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Soil compaction in a *Cambisol* under grassland in Estonia

Kadri KREBSTEIN[1], Katrin von JANOWSKY[2], Endla REINTAM[1], Rainer HORN[3],
Janar LEEDUKS[1], Jaan KUHT[1]

[1]Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences
Kreutzwaldi 1A, 51014 Tartu, Estonia
E-mail: kadri.krebstein@emu.ee

[2]Institute for Hygiene and Environment
Marckmannstraße 129B, 20539 Hamburg, Germany

[3]Christian Albrecht University of Kiel
Hermann-Rodewald 2, 24118 Kiel, Germany

Abstract

In soil compaction research, more attention has been given to arable land than to grasslands. Our objective was to investigate the effect of agricultural machinery on the physical and mechanical properties of soil under intensively cut lucerne (*Medicago sativa* L.). A field experiment was conducted in South Estonia, near the city of Tartu, on a second-year mainly lucerne field on a sandy loam *Calcaric Cambisol* (*CMca*). After the third silage cut, soil properties were measured in the wheel traffic lanes (compacted) and between the traffic lanes (uncompacted). Our results showed that wheeling significantly affected the soil structure. Soil compaction increased soil bulk density (BD) by 0.19 g cm^{-3} at 5 cm depth and by 0.14 g cm^{-3} at 10 cm depth. Soil compaction also affected the pore distribution: soil air capacity (AC) in compacted soil at 5 and 10 cm depth was significantly (more than 10 vol. %) lower than in uncompacted soil, and plant-available water (PAW) increased at 10 and 20 cm depth but decreased at 5 cm depth. Air conductivity (k_a) and saturated hydraulic conductivity (k_s) decreased significantly at 5 and 10 cm depth. Soil precompression stress (P_c) was lower in the uncompacted area: soil compaction increased P_c by 60 kPa at 5 cm depth and by 30 kPa at 10 cm depth. Cohesion was greater in the compacted area than in the uncompacted area (mean difference 10 kPa). This study clearly indicates that soil compaction is a problem for grasslands.

Key words: air conductivity, bulk density, cohesion, grassland, hydraulic conductivity, precompression stress, soil compaction.

Introduction

Soil compaction is a worldwide environmental problem in arable systems. According to Oldeman et al. (1991), over 68 Mha of global land in agricultural use is affected by soil compaction, 33 Mha of which is in Europe. In Estonia in 2010, according to Statistics Estonia (Statistikaamet, 2012), the total area used for agricultural production was 948 826 ha, of which 20% is permanent grassland. Grasslands are often located in areas in which conventional cultivation is impossible. Hydromorphic or semi-hydromorphic soils are often used as grassland instead of arable land in Estonia.

The focus on cultivated land in soil compaction research is based on the belief that grassland soils are stable because of the perennial plant cover and root reinforcement. The perennial nature and root structure of grassland vegetation are thought to improve the stability and bearing capacity of its soil (Cofie et al., 2000) and reduce the stress transmitted to greater depths (Stahl et al., 2009). Trükmann (2011) showed that plant roots increased soil stability on grassland: shear strength at the densely rooted 5 cm depth was significantly higher than that at the less densely rooted 20 cm depth. The strength of rooted soil depends on the individual strengths of the soil and the roots as well as on the interface strength between the soil and the roots.

Despite the stability provided by the vegetation, soil compaction can occur in grasslands. Higher wheel loads are causing an increasing severity of soil compaction. Machinery power and the weight of tractors and harvesting machines have increased, affecting grasslands and arable lands. Stahl et al. (2009) noted that machines typically used for grassland management have wheel loads of more than 5 Mg. Furthermore, the production of perennial forage crops results in a high level of traffic (fertiliser and slurry spreading, rolling, harvesting and transport), particularly during crop harvesting operations (Jorajuria, Draghi, 1997). Frost (1988) showed that in grasslands used for silage, the entire area of a field is passed over by tractor wheels up to nine times each year. Frame and Merrilees (1996) noted that the production of high-quality fodder requires an early first cut, which cannot always be conducted under ideal weather and soil conditions. If the cut is conducted while the soil remains wet, wheeling takes place on weak soil.

