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EXPRESS-DIAGNOSTICS METHOD FOR ASSESSMENT OF SOIL COMPACTION FOR DIFFERENT CULTIVATION METHODS

Edvin Nugis[1], Kalvi Tamm[1], Taavi Võsa[1], Tiit Plakk[1], Veli Palge[2]

[1]*Estonian Crop Research Institute, J. Aamisepa 1, Jõgeva vald 48309, Estonia*
[2]*Estonian University of Life Sciences, Institute of Technology, Fr. R. Kreutzwaldi 56, Tartu, Estonia*

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Vastutav autor: Corresponding author: Edvin Nugis
E-mail: edvin.nugis@mail.ee
Phone: +372 505 6211

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ABSTRACT. Soil compaction remains a concern because of the heavy tractors used in intensive agriculture. When axle loads of vehicles increase, soil compaction is affected in deeper soil layers. An efficient tool is needed to assess the impact of machines on soil. Therefore, an express-diagnostics method was developed and implemented under Estonian agricultural conditions. Since 1976, an investigation has been carried out on how wheeled or tracked vehicles (WTV) influence soil under agricultural conditions in Estonia. The main goal of the investigation was to develop a mathematical model and a corresponding computer simulation system. Uncompacted and compacted soil was modelled using a vegetation model of "guttated vegetation miniatures". The system allows soil vulnerability to compaction to be assessed by the criterion (q_{abc}) agro-empirical bearing capacity (ABC). Both field and laboratory data were used in the development of the system. We have found that at the deepest layer the bulk density was higher for tilled soil compared to no-tilled soil. Dry soil bulk density in no-tilled soil after 2 years in the deepest layer was 0.11 Mg $m^{3\,-1}$ less than tilled soil, and for no-tilled soil after 3 years in the deepest layer, it was 0.12 Mg $m^{3\,-1}$ less compared to the tilled field soil. The amount of agronomically preferable aggregates (2–4.75mm) was major in tilled soil compared to no-tilled soil. It means that the preferred (in an agronomical sense) soil particles K_{str} in conventionally tilled (ploughing – K2; K3) fields were significantly better compared to no-tilled (O2; O3) fields in the trial plots. These results emphasize the benefits of multifunctional modelling systems (computer simulation and simulation by vegetation miniatures) and the need to improve assessment of methodology for receiving adequate and probable results, and finally for yield prediction.

Introduction

In order to determine the cause and extent of soil compaction, one needs to carry out an analysis using special complex methodology. Usually this methodology is based on complex investigations of the "machine-soil-crop" system (Nugis, 1988). Soil tillage alongside any compacting effect caused by wheels or tracks complicates the task of solving the impact of soil compaction (Horn, Kutilek, 2009; Tullberg *et al.*, 2007). In other words, while wheels or tracks have a compacting effect on soil, any soil loosening that occurs due to digging booms will reduce soil compaction (Nugis, 1988). Research has shown that in addition to the effects of compaction, which become fixed in different soil layers (Nugis, 1988), all of the various cultivation activities also imposes long lasting impacts on the various soil layers (Håkansson *et al.*, 1987). Soil compaction problems have a multi-disciplinary character, in which complex machine/soil/crop/weather interactions all play important roles (Soane, Ouwerkerk, 1994). However, it is believed that a theoretical soil compaction model can be developed to provide a suitable method of tackling soil compaction problems (Blight, Soane., 1986).

Historically, agricultural vehicles often weighed less than 2 Mg. However, in more recent times, agricultural vehicles may weigh as much as 60 Mg. The latter applies for instance to some sugar beet harvesters in Central Europe (Horn, Fleige, 2005). The increasing weight has often led to tyres with higher inflation pressure than was needed for the lighter equipment (Blight, Soane, 1986). Therefore, there is a need to establish quantitative criteria to characterize the trafficability of heavy machines as well as their influence on soils. There have been many efforts to develop these criteria (Söhne, 1953; Skotnikov *et al.*, 1982; Rydberg, 1984; Arvidsson *et al.*, 1991; Richards *et al.*, 2000; Tarkiewicz, Lipiec, 2000; Tullberg, 2000; Dawidowski *et al.*, 2000; Tijink, van der Linden, 2000; Koolen, van den Akker, 2000; van den Akker, 2001), all of which are interesting and contribute to the understanding of the soil compaction problems. However, more effort is required to develop the methodology needed to assess machinery-induced soil degradation based on soil bearing capacity and to make it possible for every farmer to avoid the potential negative influences on their soils.

If wheel pressure contacting soil (normal dynamic stress q_d) of the wheeled or tracked vehicles (WTV) is higher than the agrotechnical soil bearing capacity (q_{abc}) (which defines the limits of soil to sustain pressure of heavy tractors), then the subsoil is endangered (Horn, Fleige, 2005; van den Akker *et al.*, 2003; Jones *et al.*, 2003). Since this is sometimes the case, ongoing research needs to focus on the potential environmental effects of soil compaction.

