Short-Term Dynamics of Soil Physical Properties as Affected by Compaction and Tillage in a Silt Loam Soil

Wei Hu,* Frank Tabley, Mike Beare, Craig Tregurtha, Richard Gillespie, Weiwen Qiu, and Peg Gosden

This study investigated short-term dynamics of soil physical properties as affected by tillage and compaction in a silt loam soil. After establishment of an autumn-sown forage oat (Avena sativa L.) crop with either NT or intensive tillage (IT), five degrees of livestock compaction (0–261 kPa) were applied in winter using a “cow treading implement.” A barley (Hordeum vulgare L.) crop was then sown following shallow cultivation of the soil in spring. After 2 yr of sheep-grazed pasture, tillage significantly improved the soil physical quality in the 0- to 0.2-m layer. Compaction significantly deteriorated soil physical quality, by, for example, decreasing macroporosity, available water content, and saturated hydraulic conductivity. Compared with IT and the top 0.1-m soil layer, soil physical properties in NT and the subsurface 0.1- to 0.2-m layer were more resistant to compaction. Irrespective of tillage, the topsoil (0–0.1 m) was more susceptible to physical degradation than the subsurface soil (0.1–0.2 m). Compaction and tillage effects on soil physical quality declined with time because of natural recovery and the shallow tillage used to establish the subsequent barley crop. This study demonstrated that using NT to establish an autumn-sown forage crop can mitigate the adverse impacts of livestock treading on soil physical quality during subsequent grazing. Although tillage and compaction effects were short lived, soil physical properties were significantly different between every two adjacent measurement times. This highlights the need to consider the short-term changes in soil hydraulic properties when modeling soil–crop systems.

Abbreviations: IT, intensive tillage; MWD, mean weight diameter; NT, no-till; RFC, relative field capacity; SWRC, soil water retention curve.

Soil physical properties including soil water retention curves (SWRCs) and saturated hydraulic conductivity ($K_s$) are the most important parameters governing soil water movement and solute transport in the vadose zone (Mohanty, 2013; Zhu and Lin, 2009). They are usually associated with other soil physical properties, such as bulk density ($\rho_b$), aggregate size distribution, macroporosity ($\varepsilon_{ma}$), relative field capacity (RFC), and what has been termed the soil physical quality index (Dexter, 2004). Land use intensification typically amplifies temporal changes in soil physical properties. These changes can affect a range of biogeochemical processes, which may in turn affect soil health and ecosystem services such as water storage and supply and crop production (Bünemann et al., 2018).

Land use change and intensification of management are important drivers of soil quality change (Bünemann et al., 2018). Soil compaction is an important impact of agricultural intensification, owing to increases in machinery wheel loads and livestock grazing intensity that pose a growing threat to many key soil functions (Drewry et al., 2008, Lamandé and Schjønning, 2018). In New Zealand, for example, dairy farming has intensified and expanded dramatically in the past two decades. This has resulted in about half of New Zealand’s monitored dairy sites failing to meet macroporosity targets (i.e., 0.08 cm$^3$ cm$^{-3}$) for soil health (Foote et al., 2015). Compaction from livestock treading is a particular concern where forage crops are grown for grazing by livestock under wet winter conditions. Many of these crops are established following intensive tillage (IT) practices, which can increase the risk of compaction from livestock treading due to a reduction in
soil strength (Thomas et al., 2008). Internationally, long-term use of IT practices has been reported to reduce soil physical, chemical, and biological quality (Pareja-Sánchez et al., 2017; Zuber and Villamil, 2016). For this reason, conservation tillage practices such as no-till (NT) have been widely recommended as strategies to mitigate the potential adverse impacts of intensive tillage practices on sustainable food production and the environment under agricultural intensification (Pittelkow et al., 2015). However, global data have indicated that crop yields under NT are frequently lower than under traditional tillage practices, especially in the short term (e.g., first 2 yr) (Cooper et al., 2016; Pittelkow et al., 2015). For this reason, IT remains a common practice, although conservation tillage practices are rapidly emerging.

Soil physical properties are among the most sensitive to disturbance from agricultural practices (Gozubuyuk et al., 2014; Strudley et al., 2008). However, the temporal changes in soil physical properties that result from a specific management practice are poorly understood. This is a result of limited experimental data and because of soil and climate variability. For example, compared with IT, NT management of crops has resulted in increased (Comia et al., 1994), decreased (Miller et al., 1998), and unchanged (Blanco-Canqui, 2017) values of $Kc$. Likewise, increased soil water retention under NT has been reported in several studies (Azooz and Arshad, 2001), but reduced (Chang and Lindwall, 1992) or unchanged (Cresswell et al., 1993) soil water retention values have also been reported. Compared with tillage effects, compaction effects are more consistent and are associated with a significant decrease in $Kc$ and soil water retention at high (more than $-10$ kPa) matric potentials (Matthews et al., 2010; Mossadeghi-Björklund et al., 2016). However, previous studies have usually focused on the effects of a single management factor on soil physical properties. Few, if any, studies have focused on the interactions between tillage and compaction and the recovery of soil physical properties with time. This may be important where tillage (or no-till management) affects the susceptibility of soils to compaction from wheel trafficking by heavy machinery or livestock treading during grazing of crops or pasture.

