Abstract: Dynamics of change of soil physical properties and growth of plants on compacted soils. The aim of the current study was to investigate the continuous compaction effect on soil properties, such as bulk density and penetration resistance and to the spring barley (Hordeum vulgare L.) growth. The experiments were made on Estonian University of Life Sciences research field at Eerika, near Tartu in 2001–2005. The sandy loam Stagnic Luvisol was compacted by tractor MTZ-82 (total weight 4.9 Mg) by multiple tyre-to-tyre passing. For all that traffic applied uniformly to cover the entire experimental plots: one time, three times and six times. One plot remained without special compaction as a control. No fertilizers and herbicides were used. After 5 years of compaction by 4.9 Mg tractor there were detected distinguishable subsoil and topsoil compaction. Soil deformation increased with the number of passes and there were no significant differences between one and three times compacted soil in the soil bulk density and penetration resistance. The effect of compaction on soil bulk density was higher when the soil was compacted in wet conditions. Compaction increased the amount of barley shoots but decreased their phytomass more than 80%.

Key words: bulk density, penetration resistance, spring barley

INTRODUCTION

Compaction of agricultural soils is a global concern because of the negative effect on crop yields and the environment. In Western and Eastern Europe it has affected because of non-site and time adjusted agricultural and forestry management strategies over 62 million ha or 11% of the total land area (van Lynden, 2000). Overuse of machinery, intensive cropping, and short crop rotations, intensive grazing and inappropriate soil management leads to compaction. Soil compaction affects in the first place soil properties, as soil compaction occurs when soil particles are pressed together, reducing pore space between them and increasing the soil bulk density and penetration resistance. Soil compaction refers to the formation of dense layers of well packed soil, often at the bottom of the cultivated layer but also deeper. As far as compaction is concerned, the infiltration of rainwater decreases parallel to an increased risk of soil surface erosion (Lipiec and Hatano, 2003), due to destroying of soil aggregates and reduced pore space. At high soil moisture, the difference in soil resistance between uncompacted and compacted soil is low and may be smaller than the value that limits root growth (> 2 MPa). But as soil gets drier, soil compaction becomes observable (in review of Hamza and Anderson, 2005). Some of the further results of soil compaction are decreased
root size, retarded root penetration and smaller rooting depth (Unger and Kaspar, 1994), decreased plants nutrient availability and uptake, and plants stress, which are among the major reasons for reduced plant productivity and yield. The main problem in wet compacted soil is poor aeration and in dry compacted soil high penetration resistance to root growth. The yield losses of cereals have been reported from 5% due to the one pass of machinery to the 90% due to several passes in the field edges. From the grain yield losses 10–30% may be the harvesting losses due to the smaller grain on compacted soil (Reintam and Kuht, 2003).

The compact ability of soils depends of soil texture, soil-water content at the moment of field operations and on the growing period, from load of machinery and from ground contact pressure, which depends from tire size and tire inflation pressure, and from traffic intensity (repeated traffic) on field (in review of Lipiec and Hatano, 2003; Hamza and Anderson, 2005; Raper, 2005). When driving a vehicle on moist, arable soil, measurable compaction may be exerted to a depth of at least 30 cm at an axle load of 4 Mg, 40 cm at 6 Mg and 50 cm at 10 Mg, and 60 cm or deeper at an axle load of 15 Mg or higher (in review of Raper, 2005). Dry soils resist loads better than moist soil. But the field operations are eligible to start when soil moisture content is 70–90% of field capacity, depending on soil texture (Nugis et al., 2004). In this range the soils are the most vulnerable to compaction as soil compact ability increases until the moisture content is approximately at the field capacity point.

The aim of the current study was to investigate the continuous compaction effect on soil properties, such bulk density and penetration resistance and to the spring barley (Hordeum vulgare L.) growth.

MATERIAL AND METHODS

Data were collected from the research field of the Estonian University of Life Sciences (58°23’N, 26°44’E) on sandy loam soil at Tartu County in 2001–2005. By tractor MTZ-82 (total load 4.84 Mg) soil compaction was done before sowing time in spring 2001, 2002, 2003 and 2004. For all that traffic applied uniformly to cover the entire experimental plots: one time, three times and six times. The inflation pressures in the wheels of tractor appropriate were 150 kPa. Four compaction treatments (split plot method) on the experimental field formed, one of them control (without special compaction). The compaction treatments were split to four replications and the size of each experimental plot (16 plots) was 3 × 9 m (27 m²). Drilling of barley (crosswise to compaction treatments) in rate of 450 germinating seeds per m² was done in middle of May. No fertilizers and herbicides were used. Every autumn (in September) the soil was ploughed at 0.21–0.22 m depth.