The changes in grassland soil properties due to soil compaction depend on several exogenous factors.

One set of factors includes machine parameters, such as wheel load, inflation pressure, loading time and wheeling frequency (Horn et al., 2003). Another important factor is soil structural stability, which depends on soil texture, organic matter content and aggregation (Horn, Rostek, 2000). If external soil stress is lower than internal soil strength, an elastic deformation (recoverable) occurs, but if internal soil strength is exceeded by external stresses, the soil reacts with plastic deformation (irreversible) (Horn et al., 2003). Plastic soil compression decreases the soil volume and changes the pore size distribution by reducing the volume of coarse pores and increasing the fraction of smaller pores (Pagliai et al., 2003). These compression processes are responsible for many adverse changes in soil functions, including low hydraulic conductivity and aeration (Lipiec, Hatano, 2003). The direct effects of soil compaction on plant growth are reduced root growth and function and reduced supply of oxygen and nutrients to roots (Lipiec, Hatano, 2003). All of these factors can constrain plant growth and lead to decreased production of perennial forages. Jorajuria and Draghi (1997) found a yield decrease of 52–76% for grassland vegetation in the traffic lane. Glab (2008) showed a decrease of up to 27% in the aboveground dry weight of lucerne, and Reintam et al. (2006) showed a decrease of up to 50% in the shoot dry weight of barley and narrow-leafed lupine. In the same study they also found that yellow lupine shoot mass decreased by 10% on the plots wheeled 6 times (total tractor weight 4.8 Mg) on a *Stagnic Luvisol* (*LVst*) sandy loam.

There are insufficient experimental data on the effect of compaction on soil properties in grasslands. The aim of this investigation was to study the effect of agricultural machinery on the physical and mechanical properties of soil under a field consisting primarily of lucerne, cut for silage.

Materials and methods

Site and soil of the experiment. The 2007 pilot study investigated changes in the soil properties of an intensively used second-year lucerne (*Medicago sativa* L.) field in Vorbuse, Estonia (latitude 58°25′ N, longitude 26°39′ E), near the city of Tartu. The climate is humid-temperate with a mean annual precipitation of 695.2 mm and average temperature of 6.7°C in 2007. The soil in the experimental area was a *Calcaric Cambisol* (*CMca*) (IUSS Working Group WRB, 2007). The texture was sandy loam containing sand (0.063–2 mm) 58%, silt (0.002–0.063 mm) 31% and clay (<0.002 mm) 11%. The average soil characteristics at 0–30 cm depth were pH_{KCl} 6.4, C_{org} 12 g kg^{-1}, sand 58%, silt 31% and clay 11%. No fertilisers were used in this trial.

Characteristics of the trial. Data were collected from the field after the third silage cut of lucerne (*Medicago sativa* L.) on 24th September 2007. There were two different levels of soil compaction: compacted (in wheel tracks) and uncompacted (between wheel tracks). Soil compaction was generated using a pick-up machine (total full load: 12 Mg) with an axle load of 3.5 Mg and calculated soil contact pressure of 258 kPa (O'Sullivan et al., 1999 a). The soil water content at 0–30 cm depth during soil compaction corresponded to pF = 1.7 (ca 30%). Undisturbed soil samples were taken with steel cylinders from 5, 10 and 20 cm depth in September. Undisturbed soil samples for porosity, bulk density (BD) and saturated hydraulic conductivity (k_s) were taken with steel cylinders (cylinder 100 cm^3, diameter 5 cm and height 4 cm) from 5, 10 and 20 cm depth. For BD and soil porosity characteristics we had 36 samples (18 for compacted and 18 for uncompacted area, for each depth – 5, 10 and 20 cm, 6 replications). For k_s we had 78 samples (39 for compacted and 39 for uncompacted area, for each depth – 5, 10 and 20 cm, 13 replications).

The undisturbed soil samples for shear parameter: precompression stress (P_c), air conductivity (k_a) and cohesion were taken with a steel cylinder 235.5 cm^3 (diameter 10 cm and height 3 cm). For P_c we had 9 samples (4 for compacted and 5 for uncompacted area). Samples had mostly two replicates, but one replicate for the treatment in compacted soil at 10 and 20 cm depth and one for uncompacted soil at 20 cm depth). For k_a we had 36 samples (18 for compacted and 18 for uncompacted area, for each depth – 5, 10 and 20 cm 6 replications) and for the cohesion 6 samples, with one replication.