Livestock treading during grazing can adversely affect soil physical conditions that may reduce subsequent plant production or increase the risk of environmental impacts (Drewry and Paton, 2005; Singleton et al., 2000). These effects appear to be particularly significant when forage crops are grazed under wet conditions and in previously tilled soils (Drewry and Paton, 2005; Franzluebbers and Stuedemann, 2008). Long-term adoption of NT has been reported to improve soil quality (Pareja-Sánchez et al., 2017). However, very few studies have investigated how NT can be used to mitigate the impact of livestock treading on soil physical properties (Thomas et al., 2008) and the persistence of these effects under subsequent crops or pastures. To this end, we hypothesized that compaction from livestock treading would adversely affect soil physical quality and that the use of NT to establish autumn-sown, winter-grazed forage crops would reduce livestock compaction impacts on soil physical properties.

This study was conducted to investigate short-term (within 1 yr) dynamics of soil physical properties under the combined impacts from tillage and livestock treading. The specific objectives were (i) to quantify the impacts of tillage and compaction on soil physical properties, (ii) to determine if NT for establishing a forage crop can be used to reduce the adverse effects of compaction on soil physical properties, and (iii) to determine the recovery of soil physical properties after compaction.

Materials and Methods
Experimental Design and Sampling

Experimental Design

This experiment was conducted in a mixed-cropping farm (43°38’ S, 172°27’ E) at Lincoln, New Zealand, between April 2016 and February 2017. The block had a history of arable cropping and pasture and was managed as a sheep-grazed pasture for the 2 yr prior to establishing the experiment. The soil was silt loam texture (sand, silt, and clay = 27, 55, and 18% at 0–0.2 m) Udic Haplustept (USDA classification). It had an organic C content of 2.6% in the 0- to 0.2-m layer. The climate is an oceanic climate (Cfb) according to the Köppen–Geiger classification (Peel et al., 2007), characterized by a mean air temperature of 11.5°C and annual mean precipitation of 640 mm, with nearly one-third of the precipitation falling in the winter months (June–August).

The experiment design was a strip-split plot with three factors (Fig. 1). These included two tillage treatments (horizontal factor), five compaction levels (vertical factor), and two urine deposition treatments (subplot factor). The various combinations of tillage treatments and compaction levels defined the intersection plots (3.6 by 6.0 m), each containing the two urine treatment split plots. The experiment was replicated in four blocks, each with 10 intersection plots (Fig. 1).

The previous pasture was sprayed off immediately before cultivation. Two different tillage methods (i.e., NT and IT) were used to establish the forage oat crop in April 2016. For NT, oat was established with a Taege direct drill. For IT, the top 0.2 m was plowed before oat establishment. Simulated grazing of the forage oat crop was performed in mid-August 2016. The forage oat crop was first removed by mowing. After the oat crop was harvested, a “cow treading implement” (designed and constructed by The New Zealand Institute for Plant & Food Research Limited) was used to simulate the compaction effects that result from different forms of livestock treading. Five pressures of 0, 147, 183, 220, and 261 kPa (referred to as C1, C2, C3, C4, and C5, respectively) were used to simulate the compaction effects that result from different forms of livestock treading. Five pressures of 0, 147, 183, 220, and 261 kPa (referred to as C1, C2, C3, C4, and C5, respectively) were applied with the soil at field capacity to achieve different degrees of compaction damage with approximately 100% surface coverage. The pressures applied essentially simulated the range of pressures that an adult Friesian cow delivers while grazing, i.e., from 130 kPa when stationary to 250 kPa when walking with a mean pressure of 220 kPa (Di et al., 2001; Scholefield and Hall, 1986). Figure 2 shows the surface condition after compaction at a pressure of 261
kPa, illustrating that tilled soils had more deformation of the soil surface than NT soils. In each intersection plot, urea-N was hand broadcasted at 400 kg N ha$^{-1}$ in one subplot (+Urea) and no urea was applied in another subplot (−Urea), both followed by 5 mm of water application to simulate N input in urine patches deposited by livestock immediately after treading. The effects of urea application on the soil physical properties were not explored by restricting sampling to the +Urea subplots. In September 2016, all plots were surface cultivated prior to establishing a barley crop with the Taege direct drill. The cultivation involved two passes with a grubber (<0.15-m depth) followed by alternating passes of a grubby-crumbler (Clough Maxitill), tine harrow, and Cambridge roller. **Sampling** Intact soil cores were collected at five critical times: immediately prior to cultivation and sowing the forage oat crop (pre-forage crop; 13 Apr. 2016); just prior to "grazing" the forage crop (pre-grazing; 2 Aug. 2016); soon after simulated grazing (post-grazing; 18 Aug. 2016); soon after cultivation and sowing the barley crop (barley cultivation; 5 Oct. 2016); and at harvest of the barley crop (barley harvest; 20 Feb. 2017). These cores were
According to Assouline and Or (2014), suction at $q$ (White, 1993), from which the mean weight diameter (MWD) of the soil aggregate was calculated. Greater MWD of the dry aggregate size distribution usually indicates poorer soil structure (Jensen et al., 1996). In the pre-forage crop phase, sampling was made at the boundary of two intersection plots, resulting in 20 sampling points. In other phases, one sampling point was set up for each +Urea subplot, producing 40 sampling points. At each sampling point, intact soil cores of 0.01 to 0.085 and 0.11 to 0.185 m were sampled to represent soil layers of 0 to 0.1 and 0.1 to 0.2 m, respectively. These sampling depths were used because compaction effects by livestock treading are typically limited to a depth of 0.2 m (Drewry, 2006). In each subplot, samples from different phases were confined to an area of 2 by 2 m to minimize the effects of spatial variability.

