 and at 60 cm depth (P = 0.017) at Site 03.

3.3 Soil structure response to traffic treatment - visual soil evaluation

VSE diagnosis is principally concerned with the productive function (Ball et al., 2007; Mueller et al., 2013; Ball et al., 2015a). The VSE methods employed proved effective at showing soil structural differences that impacted on the productive function. VESS, which assessed to 20 cm depth, showed a significant response to treatment at all sites (Table 7) and in agreement with quantitative soil measurements. *Sq* scores progressively increased with treatment level indicating progressively poorer soil structural quality with increasing traffic treatment intensity, including the sandy soil (Site 02). According to the classification system described by Ball et al. (2007) mean minimum and maximum *Sq* scores indicated moderate to poor structural quality at Site 01 in both years, though *Sq* scores from 2.7 to 3.8 in Year 1 and 2.8 to 4.1 in Year 2 were observed. This suggested a temporal deterioration in structural quality as the experiment continued, in agreement with quantitative soil measurements. The sandy soil exhibited good to poor structural quality with *Sq* scores ranging from 1.8-1.9 to 3.1 in both years, perhaps suggesting some resilience to the treatment over time. This was also indicated by the trend of quantitative soil measurements. Structural quality ranged from moderate (*Sq* 2.9) to poor (*Sq* 4.1) at Site 03 in Year 2. Overall, the loamy soils had higher *Sq* scores, indicative of poorer structural quality. Higher *Sq* scores can be associated with soils with greater clay and silt contents compared to sandy textures (Franco et al., 2019). The signals from quantitative soil and crop measurements suggested that the poorer structural quality indicated by VESS on the loamy soils was indeed associated with a crop response and changes in ρ_b, TP, shear and penetration resistance. Yield was found to significantly negatively correlate with April (r_s = -0.64, *sig* = 0.008) and post-harvest (r_s = -0.63, *sig* = 0.009) assessment VESS *Sq* scores at Site 01, but only in Year 2 and when *Sq* scores were rounded to whole numbers (integers) (Fig. 3.). Interestingly, non-integer VESS *Sq* scores were found to significantly correlate with yield at Site 01 in Spring of Year 1 (r_s = -0.55, *sig* = 0.03) but not post-harvest or for either assessment in Year 2 (data not shown). At Site 03, yield strongly negatively correlated with both integer (r_s = -0.72, P = 0.009; r_s = -0.67, P = 0.018) (Fig. 4) and non-integer (r_s = -0.71, P = 0.009; r_s = -0.63, P = 0.03) VESS *Sq* scores for April and post-harvest assessments respectively. Correlation of integer *Sq* scores with yield was reported in other studies (Giarola et al., 2013; Munkholm et al., 2013) but difference in findings according to *Sq* score format (integer or non-integer) was not mentioned. No significant relationship was observed between VESS and yield at Site 02 for either assessment in either year regardless of *Sq* score format. The site-specific nature of relationships between VSE and yield, considering factors such as soil texture, climatic conditions and agronomic management, has been highlighted elsewhere (Mueller et al., 2013), including with VESS (Abdollahi et al. 2015). Considering below 20 cm depth, overall DS (0 to 40 cm) showed significant treatment effect in the loamy soils (Sites 01 and 03) following one year of treatment, suggesting structural change to 40 cm depth. This effect was not picked up by quantitative soil measurements at Site 01 (Table 5 and Fig. 2). Either traffic treatment impacts evident at 0 to 20 cm depth were sufficient to influence the overall DS score, or the DS method has better resolution due to its ability to assess impacts on aggregate characteristics and other soil properties not assessed by quantitative measurements. Indeed, the quantitative soil measurements deployed in this study, may have been insufficient in capturing the full extent of the treatment effect, which VSE was able to indicate. Considering specifically 20 to 40 cm depth, DS $_{20\text{-}40\ cm}$ showed significant treatment effects at both loam sites in Year 2; however, of the quantitative measurements, only PR measurements were sensitive to capture these effects. The utility of PR in soil structural response determination, can be compromised by soil moisture levels (Vaz and Hopmans, 2001). Neither overall DS nor DS $_{20\text{-}40cm}$ scores significantly correlated with yield at the loam sites. However, in the second year of treatment, DS results suggested significant change below 20 cm depth in the sandy soil (Site 02) where quantitative measurements failed to capture these changes. A significant negative correlation was observed between yield and overall DS scores when rounded to integers at Site 02 (r_s = -0.69, P = 0.003) in Year 2 and overall non-integer DS scores at Site 03 (r_s = -0.60, P = 0.04) in Year 2. While the crop response to traffic treatment was not significant on the sandy soil (Site 02), and consequently correlation with soil structure effects were weak, the ability of DS to discern between traffic intensities at levels that did not impact on yields on these soils, is highly useful. The potential cumulative nature of soil structural damage (Gameda et al., 1987; Creamer et al., 2010) and the challenge of measuring damage with point specific quantitative measurements are recognised (Newell Price et al., 2013). Therefore the ability of VSE, including DS, to detect structural damage on these soils, before a significant crop response including a yield penalty occurs, offers scope to alter management to prevent more severe structural damage.

The significant treatment effect shown by the overall SubVESS *Ssq* score at Site 01 in Year 2 (Table 7) must be treated with caution. SubVESS is designed to examine layers and their position (Ball et al., 2015a), not to generate an overall profile *Ssq* score (Emmet-Booth et al., 2018). Structural layers observed using SubVESS are illustrated (Figs. 2 and 3). Combining information on structural layers, their positions and mean *Ssq* scores for replicates according to treatment, proved difficult due to great variation in layers between individual profiles. Compaction trials described by Ball et al. (2015a) and Obour et al. (2017) found consistent layer positions across treatments, therefore allowing potentially easier comparison. Examination of the position of the most frequently occurring structural layers and their mean values for the four replicates per treatment, showed degradation down to 80 cm depth under T4 at Site 01 in Year 2 (Fig. 3). SubVESS also suggested a decline in structural quality to 80 cm depth at Site 02 in Year 1 (Fig. 2). These findings were not recorded by quantitative measurements. It is worth noting that *Ssq* 4 (indicating poor structural quality) had to be applied to the lower layer (> 40 cm depth) at Site 02 due to single grain material. Therefore, higher *Ssq* scores in the lower profile did not necessarily indicate anthropogenic degradation, but inherent structural quality. Constraints associated with sandy, gravely textures and SubVESS deployment have been noted before (Ball et al., 2015a). SubVESS indicated no clear traffic treatment effects at Site 03. Significant change in penetration resistance was observed to 50 cm depth (Fig. 3). Obour et al (2017) found SubVESS indicated clear and gradual degradation due to compaction treatments. Clearer signals from SubVESS and quantitative measurements at greater depths may be obtained over a longer timeframe.

5. Conclusion

VSE techniques showed significant soil structural response to 20 cm depth in both the loam and sandy soil following one year and to 80 and 40 cm depth respectively following two years of imposed compaction treatment. Progressive change in VSE scores was observed with treatment level. Significant treatment effects were observed from quantitative soil measurements to 30 and 20 cm depth for the loam and sandy soil respectively following two years of treatment. It was concluded that the VSE techniques employed to 40 cm depth were sensitive enough to capture change in soil structure resulting from traffic treatment, which led to a significant soil productive function (yield) response in loamy but not a sandy soil. Signals from VSE for the sandy soil may have indicated potential yield penalties if compaction remained or worsened. This highlights the utility of VSE and the site-specific nature of relationships between VSE scores and yield. VSE techniques that examine below 20 cm depth indicated treatment differences that were not always detectable by the quantitative measurements deployed. While these indications were not strongly associated with a yield response, the ability to detect soil structural changes below 20 cm depth, should prove a useful tool in guiding soil management decisions and thereby help prevent yield-impacting damage at soil depths that may be difficult to remedy.