Laboratory methods. To obtain the water retention characteristics, undisturbed soil samples were saturated and equilibrated to a matric potential of −3 kPa on a sand bed. The samples were then equilibrated to matric potentials of −6, −15, −30 and −50 kPa using ceramic plates and to the matric potential of −1500 kPa using a pressure chamber. We used for pressure −1500 kPa disturbed soil samples (diameter 2 cm and height 1 cm) and left the samples under the pressure for 30 days. To determine BD and total porosity, the samples were dried in an oven at 105°C for 24 h. Air capacity (AC) was defined as the difference between total porosity and water content at −6 kPa matric potential. Plant-available water (PAW) was calculated as the difference between volumetric water content at field capacity (matric potential of −6 kPa) and wilting point (matric potential of −1500 kPa) (Hartge, Horn, 2009). Saturated hydraulic conductivity (k_s) was measured using the falling-head method, as described by Hartge and Horn (2009). Air conductivity (k_a), P_c and shear parameter were measured on undisturbed soil samples (predrained to a matric potential of −6 kPa). Air conductivity (k_a) was measured before the shear strength. For more details, see Vossbrink and Horn (2004). Precompression stress (P_c) was determined by a confined multi-step compression device using an odometer. Defined pressures (10, 20, 30, 50, 70, 100, 150, 300 and 400 kPa) were applied stepwise for 10 min each to the soil sample. Plates of sintered metal above and beneath each soil sample ensured free drainage. Shear parameter cohesion was measured in a frame test under consolidated and drained conditions with normal stresses between 40 and 400 kPa for each normal stress level (40, 70, 100, 200 and 400 kPa). Vertical soil deformation and shear resistance were recorded during the shear test at a constant speed of 0.3 mm min^{-1}. Parameter cohesion was derived by performing linear regression on shear resistance as a function of normal stress according to the Mohr-Coulomb equation:

$$\tau = c + \sigma \cdot \tan\varphi,$$

where τ is shear strength, c – cohesion, σ – the normal stress, φ – angle of internal friction.

The values of soil physical characteristics were classified according to DVWK (1995; 1997) and Bodenkundliche Kartieranleitung (AG Bodenkunde, 2005) described in Table.

Table. Classification of the values of soil physical characteristics

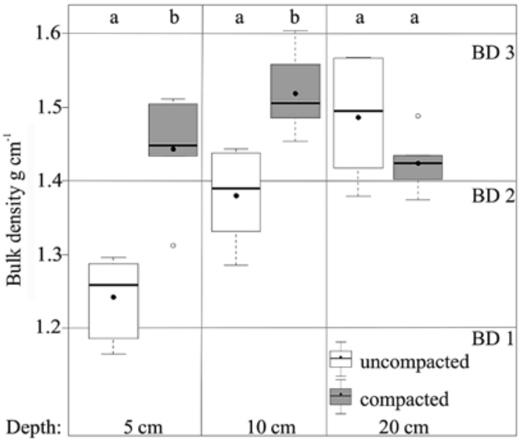
	Unit	1 – very low	2 – low	3 – medium	4 – high	5 – very high	6 – extremely high
BD	g cm^{-3}	<1.2	1.2–1.4	1.4–1.6	1.6–1.8	≥1.8	–
AC	vol. %	<2	2–5	5–13	13–26	≥26	–
PAW	vol. %	<6	6–14	14–22	22–30	≥30	–
k_s	cm d^{-1}	<0	0–1	1–1.6	1.6–2	2–2.5	≥2.5
k_a	cm s^{-1}	<−3.3	−3.3–−2.9	−2.9–−2.6	−2.6–−2.3	≥−2.3	–
P_c	kPa	<30	30–60	60–90	90–120	120–150	≥150

BD – bulk density, AC – air capacity, PAW – plant-available water, k_s – saturated hydraulic conductivity, k_a – air conductivity, P_c – precompression stress