**Measurements and Calculations**

**Soil Water Retention Curves**

Soil water retention curves were determined from measurement of the soil water content at pressures of 0, −5, −10, −40, −100, and −600 cm using a tension table and vacuum plate. These pressure ranges were selected because tillage and compaction effects on pore space have been reported to be more pronounced in these ranges (Kargas et al., 2016). To describe the SWRCs, the van Genuchten (1980) model was fitted to the data:

$$\frac{\theta(\psi)-\theta_r}{\theta_i-\theta_r} = \left[1 + \left(\frac{\theta_i-\theta_r}{\theta_i-\theta_f}\right)^n\right]^{-1+1/n}$$  \hspace{1cm} [1]

where $\theta_i$ and $\theta_r$ are residual and saturated soil water contents, respectively, on a volume basis ($cm^3 cm^{-3}$). In this study, $\theta_i$ was set as the air-dried gravimetric water content (0.021 g g$^{-1}$) times the bulk density (g cm$^{-3}$) (Poepplau et al., 2015); $\theta_r$ is the volumetric water content at a pressure of 0 kPa; $\theta(\psi)$ is the volumetric soil water content ($cm^3 cm^{-3}$) at soil water potential $\psi$ (cm). The parameter $\alpha$ ($cm^{-1}$) is inversely related to the air-entry pressure, and $n$ (dimensionless) is a pore-size distribution index, being positively related to the slope of the SWRC.

Soil water content at field capacity ($\theta_{fc}$) is usually determined at a specific suction (e.g., 50–500 cm) (Assouline and Or, 2014). According to Assouline and Or (2014), suction at $\theta_{fc}$ ($S_{fc}$) is related to a soil-specific characteristic length (i.e., the maximum extent of hydraulically connected pathways that supports unsaturated capillary flow) and can be derived from $\alpha$ and $n$ as

$$S_{fc} = \frac{1}{\alpha} \left(\frac{n}{n-1}\right)^{1-2n/n}$$  \hspace{1cm} [2]

The $\theta_{fc}$ was calculated using Eq. [1] by replacing $\psi$ with $-S_{fc}$, and plant-available water content ($\theta_{wp}$) was then calculated as the difference between $\theta_{fc}$ and the water content at the wilting point ($\theta_{wp}$) defined at a pressure of −15,000 cm fitted from Eq. [1].

**Soil Physical Quality Indices**

Three soil physical quality indices were derived from the SWRC measurements: macroporosity ($\varepsilon_{ma}$ > 30 μm in diameter), the soil physical quality index $S$, and relative field capacity (RFC).

The $\varepsilon_{ma}$ was calculated as the soil porosity minus the water content at a soil water pressure of −100 cm (Bell et al., 2011). Typically, $\varepsilon_{ma}$ of ≥0.05 to 0.10 cm$^3$ cm$^{-3}$ has been cited as optimal, while $\varepsilon_{ma}$ of ≤0.04 cm$^3$ cm$^{-3}$ has been used to represent the “lower critical limit” below which soil aeration and drainage may be limiting for plant growth (Drewry and Paton, 2005; Reynolds et al., 2009).

The $S$ index was calculated as (Dexter, 2004)

$$S = \left[-n \left(\theta_{rg} - \theta_{rs}\right) \left(\frac{2n-1}{n-1}\right)^{1/n-2}\right]$$  \hspace{1cm} [3]

where $\theta_{rg}$ and $\theta_{rs}$ are residual and saturated soil water content on a mass basis (g g$^{-1}$), respectively. Soil physical quality was defined as very poor ($S < 0.02$), poor (0.02 < $S < 0.035$), good (0.035 < $S < 0.05$), or very good ($S > 0.05$) (Dexter, 2004).

The RFC was calculated as (Reynolds et al., 2008)

$$RFC = \frac{\theta_{fc}}{\theta_{rs}}$$  \hspace{1cm} [4]

It has been suggested that RFC values of 0.6 to 0.7 are an optimal range (Reynolds et al., 2008), and an RFC of 0.66 is the optimal equilibrium (Pranagal and Podstawka-Chmielewska, 2012) for soils to reach a balance between soil water capacity and air capacity in the root zone. Water supply limitation and aeration limitation for plant growth may exist when the RFC is <0.6 and >0.7, respectively (Reynolds et al., 2009).

**Saturated Hydraulic Conductivity**

After SWRC measurements, the soil cores were saturated for $K_s$ measurement using the constant-head method (Klute, 1965). All $K_s$ values were corrected for 20°C to minimize the temperature effects on $K_s$:

$$K_{s20} = K_s \frac{\eta_{20}}{\eta_t}$$  \hspace{1cm} [5]

where $\eta_t$ and $\eta_{20}$ refer to viscosity at a given temperature $t$ and 20°C, respectively; $K_s$ and $K_{s20}$ refer to $K_s$ at temperature $t$ and 20°C, respectively. Note that $K_s$ in this study denotes corrected $K_s$ for temperature of 20°C unless stated otherwise.

After $K_s$ measurement, soil cores were oven dried at 105°C for 24 h for measuring $\rho_b$.