Soil type of experiment area was sandy loam Stagnic Luvisol in WRB (1998) classification. From the diagnostic and genetic horizons the Humus horizon (A), ferralic (Bw), stagnic (Ew) and argillic (Bt) horizons were founded in soil of experimental area. The soil characteristics of humus horizon of experiment area are

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presented in following: C 1.4%, N 0.11%, K 164 mg·kg\(^{-1}\), P 183 mg·kg\(^{-1}\), Ca 674 mg·kg\(^{-1}\), Mg 101 mg·kg\(^{-1}\), pH\(_{KCl}\) 6.2, sand (2.0–0.02 mm) 67.9%, silt (0.02–0.002 mm) 22.9% and clay (< 0.002 mm) 9.2%. Detailed description to the soil of experimental area is presented by Reintam and Köster (2006).

The samples of soil and plants were taken in earing phase of barley in growth stage 75–79 by numeric code description according by BBCH Growth Scale of plants (Tottman, 1987; Lancashire et al., 1991) when all fruits of barley have reached final size (middle of July) from each experimental plot. Data regarding the content of plant community were obtained from taking vegetation samples from a plot of 0.25 m\(^2\) (\(n = 4\)). The types of components (barley and different weed species) were determined, counted, measured and weighed. The soil bulk density was measured with 50 cm\(^3\) (\(h = 5\) cm, \(\varnothing = 3.5\) cm) cylinders in 0.1 m layers down to 0.4 m in four replications. At the same layers were taken samples for measuring soil moisture. Penetration resistance was measured with cone penetrometer (cone angle 30°, stick diameter 12 mm) in every 0.05 m layer down to 0.6 m in six replications.

For statistical the one-way analysis of variance (ANOVA) were used to process the collected data. The factor was soil compaction treatment. To compare the differences between values the standard Student’s \(t\)-test was used and least significant differences (LSD) at significance \(P < 0.05\) founded.

RESULTS

Due to the different weather conditions during sampling period in different years, the values of soil penetration resistance and bulk density were changed among the experiment years (Fig. 1). The value of both, penetration resistance and bulk density is depending from the soil moisture content. However, the effect of traffic on the soil properties was significant in every year of experiment between uncompacted and six times compacted soil. The differences in soil penetration resistance between one and three times compacted soil were significant after five years of soil

![FIGURE 1. Change of soil penetration resistance (a) and soil bulk density (b) due five years of soil compaction (average of 0–40 cm soil layer). Bars are indicating standard deviation of the value](image-url)
compaction (Fig. 1a), but in average of five years data there was no significant differences between those treatments. In the same time the six passes increased the soil penetration resistance by 2.0–3.0 MPa compared with uncompacted soil.

Compaction effect on the soil bulk density was depending more from the soil moisture content at the moment of soil compaction. Soil compaction by 4.9 Mg tractor increased soil bulk density significantly \( (P < 0.05) \) already by one single passes in 0–0.1 m depth in all years of investigation (Fig. 1b). In 0.1–0.2 m depth the increase of soil bulk density was caused mostly by 3 and 6 passes in first year, but also by one pass in second and third year of soil compaction. The bulk density increase in topsoil (0–0.2 m) reach from 0.05 up to 0.3 Mg·m\(^{-3}\) depending from number of passes compared to uncompacted soil. Below plough layer (0–0.2 m) compaction by 4.9 Mg tractor did not caused any significant differences of soil bulk density in first year, where the soil moisture content was only 110 g·kg\(^{-1}\) at the moment of compaction. The significant increase of bulk density with 0.15 Mg·m\(^{-3}\) was observed in second year by 6-times compaction in 0.2–0.3 m depth, where the soil moisture content was 200 g·kg\(^{-1}\) at the moment of compaction. Third, fourth, and fifth year continuous compaction (moisture content 190 g·kg\(^{-1}\) at the moment of compaction) caused significant increase of bulk density already by one pass by 0.1 Mg·m\(^{-3}\) down to 0.3 m depth. No significant increase of bulk density was detected in 0.3–0.4 m depth in most experiment years. In average of five years data, there were no significant differences between compaction treatments in soil bulk density (Fig. 2b). However, there were significant differences between

![FIGURE 2. Soil penetration resistance (a) and soil bulk density (b) depending on soil compaction and depth (average of 5 year measures). Bars are indicating the standard deviation of the value](image-url)
uncompacted control and six time compacted soil in soil bulk density.

