Impacts of simulated subsurface soil compaction on soil properties and barley growth in Canterbury, New Zealand

Guillermo Hernandez-Ramirez[1], Erin J Lawrence-Smith[1], Sarah M Sinton[1], Frank Tabley[1], Andreas Schwen[2], Michael H Beare[1], and Hamish E Brown[1]

[1]The New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch, 8140, New Zealand
[2]University of Natural Resources and Applied Life Sciences (BOKU), Vienna, Austria

Abstract

Soil compaction can limit plant growth. This effect is frequently attributed to restricted nutrient acquisition and water stress. However, the underlying mechanisms and their relative contribution remain partly unknown. This study assessed the effects of subsurface compaction (i.e., similar to a tillage pan) on selected soil properties as well as on root morphology, aboveground biomass and yield of a barley (*Hordeum vulgare* L.) crop grown on a Templeton silt loam soil. The experiment was established using a Latin square design with 5 replicates. Following removal of the top 15 cm of soil, five treatments were established: untreated control, mechanically loosened (i.e., cultivation), and mechanically compacted using a 10 Mg roller to achieve three increasing compaction levels (i.e., one pass, eight passes, and eight passes with vibration). Subsequently, the top 15 cm of soil was repositioned on the corresponding plots and barley was planted. Measured soil properties encompassed pore size distribution, hydraulic conductivity (K) using *in situ* tension infiltrometry, penetration resistance (PR), and bulk density (BD). Quantified soil properties indicated that subsurface compaction can occur in these fine-textured soils (e.g., 1.5 times increased PR, ≥ 27% decreased macroporosity, 66% decline in saturated K, and 6% increased BD). Increased root diameter values also indicated the adverse effects of compaction on root development. However, these belowground effects did not translate into aboveground barley responses. These results could suggest that effects of impeding subsurface layers in fertile, fine-textured, irrigated soils depend on plant species and the ability of their root systems to penetrate compacted layers.

Key Words

Soil compaction, tillage pan, water stress, soil porosity, root growth, barley

Introduction

Soil compaction can limit plant growth and productivity (Unger and Kaspar 1994; Batey 2009). The underlying causes of these negative effects on plant productivity are typically associated with changes in soil physical properties such as decreases in porosity and the conductivity of water and air as well as increases in PR (Sadras 2005; Huang 2006; Garside 2008). Also, compacted soil layers can become physical obstacles for root growth limiting access to water and nutrients within the soil profile (Unger and Kaspar 1994; Batey and McKenzie 2006). Overall, this adverse scenario of increasing water stress and restricted nutrient acquisition with soil compaction can be expected to constrain plant growth (Sadras 2005).

In New Zealand, the Canterbury plains are the most important area for intensive cultivation of cereal crops such as barley and wheat (*Triticum aestivum* L.) (White and Hodgson 1999). Hence, it is relevant to assess the susceptibility of the soils within this region to compaction, and the response of typical arable crops to the altered soil conditions caused by compaction processes. Within this context, it can be hypothesized that tillage-induced subsurface compaction decreases crop productivity. Thus, this study examined the effects of a range of simulated cultivation pan layers on selected soil physical properties and barley growth.

Methods

Experiment site

The study site was located at the experimental farm of Plant & Food Research near Lincoln, New Zealand (43?38′S 172?30′E) on a well-drained Templeton soil series (Immature Pallic) over gravels. Soil textural analysis for the 0 to 30 cm depth increment using the sedimentation method resulted in sand and clay contents of 230 and 250 g kg^{-1}, respectively. The mean air temperature and annual precipitation at this location are 11.4?C and 583 mm, respectively (20-yr data).

To simulate different degrees of subsurface soil compaction that can result from repeated tillage operations (typically referred as cultivation pan), five treatments were established using a Latin square design with 5 replicates. Following removal of the top 15 cm of soil, the treatments were: untreated (control), mechanical compaction using a 10 Mg roller (transverse length: 5.6 m, drum width: 2.13 m) to achieve three increasing compaction levels (i.e., one roller pass, eight roller passes, and eight roller passes with vibration), and mechanical cultivation (i.e., maxitill) to loosen the 15 to 25 cm soil layer with the aim of decreasing any impediment to root penetration. Subsequently, the top 15 cm of soil was repositioned in the corresponding plots. These treatments were applied between 21 and 23 Oct. 2009. On 5 Nov. 2009, all experimental plots were tilled to a soil depth of 5 to 8 cm, fertilized at rates of 31, 198, 24, and 19 kg ha^{-1} of N, P_2O_5, K_2O, and S, respectively, and mechanically planted to barley (*Hordeum vulgare* L.) at 170 kg seed ha^{-1} and 7 cm depth. Urea was surface-applied at 100 kg N ha^{-1} on 11 Dec. 2009. Irrigation was applied based on a soil water deficit approach using a linear boom. Dimensions of the experimental plots were 20 m ? 3 m.