**Statistical Analyses**

A multivariate analysis of variance (ANOVA) within the general linear model procedure was performed to explore the impact of different factors (compaction, tillage, depth, and time) and their interactions on soil physical properties. Least significant differences (LSD) of means were used for multiple comparison. Log_{10} transformation was made for skewed data to help achieve variance.
Results and Discussion

Data Summary

All physical properties were normally distributed except for MWD, $\alpha$, and $K_s$, which were lognormally distributed. In general, all physical properties reflected a similar trend in change with time (Fig. 3 for some selected properties). For example, from the pre-forage crop to the barley harvest, the mean $\varepsilon_{ma}$ values of the 0- to 0.2-m soil were $0.13, 0.17, 0.10, 0.18$, and $0.20$ cm$^{-3}$, respectively; mean $S$ indices were $0.031, 0.036, 0.024, 0.044$, and $0.047$, respectively. This indicated that soil physical quality was poor during the pre-forage crop and post-grazing phases but good during other phases (Dexter, 2004). Of particular note is that the grand mean of $S_{fc}$ for the experiment as a whole was 9 kPa, being close to 10 kPa commonly reported for New Zealand soils (Grewal et al., 1990). However, the $S_{fc}$ value was affected by both tillage and compaction. During the pre-grazing phase, for example, the $S_{fc}$ values for NT and IT soils were 11 and 3 kPa, respectively. During the post-grazing phase, the $S_{fc}$ values of C1 and C5 were 12 and 18 kPa, respectively. This result suggests that tillage and the absence of compaction tend to reduce $S_{fc}$, which is beneficial to water storage.

Nearly all properties were significantly ($P < 0.01$) correlated with each other (Table 1). For example, $\rho_b$ was negatively correlated with $\varepsilon_{ma}$, $\alpha$, $n$, $\theta_{fc}$, $\theta_{aw}$, $K_s$, and $S$, while it was positively correlated with MWD, $S_{fc}$, $\theta_{wp}$, and RFC. The soil physical quality index $S$ was also significantly correlated with other soil physical quality indices. Greater $S$ values were usually associated with higher macroporosity, available water content, and drainage capability (i.e., greater $K_s$) and less risk of aeration stress (i.e., lower RFC). From the pre-forage crop to the barley harvest, the mean RFC values of the 0- to 0.2-m depth were $0.71, 0.75, 0.79, 0.67$, and $0.68$ cm$^{-3}$, respectively, showing the risk of aeration stress resulting from compaction. The significant correlations between physical properties indicated that they responded similarly to environmental condition and management, and some can be used as proxies for others. For this reason, we focused on $\rho_b$, MWD, $\varepsilon_{ma}$, $\theta_{aw}$, $K_s$, and $S$ in this study.

Compaction Effects

Significant ($P < 0.01$) compaction effects on MWD, $\theta_{aw}$ and $S$ were found when all data were pooled together (Table 2). With increased compaction from C1 to C5, log$_{10}$MWD increased from 0.90 to 1.00, $\theta_{aw}$ decreased from 0.18 to 0.16 cm$^{-3}$, and $S$ decreased from 0.039 to 0.035. Not surprisingly, the effect of compaction changed significantly ($P < 0.01$) with time. During the post-grazing phase, compaction resulted in a significant ($P < 0.01$) increase in $\rho_b$ and MWD, and a reduction in $\varepsilon_{ma}$, $\theta_{aw}$, $K_s$, and $S$ index (Fig. 4 and 5; Table 3). This indicated that increased $\rho_b$ coincided with an increase in aggregate size and reduced $\varepsilon_{ma}$, which would decrease both drainage and plant-available water capacity, increasing the risk of aeration limitations when
Table 1. Spearman’s correlation coefficients among soil physical properties (bulk density, $\rho_b$; mean weight diameter of dry aggregate size distribution, MWD; macroporosity, $\varepsilon_{ma}$; shape parameter related to the inverse of the air-entry suction, $\alpha$; pore size distribution parameter, $n$; suction at field capacity, $S_{fc}$; water content at field capacity, $\theta_{fc}$; water content at the wilting point, $\theta_{wp}$; available water content, $\theta_{aw}$; saturated hydraulic conductivity, $K_s$; relative field capacity, RFC; index of soil physical quality, $S$).

<table>
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<tr>
<th>Parameter</th>
<th>$\rho_b$</th>
<th>MWD</th>
<th>$\varepsilon_{ma}$</th>
<th>$\alpha$</th>
<th>$n$</th>
<th>$S_{fc}$</th>
<th>$\theta_{fc}$</th>
<th>$\theta_{wp}$</th>
<th>$\theta_{aw}$</th>
<th>$K_s$</th>
<th>RFC</th>
<th>$S$</th>
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<tr>
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<td>-0.84**</td>
<td>-0.53**</td>
<td>-0.44**</td>
<td>0.74**</td>
<td>-0.57**</td>
<td>0.48**</td>
<td>-0.88**</td>
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<td>0.54**</td>
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Table 2. Significance of all factors and their interactions on soil physical properties (bulk density, $\rho_b$; mean weight diameter of dry aggregate size distribution, MWD; macroporosity, $\varepsilon_{ma}$; available water content, $\theta_{aw}$; saturated hydraulic conductivity, $K_s$; index of soil physical quality, $S$) when all data were pooled together.

<table>
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<tr>
<th>Factors</th>
<th>$\rho_b$</th>
<th>MWD</th>
<th>$\varepsilon_{ma}$</th>
<th>$\theta_{aw}$</th>
<th>$K_s$</th>
<th>$S$</th>
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<tr>
<td>Time $\times$ tillage</td>
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<td>0.40</td>
<td>0.75</td>
<td>0.62</td>
<td>0.06</td>
<td>0.29</td>
</tr>
<tr>
<td>Time $\times$ compaction $\times$ tillage</td>
<td>0.19</td>
<td>0.71</td>
<td>0.07</td>
<td>0.16</td>
<td>0.40</td>
<td>0.63</td>
</tr>
<tr>
<td>Depth $\times$ time $\times$ compaction $\times$ tillage</td>
<td>0.27</td>
<td>0.96</td>
<td>0.53</td>
<td>0.35</td>
<td>0.60</td>
<td>0.17</td>
</tr>
</tbody>
</table>

† Log10–transformed before analysis.