Acknowledgements

This work forms part of the SQUARE Project, funded by the Irish Department of Agriculture, Food and the Marine (Ref. 13/S/468). The authors thank K. Murphy, F.

Ryan, M.G. Ward, M. Nolan, S. Laisne, L. Chauchard and J. Grant for their technical support and kind help.

References

Abdollahi, L., Hansen, E.M., Richardson, R.J., Munkholm, L.J, 2015. Overall assessment of soil quality on humid sandy loams: Effects of location, rotation and tillage. Soil and Tillage Research 145, 29-36.

Arvidsson, J., Håkansson, I., 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil and Tillage Research 39, 175-197.

Arvidsson, J., Håkansson, I., 2014. Response of different crops to soil compaction – short-term effects in Swedish field experiments. Soil and Tillage Research 138, 56-63.

Askari, M.S., Cui J., Holden N.M., 2013. The visual evaluation of soil structure under arable management. Soil and Tillage Research 134, 1-10.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use and Management 23, 329-337.

Ball, B.C., Batey, T., Munkholm, L.J., Guimarães, R.M.L., Boizard, H., McKenzie, D.C., Peigné, J., Tormena, C.A., Hargreaves, P., 2015a. The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. Soil and Tillage Research 148, 85-96.

Ball, B.C., Batey, T., Munkholm, L.J., Guimarães, R.M.L., Boizard, H., McKenzie D.C., Peigné, J., Tormena C.A., Hargreaves, P., 2015b, Corrigendum to “the numeric visual evaluation of subsoil structure (SubVESS) under agricultural production” [Soil & Tillage Research 148, 85-96]. Soil and Tillage Research 154, 145.

Ball, B.C., Guimarães, R.M.L., Cloy, J.M., Hargreaves P.R., Shepherd, T.G., McKenzie, B.M., 2017. Visual soil evaluation: a summary of some applications and potential developments for agriculture. Soil and Tillage Research 173, 114-124.

Ball, B.C., Hargreaves, P.R., Watson, C.A., 2018. A framework of connection between soil and people can help improve sustainability of the food system and soil functions. Ambio 47, 269-283.

Batey, T., McKenzie, D.C. 2006, Soil compaction: identification directly in the field. Soil Use and Management 22, 123-131

Boizard, H., Batey, T., McKenzie, D., Rihard, G., Roger-Estrade, J., Ball, B.C., Bradley, I., Cattle, S., Hasinger, G., Munkholm, L., Murphy, B. W., Nievergelt, J., Peigné, J., Shepherd, G., 2005. Field meeting “visual soil structure assessment” held at the INRA Research Station, Estées Mons, France, 25-27 May 2005. Available from: http://iworx5.webxtra.net/~istroorg/download/WG%20Visual%20Soil%20Structure%20Assessment_Field%20meeting.pdf (accessed 5th March 2018).

British Standards Institution, 1989. Pipette method (BS 1796, 1989). British standard methods of test for soil for civil engineering purposes. British Standards Institution.

Cherubin, M.R., Chavarro-Bermeo, J.P., Siva-Olaya, A.M. 2019. Agroforestry systems improve soil physical quality in northwestern Colombian Amazon. Agroforestry Systems 93, 1741-1753

Cherubin, M.R., Franco, A.L.C., Guimarães, R.M.L, Tormena, C., Cerri, C.E.P., Karlen, D.L., Cerri, C.C., 2017. Assessing soil structural quality under Brazilian sugarcane expansion areas using visual evaluation of Soil Structure (VESS). Soil and Tillage Research 173, 64-74.

Creamer, R.E. Brennan, F., Fenton, O., Healy, M.G.,, Lalor, S.T.J., Lanigan, G.J., Regan, J.T., Griffiths, B.S. 2010. Implications of the proposed soil framework directive on agricultural systems in Atlantic Europe – a review. Soil Use and Management 26, 198-211.

Emmet-Booth, J.P., Forristal. P.D., Fenton, O., Ball, B.C., Holden, N.M., 2016. A review of visual soil evaluation techniques for soil structure. Soil Use and Management 32, 623-634.

Emmet-Booth, J.P., Forristal, P.D. Fenton, O. Bondi, G., Holden, N.M., 2019. Visual soil evaluation – Spade vs. profile techniques and the information conveyed for soil management. Soil and Tillage Research 187, 135-143.

FAO. 2015. World reference base for soil resources 2014, International soil classification system for naming soils and creating legends for soil maps. Update 2015. World soil resource reports 106, Food and Agriculture Organisation of the United Nations, Rome. Available from: http://www.fao.org/3/i3794en/I3794en.pdf (accessed 6th April 2018).

Franco, H.H.S., Guimarães, R.M.L., Tormena, C.A., Cherubin, M.R., Favilla, H.S. 2019. Global application of the Visual Evaluation of Soil Structure method: a systematic review and meta-analysis. Soil and Tillage Research 198, 61-69.

Gameda, S., Rsghavan, G.S.V., McKyes, E., Theriault, R. 1987. Subsoil compaction in a clay soil. I. Cumulative effects. Soil and Tillage Research 2, 113-122.

Giarola, N.F.B., da Silva, A.P., Tormena, C.A., Guimarães, R.M.L., Ball, B.C. 2013. On the visual evaluation of soil structure: The Brazilian experience in Oxisols under no-tillage. Soil & Tillage Research 127, 60-64.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use and Management 27, 395-403.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., Giarola, N.F.B., da Silva, A.P., 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil and Tillage Research 127, 92-99.

Grossman R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds), Methods of soil analysis. Part 4. Physical Methods. Soil Science Society of America, pp. 201-228.

Hénin, S., Féodoroff, A., Gras, R. & Monnier, G. 1960. Le profil cultural, principes de physique du sol. Société d'Editions des Ingénieurs Agricoles, Paris.

Kay, B.D., 1990. Rates of change of soil structure under different cropping systems. In: Stewart B.A. (Ed), Advances in soil science. Springer, New York, 12, pp. 1-52.

Manichon, H. 1987. Observation morphologique de l'état structural et mise en évidence d'effets de compactage des horizons travaillés. In: Monnier, G., Goss, M.J. (Eds), Soil compaction and regeneration, proceedings of the workshop on soil compaction: consequences and structural regeneration processes, Avignon 17-18 September 1985. AA Balkema, Rotterdam, Boston, pp. 39-52

McKenzie, D. 1998. SOILpak for cotton growers, 3rd Ed. NSW Agriculture, Orange. Available at: http://www.dpi.nsw.gov.au/agriculture/resources/soils/guides/soilpak/cotton (accessed 3rd April 2018).

McKenzie, D.C., 2013. Visual soil examination techniques as part of a soil appraisal framework for farm evaluations in Australia. Soil and Tillage Research 127, 26-33.

Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009. Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany, Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil and Tillage Research 103, 178-187.

Mueller, L., Shepherd, G., Schindler, V., Ball, B.C., Munkholm, L.J., Hennings, V., Smolentseve, E., Rukhovic, O., Lukin, S., Hu, C., 2013. Evaluation of soil structure in the framework of an overall soil quality rating. Soil and Tillage Research 127, 74-84.

Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil and Tillage Research 127, 85-91.

Newell Price, P., Whittingham, M.J., Chambers, B.J., Peel, S. 2013. Visual soil evaluation in relation to measured soil physical properties in a survey of grassland soil compaction in England and Wales. Soil and Tillage Research 127, 65-73.

Obour, P.B., Schjønning, P., Peng, Y., Munkholm, L.J., 2017. Subsoil compaction assessed by visual evaluation and laboratory methods. Soil and Tillage Research 173, 4-14.

Peigné, J., Vian, J-F, Cannavacciuola, M., Lefeure, V., Gautronneau, Y. Boizard, H. 2013. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. Soil & Tillage Research, 127, 13-25.

Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, J.C. Cornelis, W.M., 2014. Visual field assessment of soil structural quality in tropical soils. Soil and Tillage Research 139, 8-18.

Pulido Moncada M., Penning, L.H., Timm, L.C., Gabriels, D., Cornelis W.M., 2018. Visual examination of changes in soil structural quality due to land use. Soil and Tillage Research 173, 83-91.

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, Available at: http://www.R-project.org/ (accessed 5th March 2018).

Sasal., M.C., Boizard, H., Andrivlo, A.E., Wilson, M.G., Léonard, J. 2017. Platy structure development under no-tillage in the northern humid Pampas of Argentina and its impact on runoff. Soil and Tillage Research 173, 33-41.

Shepherd, T.G., 2009. Visual soil assessment, Field guide for pastoral grazing and cropping on flat to rolling country. 2nd Ed. Horizons Regional Council, New Zealand.

Schjønning, P., Elmholt, S., Munkholm, L.J., Debosz, K., 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agriculture, Ecosystems and Environment 88, 195-214.

van Leeuwen, M.M.W.J., Heuevelink, G.B.M., Wallinga, J., de Boer, I.J.M., van Dam J.C., van Essen, E.A., Moolenaar, S.W., Verhoeven F.P.M, Stoorvogel, J.J., Stroof, C.R., 2018. Visual soil evaluation: reproducibility and correlation with standard measurements. Soil and Tillage Research 178, 167-178.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Research 14, 415-421.

Table 1 Soil descriptions of experimental sites

Site 01				**Site 02**				**Site 03**			
Haplic Luvisol				Haplic Cambisol				Haplic Cambisol			
Layer Depth (cm)	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Layer Depth (cm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Layer Depth (cm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**
0 - 30	44	34	22	0 - 35	57	28	15	0 - 17	45	36	19
30 - 70	37	43	20	35 - 70	66	24	10	17 - 26	45	36	19

70 - 150	47	17	36	70 - 100	24	23	24	26 - 50	27	38	35
				100 +	Coarse sand and gravel						

Table 2 Traffic treatment specifications

Treatment	Year 1	Year 2
1	No additional traffic	No additional traffic
2	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure
3	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure One pass 7.8 t axle load; 650/65R 38 tyres; 1.2 bar inflation pressure	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure One pass 7.8 t axle load; 650/65R 38 tyres; 1.2 bar inflation pressure
4	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure Three passes 7.8 t axle load; 650/65R 38 tyres; 1.2 bar inflation pressure One pass 6.3t axle load; 460/70R24 tyres; 2.4 bar inflation pressure	One pass 6.5 t axle load; 600/65R 38 tyres; 1.1 bar inflation pressure Three passes 7.8 t axle load; 650/65R 38 tyres; 1.2 bar inflation pressure One pass 8.0 t axle load; 18R22.5 tyres; 4.0 bar inflation pressure
SMD *	Sites 01 & 02 = 19.4 mm	Sites 01& 02 = 4.6 mm, Site 03 = 7.6 mm

* SMD = Soil Moisture Deficit at time of compaction as predicted by Met Éireann (2018)
Note 1: Details are only given for the heaviest axle load applied with two axle tractor/mounted implement combinations or tractor/trailer combinations.
Note 2: For treatment 4, in year one a ballasted materials handler with relatively small tyres was used to exert high ground pressures. In year two an increased loading was achieved by using a loaded tractor trailer.
Note 3: One pass over the plots involved driving successive runs across the plot at a distance equal to the width of the tyre fitted to the axle exerting the heaviest load, until all of the plot was covered by wheelings.

Table 3 Relationship between mean crop measurements and traffic treatment for Year 1

Measurement	Compaction Treatment				Significance *(ANOVA)*	
	T1	**T2**	**T3**	**T4**	**SED**	**P Value**
			Site 01			
Establishment (plants m^2)	280	288	304	298	2.55	0.111
Heads / m^2	845	941	941	853	6.33	0.222
Yield (t / ha)	8.5	8.7	8.6	7.7	0.45	0.033
Harvest Index (%)	0.46	0.49	0.49	0.48	0.10	0.169
TGW (g)	50.0	49.9	50.7	50.5	0.78	0.811
Hectolitre (*hl*)	62.45	63.4	65.3	63.4	0.85	0.100
			Site 02			
Establishment (plants m^2)	314	316	315	315	2.43	0.998
Heads / m^2	853	952	911	861	5.90	0.222
Yield (t / ha)	6.8	6.7	6.9	6.7	0.35	0.725
Harvest Index (%)	0.52	0.54	0.52	0.50	0.09	0.094
TGW (g)	52.4	54.2	54.5	53.4	1.07	0.595
Hectolitre (*hl*)	67.1	66.8	67.6	67.3	0.55	0.328

SED = Standard error of difference

Table 4 Relationship between mean crop measurements and traffic treatment for Year 2

Measurement	Compaction Treatment				Significance *(ANOVA)*	
	T1	**T2**	**T3**	**T4**	**SED**	**P Value**
			Site 01			

Establishment (plants m^2)	280	274	287	277	2.52	0.563
Heads / m^2	1,003	1,053	1,036	893	6.16	0.058
Yield (t / ha)	9.8	9.8	9.5	7.6	0.55	0.001
Harvest Index (%)	0.55	0.56	0.56	0.58	0.08	0.020
TGW (g)	52.2	51.5	52.1	55.7	0.81	0.006
Hectolitre Mass (*hl*)	64.7	64.6	65.1	64.1	0.65	0.483
			Site 02			
Establishment (plants m^2)	257	284	281	274	3.17	0.278
Heads / m^2	1,032	1,064	1,121	1,020	5.91	0.243
Yield (t / ha)	7.6	7.7	7.7	7.5	0.26	0.235
Harvest Index (%)	0.58	0.57	0.57	0.57	0.08	0.844
TGW (g)	51.1	50.3	51.9	50.9	1.14	0.841
Hectolitre (*hl*)	68.8	68.6	69.1	68.5	0.53	0.507
			Site 03			
Establishment (plants m^2)	269	--	254	236	3.41	0.095
Heads / m^2	811	--	864	911	7.37	0.295
Yield (t /ha)	7.6	--	7.5	6.1	0.51	0.002
Harvest Index (%)	0.55	--	0.56	0.57	0.09	0.333
TGW (g)	51.9	--	51.3	53.1	1.03	0.355
Hectolitre (*hl*)	71	--	71	64	1.36	0.029

SED = Standard error of difference

Table 5 Significant relationships between quantitative soil measurements and traffic treatment in Year 1

Measurement	Assessment	$\theta_{15\text{-}20\ cm}$ [a]	Compaction Treatment				Significance *(ANOVA)*	
			T1	**T2**	**T3**	**T4**	**SED**	**P Value**
			Site 01					
$\rho_{b\ 5\text{-}10\ cm}$ (g cm^{-3})	April	0.3	1.3	1.4	1.4	1.4	0.14	0.026
$\rho_{b\ 15\text{-}20\ cm}$ (g cm^{-3})			1.3	1.4	1.4	1.4	0.13	0.015
TP $_{5\text{-}10\ cm}$ (%)			44.3	43.4	43.4	41.3	0.74	0.020
TP $_{15\text{-}20\ cm}$ (%)			45.5	44.5	43.4	40.5	0.76	0.001
Shear R. 5 cm (*kPa*)			14.3	17.5	18.5	28.3	1.06	< 0.01
Shear R. 15 cm (*kPa*)			20.0	26.3	37.0	49.0	1.26	< 0.01
TP $_{5\text{-}10\ cm}$ (%)	Post-harvest	0.3	45.3	44.1	43.5	41.4	0.78	0.009
			Site 02					
Shear R. 15 cm (*kPa*)	April	0.2	30.0	48.8	55.0	68.0	2.12	0.002
$\rho_{b\ 35\text{-}40\ cm}$ (g cm^{-3})	Post-harvest	0.1	1.0	1.1	1.1	1.0	-	< 0.01
Shear R. 5 cm (*kPa*)			35.5	42.8	39.3	41.0	1.20	0.033
Shear R. 15 cm (*kPa*)			52.8	77.0	86.0	91.5	2.54	0.009