In Estonia, the potential damage to soil resources is not as common as in some other countries since there is currently no sugar-beet production, and therefore no use of heavy sugar-beet harvesters. Furthermore, in Estonian soils freeze every winter, which reduces the persistence of compaction effects. However, the remediation effects of freeze/thawing is less effective in the subsoil than in the plough layer (Håkansson, 2001; Blight, Soane, 1986). Therefore, the problems resulting from soil compaction are factors of great importance when designing and operating field vehicles and when deciding which tillage practices should be utilized.

Recently, the University of Agricultural Sciences (SLU) in Sweden has carried out an investigation related to the impacts on soil from the complex interactions from various tillage operations (ploughing 20–25 cm, versus shallow cultivation 10 cm (Rydberg, 1984). In these long-term investigations (1973–1983) by Rydberg (1984) in the southern part of Sweden, no significant decrease in yield was observed between ploughing and shallow cultivation treatments. Therefore, it can be concluded that in these areas, planting of cereals cultures without ploughing can be performed without negative impacts to production. However, the same studies demonstrated that the further north in Sweden that ploughing occurred the more important deep ploughing becomes to ensure higher yields. In this study, a yield advantage was observed through ploughing at the same parallel that would correspond to Estonia. The yield increased 5–35% (average 18%) for oat and 0–32% (average 12%) for barley with deep ploughing compared to the shallow ploughing. Similar results were found for other crops, with yield without ploughing decreasing by 14–21% for sugar beet, and decreased an average of 22% for pea and 21% for winter rape (Rydberg, 1984). The results published in these studies justifies more intensive research under the conditions found in Estonia.

Due to the complex nature of this research, investigations using multifunctional and multidisciplinary modelling systems is needed with a comprehensive view of soil conditions. This modelling system would require engineering functions that are essential to be able to carry out a quantitative assessment. This would include the investigation of current soil conditions under tractor wheel and an assessment of soil restoration afterwards. A fruitful way of studying soil processes is by simulating them in a modelling environment. Powersim v2.5 (Powersim Software AS) is a tool that can be used to create models of complex processes which involve many different parameters (Persson, 1995). The temporal dynamics of these processes can then be investigated by varying the initial parameters. Research is need to describe the state of soil after the complex interactions of direct drilling and ploughing, therefore, the objective of this investigation was to develop an express-diagnostics method to describe relationships between q_d (WTV) and q_{abc} (soil) in such a way that the functions of the machine-soil-crop system could be predicted. This research comprised of laboratory and field experiments including modelling of soil compaction by computer simulation and simulation by vegetation miniatures. This involved examination of soil conditions under fields associated with different cultivation methods.

Material and Methods

Field experiments

The field experiments were carried out on fields of permanent observation points in different regions of Estonia: South-Viljandi County at Abja-Paluoja (58º7´39´´N, 25º15´32´´E) – trial No 2 (by WRB – *GleicAlbeluvisol*); Valga County (57º56´31´´N, 26º9´17´´E) – trial No 3 (*Fragi-Stagnic Albeluvisol*); and Pärnu County (58º38´18´´N, 24º21´17´´E) – trial No 8 (*MollicGleysol*). Trial plots were located on farmers' fields in which regular crop rotation was maintained. These plots included direct drilled plots (designate as "O") and tilled plots (designate as "K"). The physical properties of soil, *i.e.* dry bulk density (Mg $m^{3\,-1}$), water content (% g g^{-1}), cone or penetrometer resistance (MPa) and volumetric water content W_v at five points (with interval 5 m) of the Z-scheme (at each point n = 3) were observed in each field. Measurements were taken in spring after seeding and in autumn after harvest, using a Percometer and Eijikelkamp Penetrologger. The Penetrologger geotagged the measurement points with an on-board GPS system. Data measured by the Percometer E_r (dielectric constant) was used to calculate the soil volumetric water content W_v using three different relationships:

1) from experimentally identified $W_v(E_r)$ graph for Estonian average loam soil;

2) by Topp *et al.*, 1980:

$$W_v = 4.3 \cdot 10^{-6} {E_r}^3 - 5.5 \cdot 10^{-4} {E_r}^2 + 2.92 \cdot 10^{-2} E_r - 5.3 \cdot 10^{-2}, (m^3 \cdot m^{-3}) \quad (1)$$

3) by Ln formula (Kadaja *et al.*, 2009):

$$W_v = 0.144 \cdot \ln(E_r) - 0.109 \quad (2)$$

The dry bulk density and gravimetric soil water content from 0–10, 10–20 and 20–30 cm layers were determined with Eijekelkmp's cylinder (100 cm^3) and compared with the Percometer results. At the same sampling locations, cone resistance was measured down to 70 cm, but only data down to 40 cm was used in the analysis because of the regular occurrence of stones below 40 cm interfered with the measurements.