Soils are compacted (i.e., increased RFC from 0.73 at C1 to 0.80 at C5). Our results were in agreement with many other studies showing that compaction results in increased $\rho_b$ (Herbaerts et al., 1996) and reduced $\varepsilon_{ma}$ (Hamza and Anderson, 2005; Matthews et al., 2010). Decreases in $K_s$ due to compaction have been reported for a range of soil textures, from clay (Marsi et al., 1998) to loamy soils (Etana et al., 2013). In this study, the mean $K_s$ of the 0- to 0.2-m depth decreased by five times from 290 mm d$^{-1}$ at a pressure of 147 kPa to 58 mm d$^{-1}$ at a pressure of 261 kPa, with an extent of decrease comparable to that reported by Matthews et al. (2010), where the $K_s$ of a silty clay loam decreased from 0.012 mm d$^{-1}$ at a pressure of 174 kPa to 0.0025 mm d$^{-1}$ at a pressure of 522 kPa. The large differences in $K_s$ between these two studies are attributed to the different soil textures.

Compaction had a significant ($P < 0.05$) interaction with depth, where the soil physical quality decreased faster with compaction in the top 0.1 m than in the 0.1- to 0.2-m layer (Fig. 4). For example, with the increase in compaction, the $\rho_b$ and MWD of the 0- to 0.1-m layer increased abruptly from C1 to C2 or C3, with maximum values, while the increase was gradual in the 0.1- to 0.2-m soil depth (Fig. 4a and 4b). Similarly, at 0 to 0.1 m, there was a big drop in $\varepsilon_{ma}$, $\theta_{aw}$, $K_s$, and $S$ (Fig. 4c–4f) from C1 to C2, beyond which there was little change. Stable $K_s$ values at higher pressures were also observed by Kuncoro et al. (2014), where compaction at pressures of 225 and 300 kPa did not result in significant differences in $K_s$ values for soils mixed with various organic matter materials. For the subsurface layer, however, all the values decreased at a much lower rate and presented better soil physical quality (e.g., lower $\rho_b$ and MWD and higher $\varepsilon_{ma}$, $\theta_{aw}$, $K_s$, and $S$ index) than in the 0- to 0.1-m layer. The greater compaction effect in the top 0.1 m than the 0.1- to 0.2-m layer was also observed during the pre-forage crop phase, when the 0- to 0.1-m layer had greater MWD ($P = 0.04$) than the 0.1- to 0.2-m layer, which was associated with physical damage from sheep-grazing 2 yr prior to the experiment establishment. The greater impact of compaction on shallower soils has also been reported in other studies (Drewry and Paton, 2005; Lamandé and Schjønning, 2018).
There was also a significant interaction between compaction and tillage treatments for some properties, such as $r_b$ ($P = 0.03$) and $e_{ma}$ ($P < 0.001$) (Fig. 5). The increase in compaction from C1 (no compaction) to C2 resulted in a significant increase in $r_b$ for IT but no changes for NT (Fig. 5a). The $e_{ma}$ of NT decreased gradually with increased compaction, while $e_{ma}$ of IT decreased markedly from C1 to C3 (Fig. 5b). The interaction effect of compaction and tillage on $e_{ma}$ was mirrored for $\theta_{aw}$ and $K_s$, although the interaction was significant only at $P = 0.06$ ($\theta_{aw}$) and $P = 0.08$ ($K_s$) (Fig. 5c and 5d). Although compacted plots (C2–C5) under NT had greater $r_b$ ($P < 0.001$) and therefore lower total porosity than those under IT, $e_{ma}$ and $K_s$ in NT soils were higher than those of IT soils. These were associated with improved soil aeration and drainage in the NT plots than the IT plots, where micropores dominated. Similarly, Yavuzcan et al. (2005) observed that plots with chisel plowing to a depth of 0.13 m were less affected by wheel

![Figure 4](image1.png)  
**Fig. 4.** Compaction effects on soil physical properties (bulk density, $\rho_b$; log$_{10}$-transformed mean weight diameter of dry aggregate size distribution, log$_{10}$MWD; macroporosity, $e_{ma}$; available water content, $\theta_{aw}$; log$_{10}$-transformed saturated hydraulic conductivity, log$_{10}$Ks; index of soil physical quality, S) at different depths (0–0.1 and 0.1–0.2 m) during the post-grazing phase.

![Figure 5](image2.png)  
**Fig. 5.** Compaction effects on soil physical properties (bulk density, $\rho_b$; macroporosity, $e_{ma}$; available water content, $\theta_{aw}$; log$_{10}$-transformed saturated hydraulic conductivity, log$_{10}$Ks) for different tillage types (intensive tillage, IT; no-till, NT) during the post-grazing phase.
traffic compaction than plots with conventional tillage involving moldboard plowing to a depth of 0.25 m. Fernández et al. (2010) found that winter grazing of crop residues caused no deterioration of topsoil porosity in a NT silty loam soil. In summation, our results show that NT can be beneficial for mitigating the effects of treading pressure on soil physical quality, which is broadly consistent with the findings of previous studies. One possible reason is that the higher bulk density in NT soils compared with tilled soils increases the soil stress, which can lower the soil’s susceptibility to compaction and the reduction in soil physical quality (Saffih-Hdadi et al., 2009).