Measurements

We quantified aboveground biomass weekly (0.2 m^2) and harvested grain at maturity (0.7 m^2) on 2 and 3 March 2010. Root morphology was also determined after collecting soil cores (n: 6, 4.99 cm i.d.) from a depth increment of 22.5 to 30 cm on 22 Dec. 2009, separating the roots, and subsequently scanning and digitizing the root samples using WinRHIZO (Regent Instruments, Inc., Quebec, QC, Canada). Measured soil properties included penetration resistance (PR) using a cone penetrometer (6 locations per experimental plot; 1.28 cm cone diameter, 30? cone angle; Field Scout SC-900, Spectrum Technologies, Inc., Plainfield, IL) every 2.5 cm depth interval from 2.5 to 40 cm soil depth (16 PR readings per location), bulk density (BD) by collecting soil cores (n: 6, 4.99 cm i.d.) within 0 to 30 cm depth, water content within 0 to 40 cm depth by time domain reflectometry and/or neutron probe, and hydraulic conductivity (K) using *in situ* tension infiltrometry (n: 9) after excavation to a depth ranging from 15 to 20 cm (as a function of the actual depth of the compacted soil layer). Both PR and BD were measured on 7 Dec. 2009, K during Feb. 2010, and water content on a weekly basis. Additional soil cores (n≥ 2, 5.1 cm i.d, 2.5 cm height) were collected within 5 to 37.5 cm depth during Jan. 2010 to assess pore size distribution using water retention measurements on tension tables with supplied suctions ranging from 5 to 100 cm. With the aim of estimating *in situ* field capacity for this soil, repeated measurements (n: 6) of water content (0-40 cm depth) were undertaken within 8 days immediately following soil saturation which was achieved through repeated irrigation (i.e., 150 mm within 9 days during mid Apr. 2010). To minimize soil evaporation and rainwater infiltration while these field capacity measurements were made, the soil surface was covered with plastic film (1 m^2).

We examined variance homogeneity and normality of data, and as needed, the corresponding Box-Cox transformations were applied. Analyses of variance (ANOVA) were run to assess treatment effects followed by Tukey tests. Significance statistics were processed at $\alpha = 0.05$.

Results

Assessed soil properties revealed measurable changes in soil physical conditions as a function of increasing compaction levels (Table 1). Compared to the control (untreated), the heaviest compaction treatment [8 roller passes (+vibration)] decreased soil macroporosity (i.e., from 600 to 60 μm pore diameter range based on water retention measurements) by 27% to 63% and saturated K by 66%. Additionally, the BD of the heavily compacted soil was 6% numerically higher than that of the untreated soil. Concurrently, the average PR was 1.5 times greater in the heavily compacted than in the loosened soil. Furthermore, observed PR values in the heavily compacted soil layers exceeded the threshold levels for optimal root development in silt loam soils (PR≥ 2 MPa; da Silva 1994). This indicates the potential of subsurface compaction to restrict root growth. In contrast, as expected, no significant differences were detected across compaction treatments at the shallow layer (0-15 cm depth) for any of the soil physical properties measured (data not shown).

In this study, both barley aboveground biomass and grain yield did not differ across compaction treatments (*P*s > 0.05). For the control, loosened, 1 roller pass, 8 roller passes, and 8 roller passes with vibration treatments, aboveground biomass means were respectively 15.6, 15.5, 15.7, 16.1, and 15.8 Mg dry matter ha^{-1}, and grain yield means were 8.55, 8.70, 8.56, 8.78, and 8.81 Mg dry matter ha^{-1} in the same order. These results are contrary to our initial hypothesis that soil compaction would have detrimental effects on barley productivity. However, in line with our results, previous studies also indicated no effects of compaction on barley yield (Brereton 1986; Alakukku and Elonen 1995). This lack of crop response to compaction can in part be explained by changes in root morphology with varying intensity of compaction. Although root length did not differ across treatments, barley roots were consistently thicker with increasing soil impedance to penetration (Figure 1) and penetrate through the most compacted layers in this experiment. This is a well-established response of root systems to physical impedance (Unger and Kaspar 1994; Batey and McKenzie 2006). Our results from root morphology analyses (Figure 1) suggest that plants could have acquired both nutrients and water within and beneath the compacted layers. Moreover, increasing levels of subsurface soil compaction could also cause distinctive patterns of vertical root distribution with greater compensatory root growth within the shallow soil layers (Unger and Kaspar 1994; Batey and McKenzie 2006).