[a] Mean volumetric water content during sampling SED = Standard error of difference
TP = Total Porosity Shear R = Shear Resistance

Table 6 Significant relationships between quantitative soil measurements and traffic treatment in Year 2

Measurement	Assessment	$\theta_{15\text{-}20\ cm}$ [a]	Compaction Treatment				Significance *(ANOVA)*	
			T1	**T2**	**T3**	**T4**	**SED**	**P Value**
			Site 01					
$\rho_{b\ 5\text{-}10\ cm}$ (g cm^{-3})	April	0.4	1.4	1.4	1.4	1.5	0.13	0.001
$\rho_{b\ 15\text{-}20\ cm}$ (g cm^{-3})			1.3	1.4	1.4	1.5	0.14	0.003
TP $_{5\text{-}10\ cm}$ (%)			47.7	44.5	44.2	41.5	0.74	< 0.01
TP $_{15\text{-}20\ cm}$ (%)			47.4	44.4	45.3	42.6	0.66	< 0.01
Shear R. 5 cm (*kPa*)			16.3	18.8	19.0	25.5	1.27	0.016
Shear R. 15 cm (*kPa*)			20.3	29.8	35.8	61.0	1.28	< 0.01

$\rho_{b\ 5\text{-}10\ cm}$ (g cm^{-3})	Post-harvest	0.3	1.4	1.5	1.5	1.5	0.14	0.007
$\rho_{b\ 15\text{-}20\ cm}$ (g cm^{-3})			1.4	1.4	1.5	1.5	0.12	0.002
TP $_{5\text{-}10\ cm}$ (%)			44.6	43.7	43.0	39.7	0.20	< 0.01
TP $_{15\text{-}20\ cm}$ (%)			44.2	43.4	43.0	40.6	0.71	0.003
Shear R. 5 cm (*kPa*)			36.0	41.0	42.0	54.5	1.65	0.006
Shear R. 15 cm (*kPa*)			47.0	55.5	63.8	111.8	1.83	< 0.01
			Site 02					
$\rho_{b\ 15\text{-}20\ cm}$ (g cm^{-3})	April	0.2	1.1	1.0	1.1	1.2	0.16	0.016
Shear R. 5 cm (*kPa*)			29.3	33.8	36.0	36.3	1.16	0.018
Shear R. 15 cm (*kPa*)			34.3	49.0	54.8	81.0	2.32	0.001
TP $_{15\text{-}20\ cm}$ (%)	Post-harvest	0.2	52.3	51.4	50.4	48.5	0.60	< 0.01
Shear R. 15 cm (*kPa*)			43.0	61.5	70.3	99.5	2.02	< 0.01
			Site 03					
$\rho_{b\ 5\text{-}10\ cm}$ (g cm^{-3})	April	0.3	1.3	--	1.4	1.5	0.18	0.011
$\rho_{b\ 15\text{-}20\ cm}$ (g cm^{-3})			1.4	--	1.5	1.5	0.20	0.027
TP $_{5\text{-}10\ cm}$ (%)			48.8	--	45.1	42.8	0.97	0.003
TP $_{15\text{-}20\ cm}$ (%)			47.1	--	43.6	41.6	0.60	< 0.01
Shear R 5 cm (*kPa*)			38.0	--	46.5	54.5	1.64	0.003
Shear R 15 cm (*kPa*)			36.3	--	51.3	89.3	1.91	< 0.01
$\rho_{b\ 5\text{-}10\ cm}$ (g cm^{-3})	Post-harvest	0.3	1.4	--	1.5	1.5	0.19	0.012
TP $_{5\text{-}10\ cm}$ (%)			46.5	--	42.9	39.9	1.05	0.004
TP $_{15\text{-}20\ cm}$ (%)			46.5	--	42.0	40.8	0.89	0.001
Shear R 5 cm (*kPa*)			44.5	--	58.5	63.0	1.79	0.004
Shear R 15 cm (*kPa*)			50.8	--	65.0	107.3	2.39	< 0.01

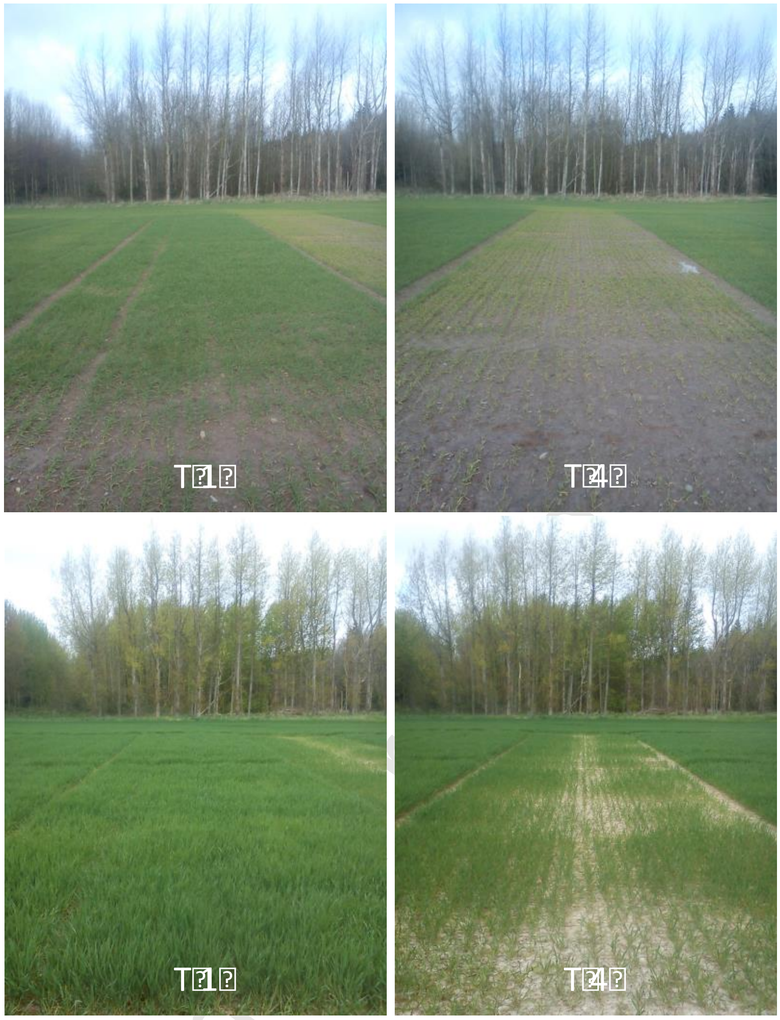
[a] Mean volumetric water content during sampling SED = Standard error of difference
TP = Total Porosity Shear R = Shear Resistance

Table 7 Significant relationships between mean overall VSE values and traffic treatment for both years