Statistical analysis. Box plots were chosen for graphical visualisation of the results. Each box plot contains information about the median (black line across the box), arithmetic mean (black point in the box), lower and upper hinges (defined as the 25th and 75th percentiles), and outliers (displayed as diamonds). Fisher's LSD post-hoc test was used to compare the differences between values (arithmetic mean). Results were classified as statistically significant when $p < 0.05$. Statistical data analyses were performed with the software *R*, version 2.9.1

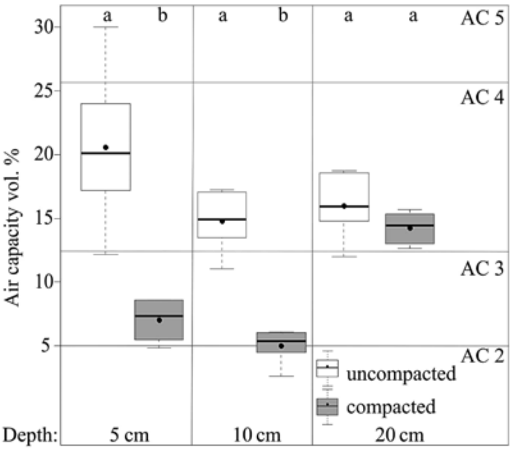
Results and discussion

Soil bulk density (BD) and porosity. The measured soil BD values showed a dependency of soil depth (Fig. 1). The BD values in the uncompacted area were lower at 5 cm of depth (classified as low) than at 20 cm depth (classified as medium). Soil air capacity (AC) values were higher at 5 cm of depth than at 10 and 20 cm of depth (Fig. 2). The mean AC values of the uncompacted area could be classified as high. The plant-available water (PAW) values showed also dependency of soil depth (Fig. 3). The PAW values at 20 cm of depth (classified as low) were more than 10 vol. % lower than PAW values at 5 cm of depth (classified as high, Table). During wheeling on the lucerne field, soil compression occurred in the wheel tracks. Soil compaction significantly increased soil BD at 5–10 cm of depth: BD increased by 0.19 g cm^{-3} at 5 cm of depth and by 0.14 g cm^{-3} at 10 cm of depth. Our results obtained in the traffic lanes of pick-up machinery showed that wheeling significantly affected pore size distribution in the grassland soils. The AC values at 5 and 10 cm of depth were significantly lower (more than a 10 vol. % difference) in the compacted area than in the uncompacted area; at 20 cm of depth, there was a difference, but this difference was not statistically significant. The PAW values increased at 10–20 cm of depth and decreased at 5 cm of depth with soil compaction.



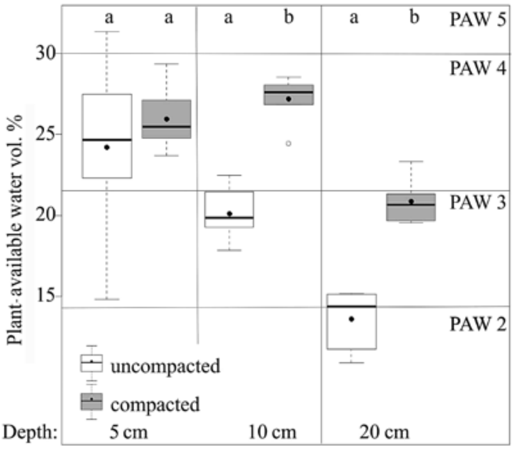
Notes. In each box plot, the median (–) and arithmetic mean (•) values are shown. Different letters indicate significant differences between the soil compaction treatments at one depth ($p < 0.05$, n = 6).

Figure 1. Soil bulk density (BD) depending on soil compaction and soil depth



Explanations under Figure 1

Figure 2. Soil air capacity (AC) depending on soil compaction and soil depth

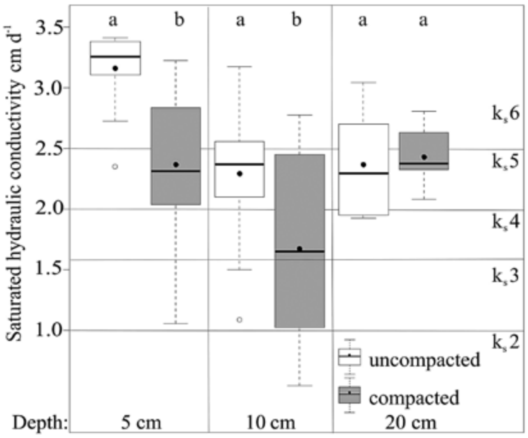


Explanations under Figure 1

Figure 3. Soil plant-available water (PAW) depending on soil compaction and soil depth