After shallow tillage to establish the barley crop, the effects of compaction were still evident for MWD and \( \varepsilon_{\text{ma}} \) but not for other properties. There were no consistent trends in the effects of compaction during the barley cultivation phase. However, the no-compaction (C1) treatment still had the lowest MWD and highest \( \varepsilon_{\text{ma}} \). The compaction effect on MWD varied with depth \((P = 0.001)\). Shallow tillage removed most of the compaction effects in the 0- to 0.1-m layer except that the highest compaction level (C5) presented significantly \((P < 0.05)\) greater MWD (i.e., poorer soil structure) than other compaction levels in the 0.1- to 0.2-m soil. During the barley harvest phase, however, the compaction effect on all properties disappeared. This indicated that compaction effects on soil physical quality can be removed to a great extent by subsequent crop cultivation.

### Tillage Effects

Significant \((P < 0.05)\) tillage effects on soil physical properties were found when all data were pooled together (Table 2). For example, overall IT reduced \( \rho_b \) (1.29 vs. 1.34 g cm\(^{-3}\)) and increased \( \varepsilon_{\text{ma}} \) (0.17 vs. 0.15 cm\(^3\) cm\(^{-3}\)), \( \theta_{\text{aw}} \) (0.18 vs. 0.16 cm\(^3\) cm\(^{-3}\)), and \( S \) (0.038 vs. 0.035) compared with NT. There were significant \((P < 0.01)\) interactions between tillage and time for all properties, indicating that the tillage effect changed with time.
During the pre-grazing phase, significant \((P < 0.05)\) tillage effects were observed for all properties 4 mo after original tillage treatments were imposed (Table 3). Compared with NT, IT had greater values of \(\varepsilon_{ma}\) (0.23 vs. 0.12 cm\(^3\) cm\(^{-3}\)), \(\theta_{aw}\) (0.23 vs. 0.14 cm\(^3\) cm\(^{-3}\)), \(K_s\) (2500 vs. 500 mm d\(^{-1}\)), and \(S\) (0.045 vs. 0.027) at 0 to 0.2 m, while the values of \(\rho_b\) (1.14 vs. 1.38 g cm\(^{-3}\)) and MWD (6.6 vs. 9.8 mm) decreased (Fig. 6). Therefore, after 2 yr of sheep-grazed pasture, tillage improved the soil structure and soil physical quality, resulting in improved available water retention and drainage. This result indicates that tillage increased not only the volume of drained pores (i.e., macropores) but also water storage pores (i.e., mesopores). There were significant interactions between tillage and depth for MWD, \(K_s\), and \(S\) (Fig. 6). The IT effects on MWD and \(S\) were significantly \((P < 0.05)\) greater in the surface layer, whereas the IT effects on \(K_s\) were significantly \((P < 0.01)\) greater in the subsurface layer. The differences could be due to the relative values of physical properties between the two depths before tillage.

Tillage effects on \(\rho_b\) during the pre-grazing phase were maintained during the post-grazing phase, i.e., IT still presented lower \(\rho_b\) (Fig. 5a). This was because \(\rho_b\) was less sensitive to compaction than other properties, especially at 0.1 to 0.2 m. Tillage also significantly \((P = 0.01)\) affected MWD, but IT plots presented greater MWD than NT plots at the post-grazing phase as a result of more vulnerability of the aggregate size distribution to compaction in tilled soils than in NT soils. A significant tillage effect on other properties such as \(\varepsilon_{ma}\), \(\theta_{aw}\), \(K_s\), and \(S\) was not observed at this stage because of the interactions between tillage and compaction.

While IT plots had greater \(\varepsilon_{ma}\) \(\theta_{aw}\), and \(K_s\) than NT plots where no treading pressure (no compaction) was applied (C1), the reverse trend was generally found for the compaction treatments (C2–C5) (Fig. 5).

The effects of tillage on the aggregate size distribution (i.e., lower MWD in NT than IT plots) during the barley harvest phase were consistent with those of the pre-grazing phase, but this consistency did not apply to other soil physical properties. Of particular note is the fact that the \(\rho_b\) of IT was lower than that of NT at the post-grazing phase, whereas this was reversed during the barley cultivation phase, i.e., NT presented slightly lower \(\rho_b\) (1.25 vs. 1.28 g cm\(^{-3}\)) than IT. This may indicate that better structured NT soils benefited more from shallow tillage than tilled soils, which also contributed to slightly greater \(\varepsilon_{ma}\) \(\theta_{aw}\) \((P = 0.36)\) and \(\theta_{aw}\) \((P = 0.25)\) in NT soils than IT soils. As opposed to the post-grazing phase, the top 0.1-m layer presented significantly \((P < 0.001)\) better physical quality (e.g., lower MWD and greater \(\varepsilon_{ma}\), \(\theta_{aw}\), and \(S\) index) than the 0.1- to 0.2-m layer during the barley cultivation phase as a result of the shallow tillage. These significant depth effects on all properties except for \(K_s\) were also retained during the barley harvest phase. This may again highlight the temporary benefit of tillage to physically constrained soils.

Many previous studies have reported that IT decreased aggregate size and \(\rho_b\) (Chang and Lindwall, 1992; Foote et al., 2015; Pareja-Sánchez et al., 2017) and increased \(\varepsilon_{ma}\) and total porosity (Pierce et al., 1994), as was observed in this study. For example, Mossadeghi-Björklund et al. (2016) reported that IT decreased the \(\rho_b\) of a 0- to 0.05-m soil by 0.16 g cm\(^{-3}\) (1.49 and 1.33 g cm\(^{-3}\)) in NT soils than IT soils. As opposed to the post-grazing phase, the top 0.1-m layer presented significantly \((P < 0.001)\) better physical quality (e.g., lower MWD and greater \(\varepsilon_{ma}\), \(\theta_{aw}\), and \(S\) index) than the 0.1- to 0.2-m layer during the barley cultivation phase as a result of the shallow tillage. These significant depth effects on all properties except for \(K_s\) were also retained during the barley harvest phase. This may again highlight the temporary benefit of tillage to physically constrained soils.