Measurement	Assessment	$\theta_{15\text{-}20\ cm}$ [a]	Compaction Treatment T1	T2	T3	T4	Significance *(Friedman)* Chi-squared	P Value
			Year 1 Site 01					
VESS (*Sq*)	April	0.3	2.7	2.9	3.0	3.6	10.15	0.017
DS	Post-harvest		2.4	2.6	2.7	2.8	10.09	0.018
			Year 1 Site 02					
VESS (*Sq*)	April	0.2	1.9	1.9	2.2	2.8	9.57	0.023
VESS (*Sq*)	Post-harvest	0.1	2.0	2.3	2.9	3.1	10.23	0.017
			Year 2 Site 01					
VESS (*Sq*)	April	0.4	2.8	3.2	3.0	4.1	8.40	0.038
VESS (*Sq*)	Post-harvest	0.3	2.9	3.1	2.9	3.7	9.77	0.020
DS			2.3	2.4	2.4	2.8	8.38	0.039
DS $_{20\text{-}40\ cm}$			2.5	2.7	2.6	2.9	10.30	0.016
SubVESS (*Ssq*)			3.0	3.3	3.0	3.8	8.29	0.040
			Year 2 Site 02					
VESS (*Sq*)	April	0.2	1.8	2.2	2.1	2.7	11.15	0.010
VESS (*Sq*)	Post-harvest	0.2	2.1	2.4	2.5	3.1	7.92	0.048
DS			1.9	2.1	2.1	2.5	8.13	0.043
			Year 2 Site 03					
VESS (*Sq*)	April	0.3	3.1	--	3.3	4.1	8.00	0.018
VESS (*Sq*)	Post-harvest	0.3	2.9	--	3.1	3.7	5.73	0.056
DS			2.4	--	2.7	3.1	7.60	0.022

DS $_{20\text{-}40\ cm}$	2.6	--	2.9	3.2	7.60	0.022

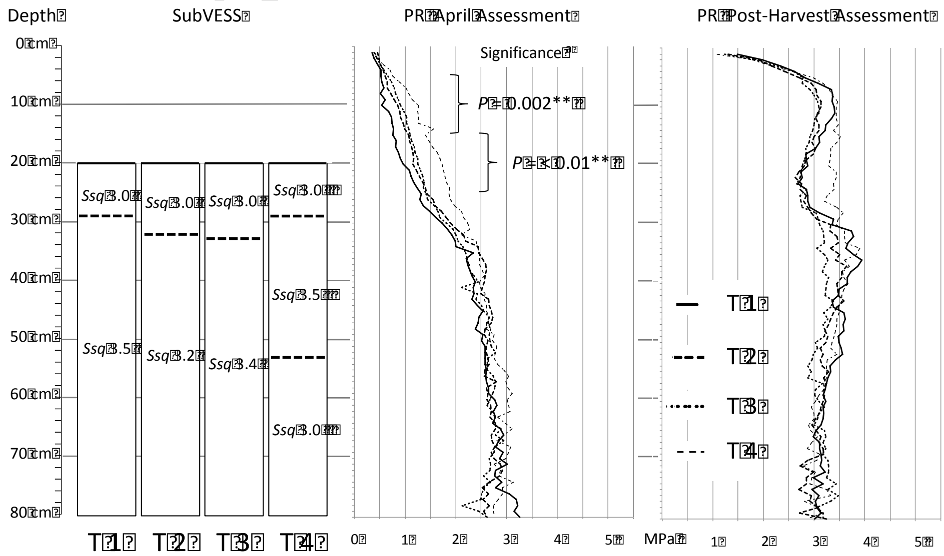
[a] Mean volumetric water content during sampling



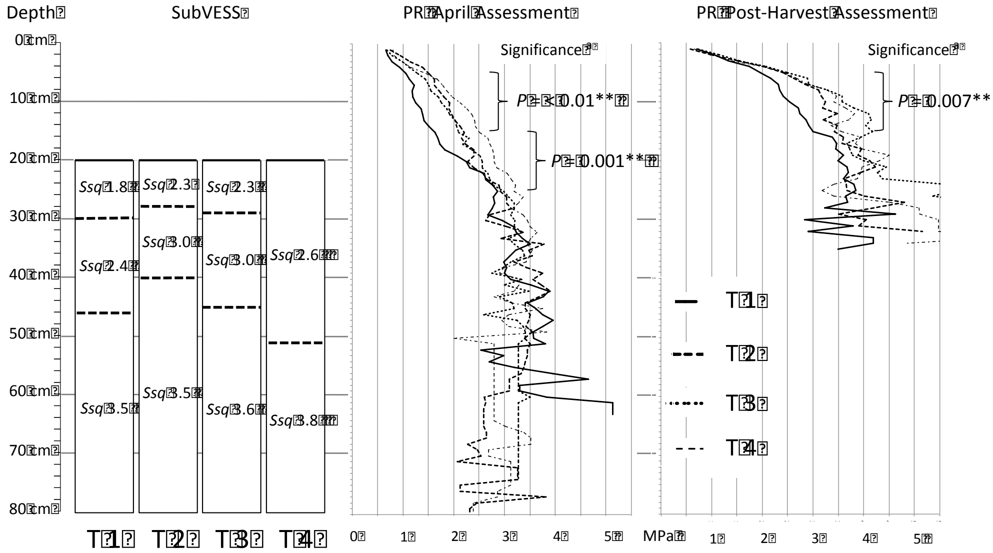
T = Traffic treatment

Fig. 1. Visible difference in crop growth between plots subjected to contrasting traffic treatments in January (*top*) and April (*bottom*) of Year 2 at Site 03

Site 01



Site 02

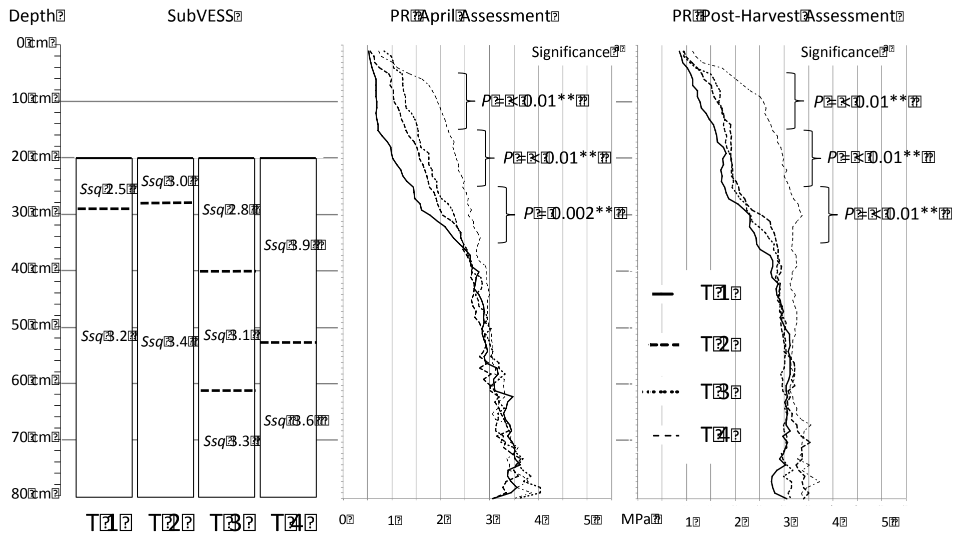


---- = Structural layer boundaries T = Traffic treatment

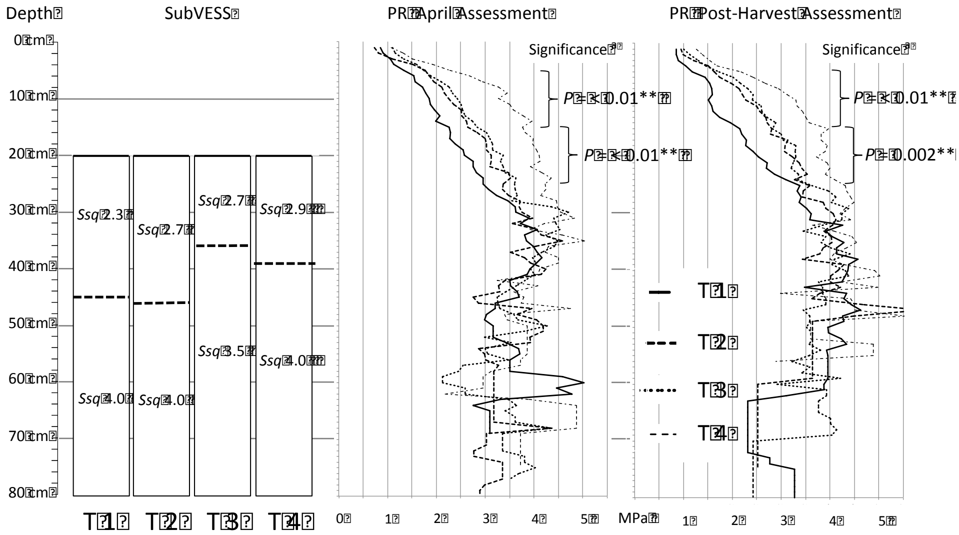
[a] Incremental mean penetration resistance for different soil depth increments that significantly differed according to traffic treatment (** Significant at P = 0.01)