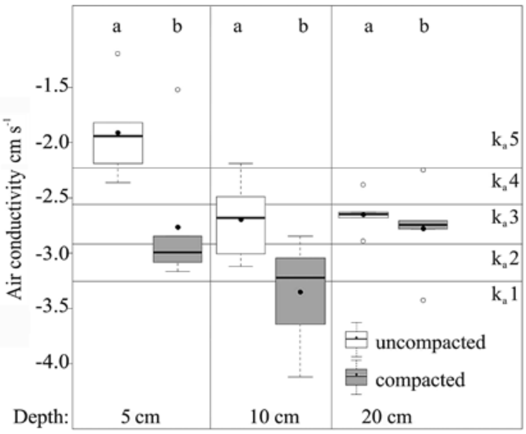
Our results are consistent with those of other studies. Frame and Merrilees (1996) found that for an intensively used silage field (diploid and tetraploid ryegrass swards) on freely drained brown alluvial (by FAO) soil with a sandy loam topsoil and a loamy sand subsoil, wheeling (7 and 15 wheel passes with a tractor mass of 3.2 Mg) increased dry BD in the compacted area by approximately 0.13 g cm^{-3} compared with the control area. The air-filled porosities of wheeled treatments were also reduced by 4.2% compared with the control treatments. Reintam et al. (2009) noted that repeated passes with even a low weight tractor (total weight of 4.8Mg with tyre inflation pressure of 150 kPa) can induce subsoil compaction and a decrease in plant productivity for spring barley on a *Stagnic Luvisol* (*LVst*) of sandy loam. In the same study, BD increased in soil passed over six times by 0.15 Mg m^{-3} compared to uncompacted soil. Glab (2008) found a BD increase of approximately 0.14 g cm^{-3} at 0–30 cm depth after six passes (tractor contact area approximately 125 kPa) over a lucerne field on a *Mollic Fluvisol* (*FLmo*) of silty loam. Hammel (1993) found a significant reduction of soil AC at 5 cm of depth in the wheel tracks on grassland. Douglas and Crawford (1998) found an increase in BD and a decrease in macropores under different grassland management intensities. Our results showed that there was an increase in PAW in the wheel tracks. This increase indicates that with the decline in macroporosity (pores larger than 50 µm diameter), the volume of pores with a diameter of 0.2–50 µm increased. This is also confirmed by results in the literature. Koppi et al. (1992) attributed the reduction of AC to the increase of smaller pores in the grassland soils. The volume of soil macropores with a diameter of >195 µm was significantly larger in the absence of traffic than after conventional traffic. Similarly, Schäfer-Landefeld et al. (2004) demonstrated that the volume of pores with a diameter of smaller than 30 µm increased on conventionally managed fields.

Saturated hydraulic conductivity (k_s) and air conductivity (k_a). Our data showed that k_a and k_s in the uncompacted area at 5 cm depth were higher (k_s extremely high, k_a very high) than at 10 and 20 cm depth, whereas there was no statistically significant difference between the values at 10 and 20 cm depth (Figs 4 and 5).



Notes. In each box plot, the median (–) and arithmetic mean (•) values are presented. Different letters indicate significant differences between the soil compaction treatments at one depth ($p < 0.05$, n = 13).

Figure 4. Soil saturated hydraulic conductivity (k_s) depending on soil compaction and soil depth



Explanations under Figure 1

Figure 5. Soil air conductivity (k_a) depending on soil compaction and soil depth

The decrease in k_a and k_s due to soil compaction was statistically significant at 5 and 10 cm depth. Although the k_s values decreased, the data of the compacted area could be classified as very high (5 and 20 cm depth) and high (10 cm depth, arithmetic mean). The decrease in k_a was from very high to medium at 5 cm depth and from medium to very low at 10 cm (difference in arithmetic mean).