Table 1. Selected soil properties as a function of applied compaction treatment. Penetration resistance (PR) and bulk density (BD) were measured on 7 Dec. 2009, and soil water content on 11 Dec. 2009. Saturated K measurements and cores for macroporosity were taken within Jan. and Feb. 2010.

Compaction treatment	Macroporosity (600 to 60 μm diameter)		Saturated K	Bulk density	Penetration resistance	Soil water content
	Soil depth (cm)					
	18 - 20.5	25 - 27.5	15 - 20	15 - 22.5	17.5 - 27.5	15 - 30
	——— m^3 m^{-3} ———		10^{-5} cm s^{-1}	Mg m^{-3}	MPa	m^3 m^{-3}
Control	0.104 ab†	0.065 a	110 ab	1.26	1.80 ab	0.28
Loosened	0.111 a	0.069 a	206 a	1.20	1.61 b	0.28
1 Roller pass	0.111 a	0.066 a	145 a	1.25	1.69 b	0.28
8 Roller passes	0.092 bc	0.043 b	138 a	1.30	2.29 a	0.28

8 Roller passes with vibration	0.076 c	0.024 c	39 b	1.33	2.35 a	0.29
Overall mean	0.099	0.053	127	1.27	1.95	0.28

† Within columns, means followed by the same letter are not significantly different according to Tukey test (α = 0.05) done after ANOVAs with probabilities beyond *F* values for treatment effects smaller than 5%.

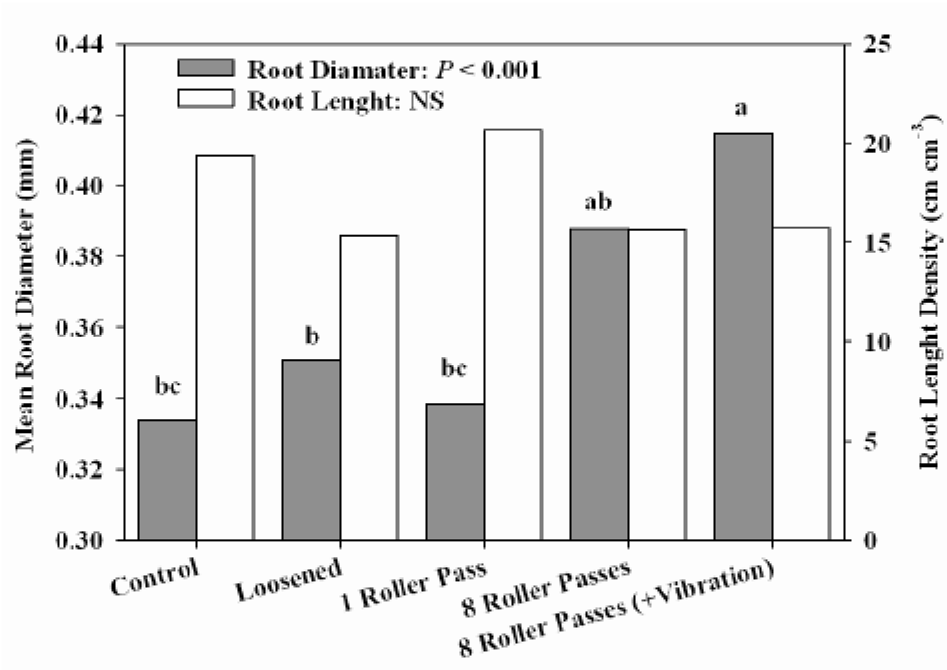

Figure 1. Mean root diameter and root length density as a function of applied compaction treatment at 22.5 to 30 cm depth increment 45 days after barley planting. Bars labelled with the same letter are not significantly different according to Tukey test (α = 0.05) after ANOVA. n= 5.