Fig. 2. SubVESS evaluations per traffic treatment (includes most frequently occurring structural layers observed within replicates, their corresponding mean layer depths and *Ssq* scores), mean overall penetration resistance values, and significant relationships observed between incremental penetration resistance (mean values calculated for 10 cm depth increments) according to traffic treatment for Year 1.

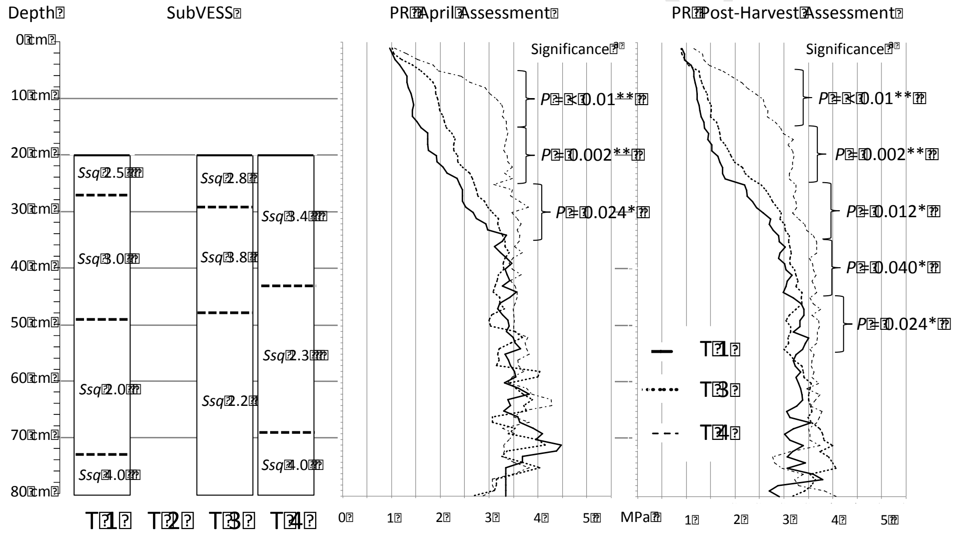
Site 01



Site 02



Site 03



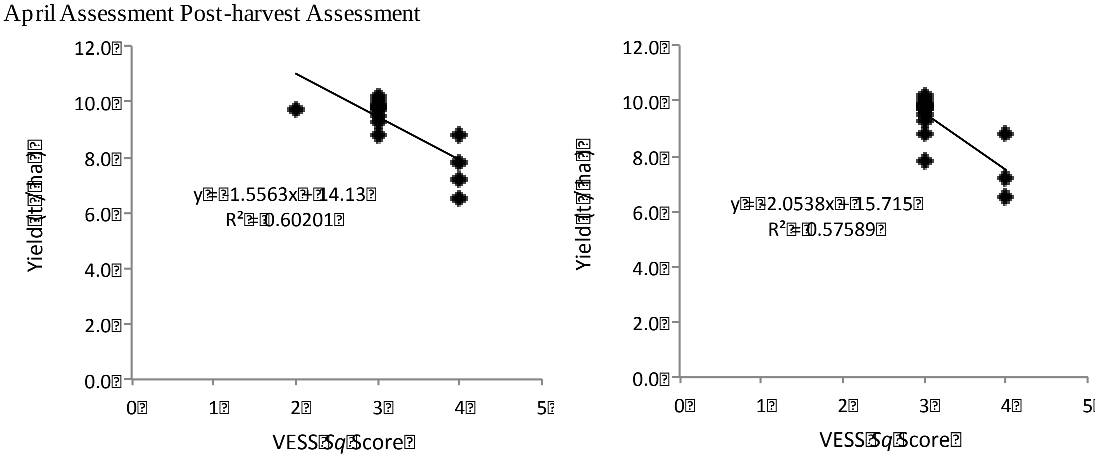
- - - - = Structural layer boundaries T = Traffic treatment

[a] Incremental mean penetration resistance for different soil depth increments that significantly differed according to traffic treatment (* Significant at P = 0.05 ** Significant at P = 0.01)

Fig. 3. SubVESS evaluations per traffic treatment (includes most frequently occurring structural layers observed within replicates, their corresponding mean layer depths and *Ssq* scores), mean overall penetration resistance values, and significant relationships observed between incremental penetration resistance (mean values calculated for 10 cm depth increments) according to traffic treatment for Year 2.