Because of the decreased soil volume and associated decrease in macroporosity, the saturated water and air conductivity were reduced in the compacted area. Many authors have shown, with the help of different soil compaction experiments on fields and grasslands, that a simultaneous reduction of total porosity and macropore volume reduces the gas and fluid conductivity. Radford et al. (2000) indicate that the unsaturated hydraulic conductivity of a clay *Vertisol* (*VR*) in wet soil conditions decreased after soil compaction during harvester traffic with 0, 10 and 12 Mg axle loads and was greater at 10 cm depth than at the soil surface. Yavuzcan et al. (2005) found that field traffic with a wheel load of 11 Mg caused a significant reduction in the air permeability of arable loess soil (*Regosol*, *RG*) down to 40 cm depth only after a single pass. Furthermore, water and air conductivity depend not only on macropore volume but also on connectivity. Wheeling on the grassland causes a load-dependent decrease of soil volume and shearing processes that cause changes in pore continuity. Pagliai et al. (2003) found a highly significant linear correlation between hydraulic conductivity and elongated continuous pores. After one and four passes in the same track of rubber-tracked tractors and wheeled tractors of medium power on a compacted clay soil (*Vertic Cambisol*, *CMvr*), k_s decreased in the 0–10 cm layer. After four passes with the rubber-wheeled tractor, hydraulic conductivity was tremendously reduced, consistent with the presence of few if any elongated pores and the finding that the pores present were thin and not vertically continuous. Additionally, O'Sullivan et al. (1999 b) demonstrated that a decrease in pore continuity can occur at the same BD as a result of shearing.

Precompression stress (P_c) and cohesion. Precompression stress is an important parameter in soil mechanics and is often used as a criterion for soil susceptibility to compaction. Soil cohesion is the tendency of the particles to stick to one another and reflects soil consistency and workability. Soil P_c increased with soil depth in the uncompacted area. P_c values of the uncompacted area were approximately 30 kPa lower at 5 and 10 cm depth than at 20 cm depth, whereas cohesion was higher at 5 and 10 cm depth than at 20 cm depth (Figs 6 and 7). P_c and soil cohesion were both lower in the uncompacted area than in the compacted area. The increase in P_c exceeded 60 kPa at 5 cm depth, whereas at 10 cm depth, the change exceeded 30 kPa. At 5 cm depth, the increase in P_c was significantly larger than at 10 and 20 cm depth. This difference may be caused by shear strength. The traffic caused soil compaction and shearing at 5 cm depth. Shearing causes disproportionately heavy soil compaction because of increased cohesion. The mean change in soil cohesion due to compaction was 10 kPa.

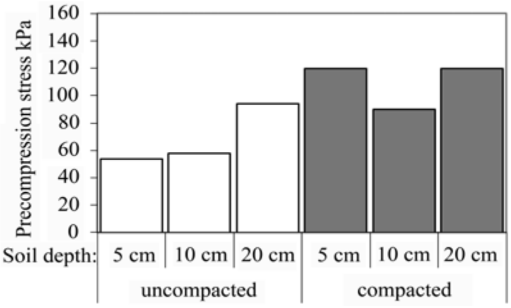


Figure 6. Soil precompression stress (P_c) (measured at pF = 1.8) depending on soil compaction and soil depth

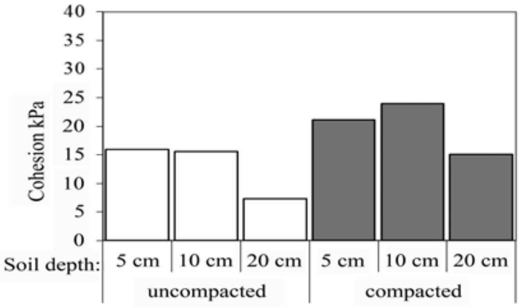


Figure 7. Soil cohesion (measured at pF = 1.8) depending on soil compaction and soil depth

We found pronounced changes in the soil stability parameters of P_c and cohesion due to soil compaction. These changes occurred because the machinery had a contact area pressure over 3.5 times higher than the soil's internal strength (P_c), causing irreversible damage to the former soil structure. During soil deformation, soil particles are pushed closer to one another, leading to a higher soil BD with more contact points between soil particles. This higher BD leads to higher values of soil cohesion in the compacted area compared with the uncompacted area. Dörner and Horn (2009) reported that cohesion is higher in the mechanically strongly loaded plough pan than in the upper layers. Stahl et al. (2009) investigated the effect of wheeling with a manure tanker (contact area of 150 kPa) on grassland under moist to wet soil conditions on soil stability and found that soil P_c was higher in the wheel tracks. Precompression stress increased 27 kPa at 10 cm depth and 17 kPa at 20 cm depth.