Changes in soil properties caused significant differences in barley shoots mass and density (Fig. 3). Only in first year the differences in barley mass and density between compaction treatments were not significant. Like in soil properties, also in barley dry weight and density were no significant differences between one and tree times compacted soil, except in 2002, where the differences were significant between all compaction treatments.

Without fertilizers use, the productivity of barley was decreasing rapidly. Second year barley monoculture decreased barley dry weight almost three times and shoots density 1.5 times. In the third year the mass and density of barley was stabilized.

DISCUSSION

Though compaction by 4.9 Mg tractor with tyre inflation pressure 150 kPa increased in first and second year soil bulk density and penetration resistance, no hardpan was formed in subsoil, mostly because of deep-freezing of soil (up to 0.5 m) in those years, but also because moderate weight of tractor. However after third year continuous direct compaction hardpan below plough layer and even deeper was formed and it even by one passes (Fig. 1 and 2). The soils of experiment area with their medium fine texture are moderate susceptible and moderately to very vulnerable to soil compaction by moist soil and not particularly vulnerable by dry soil according to the classes of vulnerability and susceptibility. Recommended maximum tyre inflation pressure to those soils is 120 to 160 kPa (van den Akker, 2002). Also other researchers are detected that the number of passes is causing differences in soil properties, but with low significance and the effect of compaction will appear after several passes (Balbuena et al., 2000). In experiments of Balbuena et al. (2000) the significant differences in soil properties were detected after ten times of soil compaction compared with control and one time compacted soil in 50 cm depth of soil.

Natural processes of freezing/thawing, wetting/drying and bioactivity

![Graphs showing soil compaction effects on barley biomass and density](image-url)
alleviate the topsoil compaction. Aura (1983) found that ploughing and frost alleviated the compaction of clay soils within the plough layer of 0.20 m due to traffic with an axle load of 3 Mg in spring by the following spring. In Sweden one pass by the 5.4 Mg tractor brought degree of compaction to the optimum, but repeated passes led to over-compaction. In the same time one pass by the wheel-loader (9.9 Mg) increased degree of compactness almost as much as three passes by the tractor (Etana and Håkansson, 1996). When the plough layer is severely compacted, however, the recovery of heavy clays may take five years in spite of annual ploughing and frost (Håkansson and Danfors, 1981).

In unsuitable conditions tillering of barley is higher and in dry year new sprouts may grow after short rain. In 2002 barley grow new sprouts in middle of the summer and it increased the density of plants on compacted soil. Planting density and ontogenetic processes significantly influence dry matter partitioning between leaves and stems. In Wisconsin, Lowery and Schuler (1991) observed that compaction by 8 and 12.5 Mg axle load treatments decreased corn grain yield 14–43% on fine mixed mesic Typic Hapludalf and 4–14% on fine-silty mixed mesic Typic Hapludalf. In our experiments there were higher yield losses (up to 90%) of barley after wet spring and relatively dry growing period and lower losses (up to 20%) after dry spring and relatively rainy growing period.

Limited water and nutrient availability to plants due to compaction are major constraints to plant growth and yields in many soils (Ishaq et al., 2001). In compacted soils plants are using their energy to penetrate the thickened soil layers with roots and they do not have energy to generate shoots. Result of that is reduced length and biomass of shoots and ears, even if the root biomass is not affected.

The reduced number of barley plants on most compacted soils was connected with seedlings emergence. Poor physical regimes may mechanically resist seedling emergence (Acharya and Sharma, 1994). The physical resistance of soil to the growing seedling is an important factor in crop production because it affects the establishment of a uniform crop stand of a desired density and subsequent plant development.

CONCLUSIONS

From the soil compaction experiment carried in 2001–2005 can conclude:

1. Soil deformation increased with the number of passes and there were no significant differences between one and three times compacted soil in the soil bulk density and penetration resistance.
2. The effect of compaction on soil bulk density was higher when the soil was compacted in wet conditions.
3. Compaction increased the amount of barley shoots but decreased their phytomass more than 80%.
4. The physical resistance of soil to the growing seedling is an important factor in crop production because it affects the establishment of a uniform crop stand of a desired density and subsequent plant development.
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