Site 01

April Assessment Post-harvest Assessment



Site 03

April Assessment Post-harvest Assessment

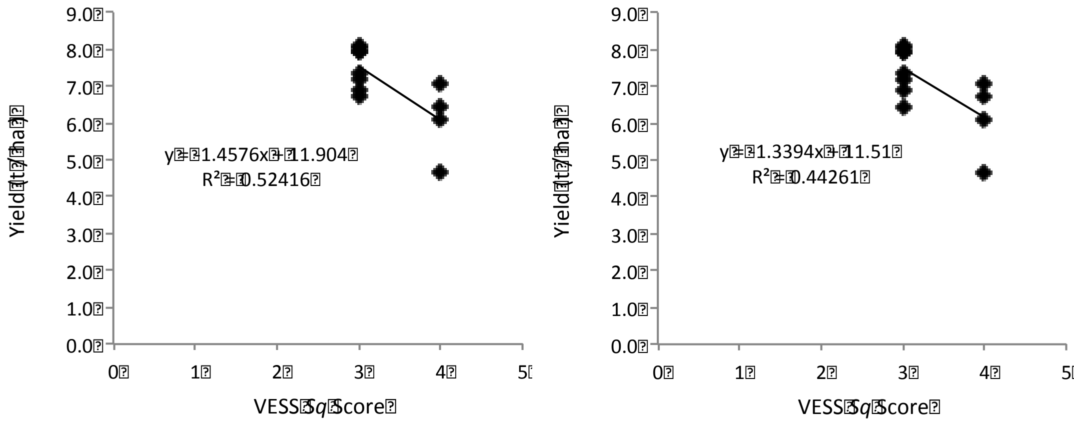
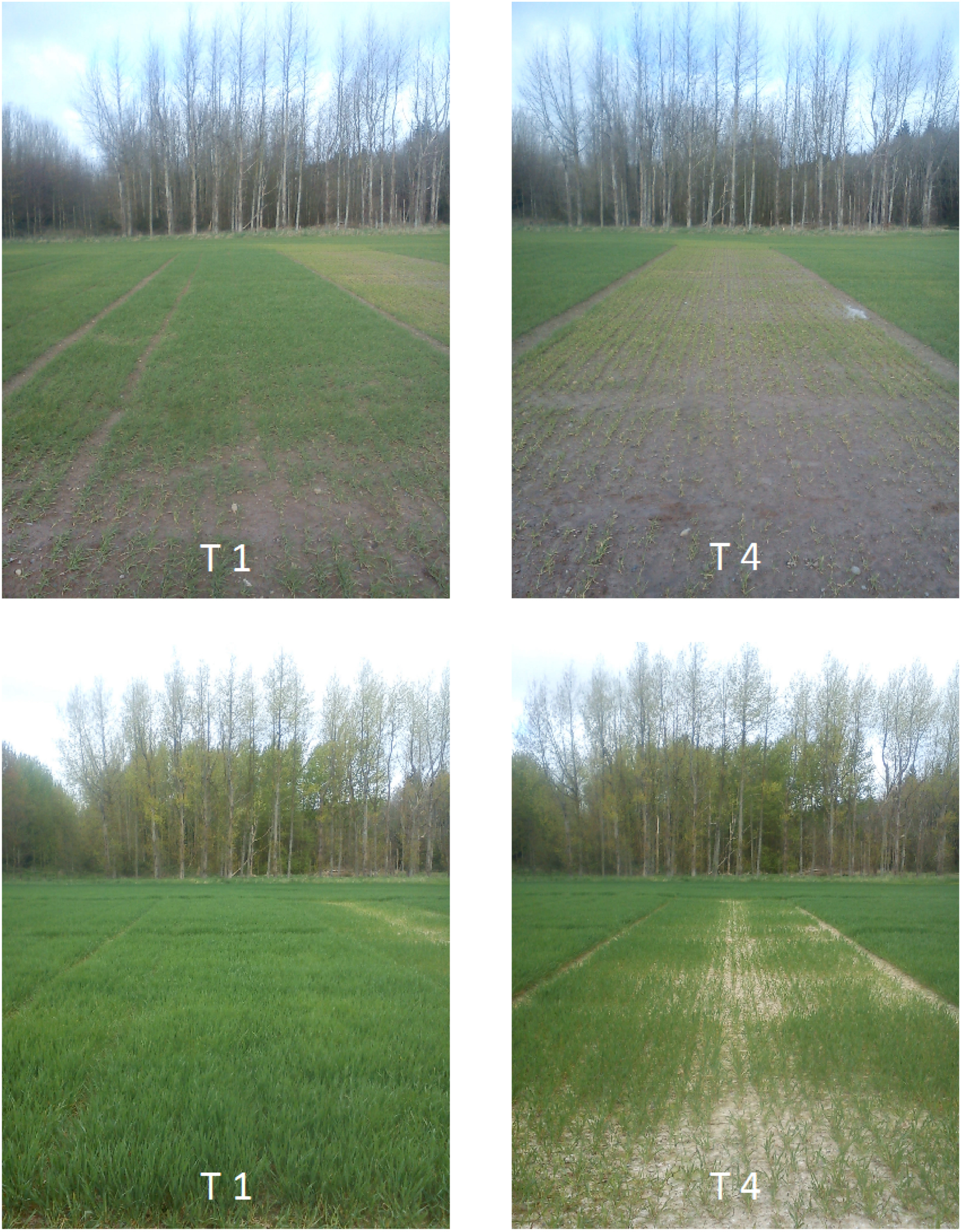


Fig. 4. Relationship between VESS *Sq* scores and crop yield at Site 01 and 03 in Year 2.

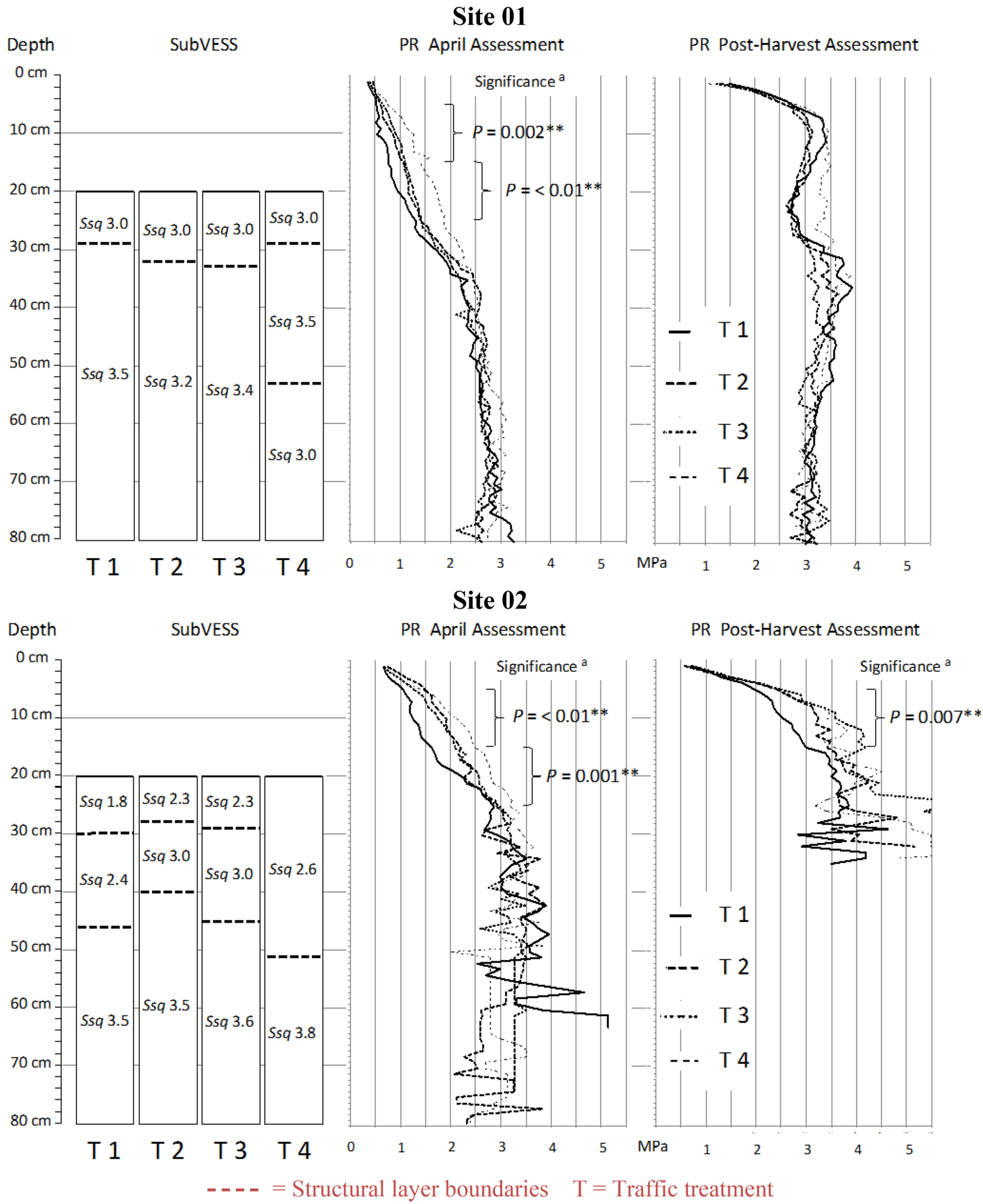
Highlights

- Imposed compaction treatments produced quantitative soil structure and crop effects
- VSE techniques to 40 cm depth were sensitive allowing treatment effects to be captured
- VSE diagnoses translated into a yield response on loam but not sandy soils
- VSE techniques can be used for early detection of yield-impacting compaction