**Fig. 6.** Tillage effects on soil physical properties (bulk density, \(\rho_b\); log\(_{10}\)-transformed mean weight diameter of dry aggregate size distribution, log\(_{10}\)MWD; macroporosity, \(\varepsilon_{ma}\); available water content, \(\theta_{aw}\); log\(_{10}\)-transformed saturated hydraulic conductivity, log\(_{10}\)\(K_s\); index of soil physical quality, \(S\)) for different depths (0–0.1 and 0.1–0.2 m) during the pre-grazing phase.
for NT and IT, respectively) in a short-term field experiment with medium loam textured soils in a Mediterranean region. Similar effects were observed in this study, where IT decreased the $\rho_b$ of the 0- to 0.1-m soil by 0.21 g cm$^{-3}$ (1.35 and 1.14 g cm$^{-3}$ for NT and IT, respectively) 4 mo after tillage. Other studies have shown that IT decreased pore connectivity (Drees et al., 1994) and hence $K_t$ or infiltration rate (Azooz and Arshad, 2001; Gozubuyuk et al., 2014), which is contradictory to our findings during the pre-grazing phase. However, the NT benefits for $K_t$ or infiltration rate have mainly been observed in long-term experiments. After more than 10 yr of tillage treatments, Gozubuyuk et al. (2014) reported that the mean infiltration rate of IT decreased by 61% compared with NT because of the reduced continuity of macropores in the soil profile.

Although the pore connectivity could be disrupted by tillage, the reduced pore connectivity might have been compensated for by the increase in macroporosity developed by tillage. The increased $K_t$ due to tillage was observed in both the pre-grazing phase and the barley cultivation phase after shallow tillage. At the pre-grazing phase, tillage increased the $\log_{10} K_t$ of the 0- to 0.2-m soil from 2.7 (NT) to 3.4 mm d$^{-1}$ (IT). The shallow tillage after grazing increased the $\log_{10} K_t$ of the 0- to 0.2-m soil from 2.2 to 2.6 mm d$^{-1}$. The increase in $K_t$ by IT during the pre-grazing phase was partly due to the fact that the area was under sheep grazing prior to establishing the experiment. This appeared to result in some compaction with an associated reduction in infiltration capacity. Therefore, tillage can be a good strategy to temporarily improve soil physical quality, especially for compacted soils, by increasing macroporosity and infiltration capacity. The paradox of tillage effects on $K_t$ may be that IT and NT can be beneficial to improving soil water retention and drainage in a short and longer term, respectively. This also agrees with the results of previous studies that showed that tillage increased $\varepsilon_{ma}$ and $K_t$ (Reichert et al., 2016; Rücknagel et al., 2016), whereas long-term NT systems tend to improve soil structure (Reichert et al., 2016; van Kessel et al., 2013).

This study has shown that the use of NT practices to establish forage crops can markedly reduce the risk of compaction from stock treading during winter grazing compared with the more commonly used IT practices (Fig. 5). While IT can help to remove some of the physical constraints imposed by sheep grazing in the short term, our results also suggest that repeated use of tillage in grazed forage crop systems can have adverse effects on soil structure. Compared with NT, the first use of tillage (IT) after 2 yr of sheep-grazed pasture increased $\varepsilon_{ma}$ (0.23 vs. 0.12 cm$^3$ cm$^{-3}$) and $\log_{10} K_t$ (3.4 vs. 2.7 mm d$^{-1}$), but the post-grazing shallow tillage reduced $\varepsilon_{ma}$ (0.17 vs. 0.20 cm$^3$ cm$^{-3}$) and $\log_{10} K_t$ (2.4 vs. 2.7 mm d$^{-1}$) in the uncompacted plots (C1). The frequent use of tillage to restore soil physical properties following compaction from stock treading may also serve to reduce soil structural integrity and, therefore, increase the risk that soil physical properties will continue to decline under the pressure of subsequent grazing events. Therefore, tillage, especially high frequency tillage (e.g., tillage for each crop establishment), is not recommended unless soils have been physically constrained for plant growth.

**Temporal Changes and Recovery**

There were highly significant ($P < 0.001$) effects of sampling time on all soil physical properties (Table 2), with clear evidence of changes ($P < 0.05$ or 0.001) between adjacent measurement times (Fig. 7). This is not surprising, given the very substantial changes in soil management from the start of the experiment under short-term sheep-grazed pasture to cultivated cropping followed by simulated winter grazing and subsequent cultivated cropping. In addition, time had a significant interaction with compaction, tillage, and depth (Table 2). This indicated that temporal changes in hydraulic properties differed with depth, tillage, and compaction levels.

Tillage influenced the temporal changes in all properties between every two adjacent phases from the pre-forage crop to the barley cultivation phase, and IT usually showed greater temporal changes in soil physical properties than NT (Fig. 7). For example, from the pre-forage crop to the pre-grazing phase, the mean $\log_{10} K_t$ in the 0- to 0.2-m layer was essentially unchanged for NT (i.e., 2.8 at the pre-forage crop vs. 2.7 mm d$^{-1}$ at the pre-grazing phase), while it increased significantly in IT (from 2.8 at the pre-forage crop to 3.4 mm d$^{-1}$ at the pre-grazing phase). From the pre-grazing phase to the post-grazing phase, $\varepsilon_{ma, aw}$, and $S$ in the 0- to 0.2-m layer decreased by 0.13 vs. 0.02 cm$^3$ cm$^{-3}$, 0.10 vs. 0.01 cm$^3$ cm$^{-3}$, and 0.021 vs. 0.003 for IT vs. NT, respectively (Fig. 7). This again indicated that the NT soil was more resilient to the damage caused by livestock treading. Similar results were observed by Kargas et al. (2016), who also found that cultivated soils had greater temporal changes in $K_t$ than uncultivated soils.