Simulated soil compaction also affected soil water content at field capacity based on *in situ* measurements. Volumetric soil water contents for the 0 to 40 cm depth increment measured at both 48 and 144 hours (h) following soil saturation was 6% (equivalent to 7.5 mm) higher for the heavily compacted treatment (eight passes of roller with vibration) than for the untreated control (P< 0.001, data not shown). However, water contents were not evenly distributed vertically within the soil profile as a function of the applied subsurface compaction at the 15 to 20 cm depth. In numerical terms, in the 0 to 15 cm depth increment more water was present in the heavily compacted than in the untreated soil (Figure 2A); while the reverse pattern was observed for the 15 to 30 cm layer (Figure 2B). Subsurface compaction may have limit or slow drainage and increase perching of added water (rain and/or irrigation) within the upper soil layer (0-15 cm depth). By contrast, in the untreated soil (control) relatively greater drainage may have occurred from surface soil into deeper subsurface soil layers allowing a more homogeneous vertical distribution of water within the soil profile. These inferences are further supported by decreases in both measured macroporosity (from 600 to 60 µm diameter) and water-conducting macroporosity (~saturated hydraulic conductivity) with increasing soil compaction as mentioned above (Table 1). This increased water storage in surface soil (above the compacted layer) could to some limited extent increase water availability to plants. However, beyond a certain water storage threshold, waterlogging conditions would detrimental effects on plant growth (e.g., root decay due to anaerobiosis, proliferation of soil-related diseases; Batey and McKenzie 2006). The end-outcome of these soil-water processes also depends in part on the intensity and temporal distribution of the water balance (in particular the input component) as well as on the water use and growth patterns for a given plant species.

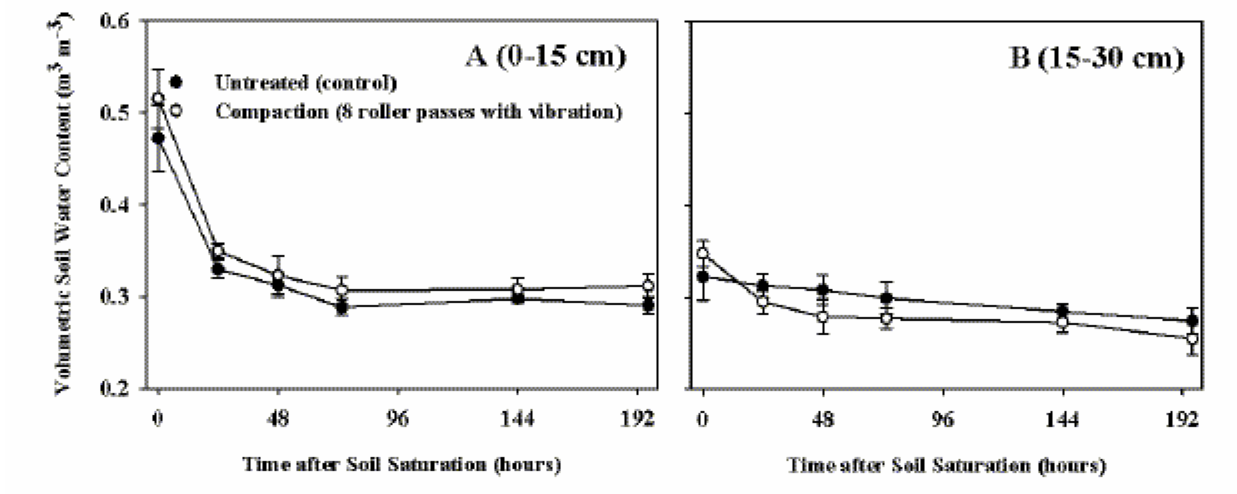

Figure 2. Soil water content with time after saturation at (A) 0 to 15 cm and (B) 15 to 30 cm depth increments. Measurements were taken using time domain reflectometry. Only the heavily compacted treatment (eight passes of roller with vibration) and control are shown for clarity. No significant differences were detected after ANOVAs ($\alpha > 0.05$). n= 5.

Conclusion

The assessed soil properties demonstrate the susceptibility of these fine-textured soils to subsurface compaction similar to cultivation pans caused by repeated tillage operations. However, barley roots exhibited the ability to adapt to these adverse physical conditions and penetrate compacted layers as shown by root morphology analyses. As a result, there was no evidence that the applied compaction treatments limited the access of barley root systems to nutrients and water resources within the entire soil profile. Consequently, barley yield was unaffected by changes in physical properties in this fertile, irrigated soil. Further research can assess how the yield response to cultivation pans vary across plant species along with their relative abilities to cope with alterations in soil physical conditions caused by subsurface soil compaction. Moreover, soil compaction under drought conditions could lead to a greater detrimental effect on plant productivity as water stress would likely be much more pronounced than in well-watered soils. These various hypotheses merit further examination.

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