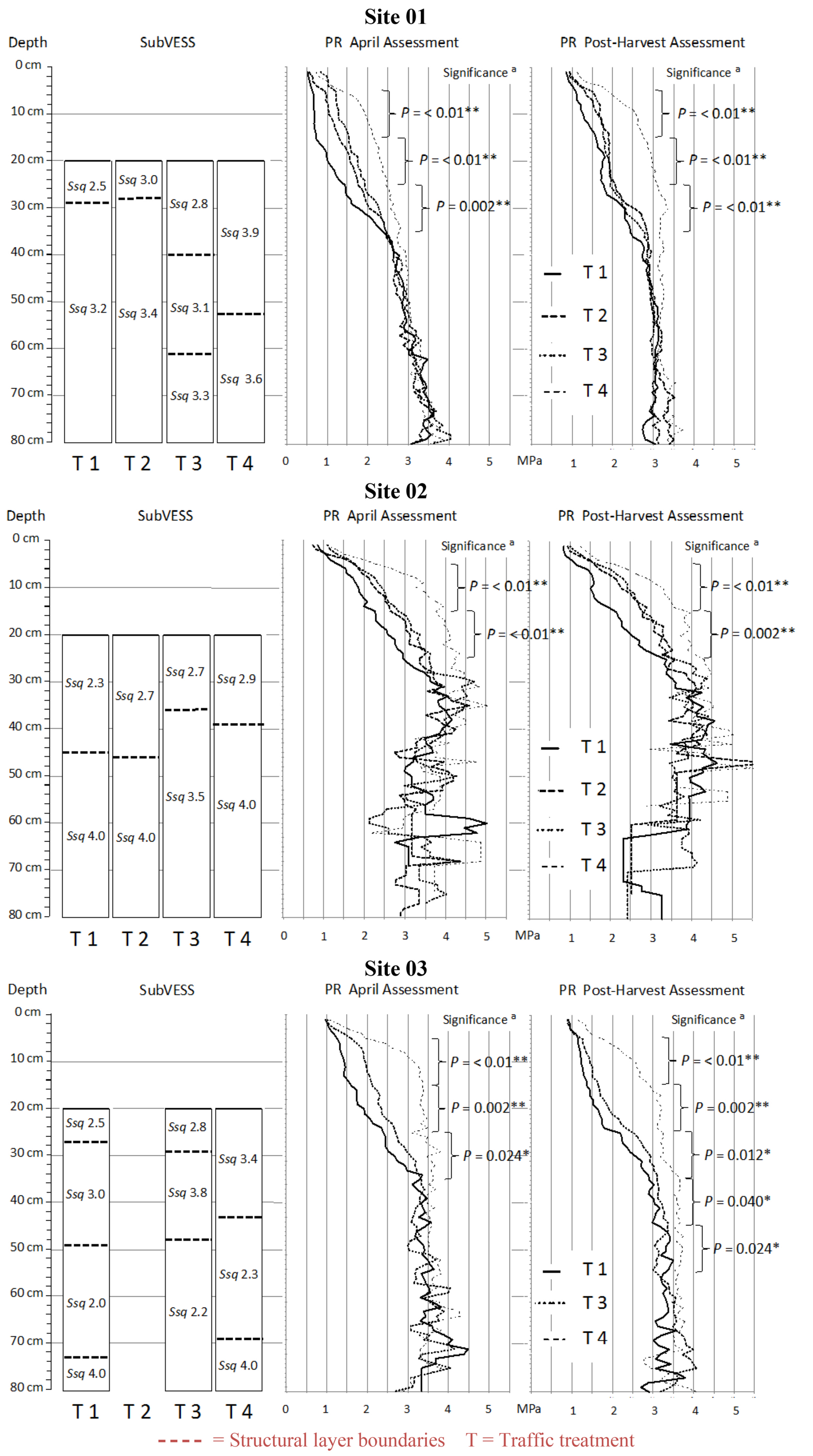
T = Traffic treatment

Figure 1



[a] Incremental mean penetration resistance for different soil depth increments that significantly differed according to traffic treatment (** Significant at $P = 0.01$)

Figure 2



[a] Incremental mean penetration resistance for different soil depth increments that significantly differed according to traffic treatment (* Significant at $P = 0.05$ ** Significant at $P = 0.01$)

Figure 3

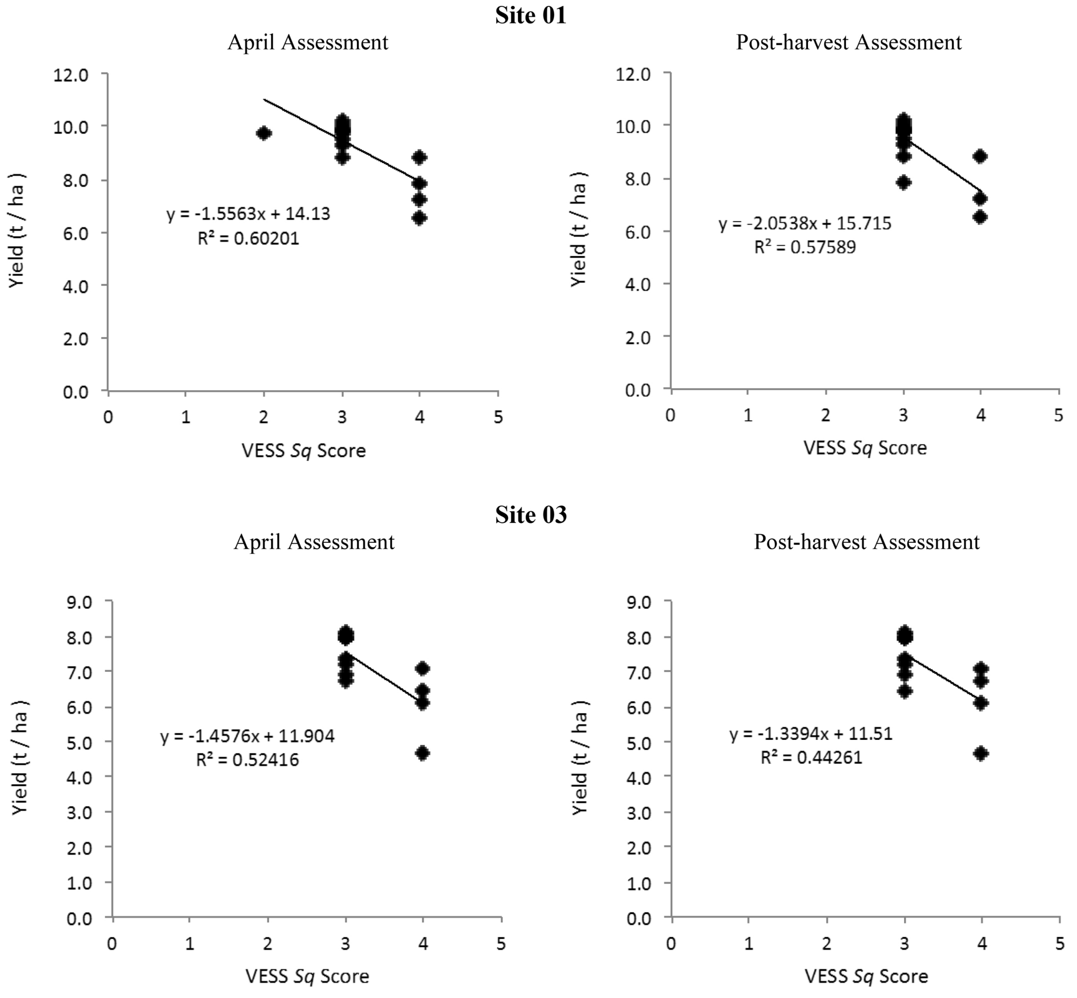

Site 01
April Assessment
y = -1.5563x + 14.13
R² = 0.60201
Yield (t / ha)
VESS Sq Score
Post-harvest Assessment
y = -2.0538x + 15.715
R² = 0.57589
Yield (t / ha)
VESS Sq Score
Site 03
April Assessment
y = -1.4576x + 11.904
R² = 0.52416
Yield (t / ha)
VESS Sq Score
Post-harvest Assessment
y = -1.3394x + 11.51
R² = 0.44261
Yield (t / ha)
VESS Sq Score

Figure 4