Compaction also had a significant ($P < 0.05$) impact on temporal changes in physical properties. From the pre-grazing phase to the post-grazing phase, there were no temporal changes in physical properties including $\rho_b$, $\theta_{aw}$, $K_s$, and $S$ for the no-compaction treatment (C1) at either sample depth. Although the temporal changes in physical properties at C1 were not significant during this period, there was a trend for increased $\rho_b$ accompanied with reduced $K_s$, possibly because of natural consolidation processes driven by rainfall (totaling 28 mm in this period) (Hu et al., 2012; Schwcn et al., 2011). From the post-grazing to the barley cultivation phase, greater compaction was associated with a decrease in $\rho_b$ and MWD and an increase in $\varepsilon_{ma, aw}$, $K_s$, and the $S$ index. Conversely, the treatment with no compaction (C1) did not trigger significant temporal changes in physical properties including $\rho_b$, MWD, $\theta_{aw}$, and $K_s$ in the 0.1- to 0.2-m layer.

Depth also significantly affected the temporal changes in physical properties. From the post-grazing to the barley cultivation phase, for example, temporal changes in all physical properties except for $K_s$ were significantly ($P < 0.001$) greater in the top 0.1 m than in the 0.1- to 0.2-m layer (Fig. 7). This was because the top 0.1-m layer was more compacted during the post-grazing phase and only the topsoil was tilled to establish barley.
Compared with temporal changes during previous stages, the temporal changes from the barley cultivation to the barley harvest phase were much smaller (Fig. 7). However, the temporal changes in all physical properties were statistically significant ($P < 0.05$ for $\rho_b$ and $S$, and $P < 0.001$ for others). During this period, $\rho_b$ and MWD decreased and $\epsilon_{ma}$, $\theta_{aw}$, $K_s$, and the $S$ index increased, indicating improved soil physical quality. Compaction and tillage contributed little to the temporal changes except that tillage before pre-grazing significantly ($P < 0.05$) affected the magnitude of temporal changes in MWD. Of particular note is that the soil was not disturbed by management practices during this period; thus, natural recovery under plant growth was most likely responsible for the improvements in physical quality.

From the barley cultivation to the barley harvest phase, temporal changes in MWD, $\theta_{aw}$, and $K_s$ differed with depth ($P < 0.05$). The top 0.1 m of soil had a greater increase in $\theta_{aw}$ (0.04 vs. 0.02 cm$^3$ cm$^{-3}$) and $K_s$ ($\log_{10} K_s$ of 0.53 vs. 0.36 mm d$^{-1}$) than the 0.1- to 0.2-m layer. This was in agreement with other studies that showed greater short-term (4 mo) improvements in $\epsilon_{ma}$ at the soil surface (0–0.05 m) than at the 0.05- to 0.1-m depth (Drewry, 2006). The $\log_{10}$MWD decreased under NT (0.88 to 0.84 mm for C1 and 0.96 to 0.86 mm for C2–C5), but remained unchanged under IT (0.89 for C1 and 0.92 mm for C2–C5). Overall, these results suggest that the surface layers and no-till soils recover faster than subsurface layers and tilled soils, regardless of compaction. This is possibly because surface soils and, in particular, those under NT management may have more active microbial communities and root growth, which may contribute to improvements in soil structure (Vezzani et al., 2018). Natural recovery of $K_s$ or the infiltration rate for periods under 1 yr following treading damage varied from 11 to 108% for surface soil (Drewry, 2006). Our results, however, showed that $K_s$ in the top 0.1 m of soil during the barley harvest increased by 240% (compared with the barley cultivation phase) or 1200% (compared with the post-grazing phase) within 6 mo for compacted plots (C2–C5). This indicated that crop cultivation after grazing may accelerate the extent of recovery of soil physical properties.

Temporal changes in soil physical properties have been widely observed as a result of irrigation, traffic machinery, grazing, and tillage (Strudley et al., 2008). In this study, tillage, compaction, and soil natural recovery were observed to be the main factors for explaining temporal changes in physical properties. Our study also indicated that temporal changes in soil physical properties, regardless of management interventions, were significant even in a short term such as a few months. Even for a natural landscape without disturbance, Hu et al. (2012) observed that the $K_s$ of the 0- to 0.05-m depth measured in summer was 26% lower than that measured in spring, and it would be unacceptable to simulate runoff in the rainy season.
This would provide a quantitative understanding to better manage soil processes such as drainage, NO$_3$ leaching, and greenhouse gas emissions (e.g., CH$_4$ and N$_2$O), as well as crop yield. This would provide a quantitative understanding to better manage soil processes such as drainage, NO$_3$ leaching, and greenhouse gas emissions (e.g., CH$_4$ and N$_2$O), as well as crop yield.

Conclusions

This study explored tillage management to mitigate negative compaction effects on soil physical properties. The use of NT practices to establish autumn-sown forage crops was an effective strategy to mitigate the physical damage to soil caused by winter grazing. Tillage and compaction effects gradually disappeared with time because of shallow tillage and the natural recovery of physical properties, which changed significantly between every two consecutive measurement times. Our results highlight the importance of considering short-term management and temporal effects on soil hydraulic properties when representing soil processes in agricultural system models.

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