Conclusions

Our field experiment shows that soil bulk density (BD), pore size distribution, air conductivity (k_a) and saturated hydraulic conductivity (k_s) were significantly affected by wheeling with pick-up machinery on intensively used grassland (cut for silage). During wheeling on the lucerne field, soil compression occurred in the wheel tracks:

1. Soil compaction increased soil BD at 5–10 cm depth, air capacity (AC) values at 5 and 10 cm depth were lower in the compacted area than in the uncompacted area and plant-available water (PAW) values increased at 10–20 cm depth and decreased at 5 cm depth with soil compaction.

2. The decrease in k_a and k_s due to soil compaction was statistically significant at 5 and 10 cm depth. Because of the decreased soil volume and associated decrease in macroporosity, the saturated water and k_a were reduced in the compacted area.

3. Soil precompression stress (P_c) and soil cohesion were both lower in the uncompacted area than in the compacted area (statistically not approved).

Our results showed that wheeling affected the soil structure in the grassland.

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Rudžemio suslėgimas Estijos pievose

K. Krebstein[1], K. von Janowsky[2], E. Reintam[1], R. Horn[3], J. Leeduks[1], J. Kuht[1]

[1]Estijos gyvybės mokslų universiteto Žemės ūkio ir aplinkos mokslų institutas
[2]Higienos ir aplinkos institutas, Vokietija
[3] Kylio Christiano Albrechto universitetas, Vokietija

Santrauka

Tiriant dirvožemio suslėgimą, daugiau dėmesio skiriama ariamai žemei nei ganykloms. Tyrimo tikslas – ištirti žemės ūkio mašinų poveikį fizinėms bei mechaninėms dirvožemio, kuriame buvo auginta ir intensyviai pjauta mėlynžiedė liucerna (*Medicago sativa* L.), savybėms. Lauko bandymas vykdytas Pietų Estijoje, netoli Tartu, antrųjų metų naudojimo žolyne, kurio pagrindą sudarė liucernos, karbonatingame rudžemyje (RDk), smėlingame priemolyje. Po trečios pjūties silosui dirvožemio savybės vertintos ratų vėžėse (suslėgta) ir tarpuvėžėse (nesuslėgta). Tyrimo rezultatai parodė, kad dirvožemio suslėgimas traktoriaus ratais smarkiai paveikė jo struktūrą. Suslėgimas dirvožemio tankį 5 cm gylyje padidino 0,19 g cm^{-3}, o 10 cm gylyje – 0,14 g cm^{-3}. Dirvožemio suslėgimas taip pat paveikė porų pasiskirstymą: suslėgto dirvožemio poringumas 5 ir 10 cm gylyje buvo gerokai (daugiau nei 10 cm^{3} cm^{-3}) mažesnis, o augalų pasisavinama drėgmė padidėjo 10 ir 20 cm gylyje, bet sumažėjo 5 cm gylyje. Dirvožemio laidumas orui ir prisotintas hidraulinis laidumas smarkiai sumažėjo 5 ir 10 cm gylyje. Dirvožemio stresas prieš suslėgimą buvo mažesnis nesuslėgtame plote: suslėgimas dirvožemio stresą 5 cm gylyje padidino 60 kPa, 10 cm gylyje – 30 kPa. Dirvožemio rišlumas buvo didesnis suslėgtame plote, palyginus su nesuslėgtu (vidutinis skirtumas – 10 kPa). Tyrimo rezultatai parodė, kad dirvožemio suslėgimas ganyklose yra problema.

Reikšminiai žodžiai: dirvožemio suslėgimas, ganykla, hidraulinis laidumas, oro laidumas, rišlumas, suslėgimo stresas, tankis.