During 2012–2014, electrical properties of soil were measured with a percometer (Adek LLC, EE 05500 B1) using a 28 mm diameter probe (type TVL) which can be pushed directly into soil. Percometer (abbreviation from Permittivity and Conductivity) is an electrical capacitive probe instrument which measures "*in situ*" the dielectric constant E_r of soil at 40–50 MHz frequencies and the bulk electrical conductivity (*ECa*) of soil at 1 kHz over the same sampling volume (Saue, 2008). The measurements were carried out in triplicate near each Z point at depths of 5 cm (soil layer 0–10 cm), 15 cm (soil layer 10–20 cm) and 25 cm (soil layer 20–30 cm) for a total of 45 measurements per plot.

Laboratory tests

In the laboratory, soil samples were compacted with the aid of an oedometer, in which the dynamic normal stress (q_d) was measured, and a guttating test-culture (spring-barley "Anni") was measured, where the latter reacted negatively to increases of bulk density (Fig. 1). The guttating test-culture method is based on the principle of abscission of guttated liquid at a constant temperature (23 °C) and at almost 100% air humidity, using a hydrothermostat.

Nine seeds for germination were sown into cylinders of 8 cm height and 6 cm diameter. Within 48 hours of sowing barley, 3 cm whitish colour germs spring up with dewdrops. The humidity or density of these drops varied depending on soil physical properties, *i.e.*, the guttated liquid was reduced at higher soil bulk densities (up to totally absent) due to the increased difficulty of the seed germs to develop. The gutta can easily be collected on filter paper and the area (mm^2) of the blot can be determined by weighing (mg) or by a planimeter (mm^2). Also, it is possible to scan the blot on the filter paper (treated with 5 per cent copper vitriol solution) to determine the area (kB) using the program Photoshop. In this study, the latter was used because of the simplicity of determining the relationship between etalon square in mm^2 and in kB. An oedometer was used for specifying the limit of normal strain in soil at the depth of 10 cm under laboratory conditions.

Figure 1. Results of guttation intensity (guttate liquid at sprouts, mm^2 at filter paper) of spring-barley "Anni" depending on bulk density

Evaluation of soil compaction from a practical point of view was based on data obtained from the assessment of relative guttation and crop yield. Also, research was carried out by this test-method to clarify the main soil-hydrolytic constant characteristics, including the smallest soil water content (FSM), ripping moisture of capillary connection (RMC), smallest field capacity (SFC) (virtually the same as field capacity (FC)), and the maximum molecular field capacity (MMFC) (Reppo, 1980). Our experience has shown that there is a definite relation between SFC and FC which can be defined as FC/SFC = 1.13.

In addition to laboratory experiments using the guttation method the others laboratory experiments were carried out which conducted with vegetative miniatures and which were also based on the guttation method.

Theoretical suppositions

The normal dynamic stress q_d could be measured immediately (by strain gage sensor) during motion of WTV, but the soil dry bulk density, penetration or cone resistance, water content of soil, and structural composition could only be measured before and after soil compaction. Also, the deph h_w of fresh wheel tracks of WTV should be immediately measured. However, WTV requires that an agroempirical bearing capacity (ABC) of the soil (q_{abc}) be found (Table 1).

Concerning that the main criterion is:

$$q_d < q_{abc} \tag{3}$$

First, determining q_{abc} required verification of the corresponding levels of dry bulk density (Mg·m^{-3}), penetration resistance (MPa), and water content (% g g^{-1}). The level of agroempirical bearing capacity (ABC) (specifically soil compaction) is required to determine the influence of WTV on soil providing an adequate picture of final results characterizing axle-load (Håkansson *et al.*, 1987) and for determining an express-diagnostics evaluation (Nugis *et al.*, 2014). Altogether for any WTV it is important to know the track depth h_w or final soil settlement after wheel traffic. Regarding crop growth for any specific soil type, it is advantageous for WTV when the rut h_c or final wheel traffic settlement is not very deep, and at the same time, the dry soil bulk density (γ_a) is not more than the suitable limit ($\gamma_{i(limit)}$). Therefore, an advantageous situation can be defined as:

$$\gamma_a < \gamma_{i(limit)} \tag{4}$$

This limit of dry bulk density $\gamma_{i(limit)}$ is determined in the laboratory by the guttation method (Reppo, 1980; SU 1018013 A1; SU 866471 A1; Nugis, Reppo, 1984).

Determination of q_{abc} can be made according to track depth h_w of soil using the following equation (Kacygin, Orda, 1977; Nugis, 1988):

$$h_w = \frac{1}{\beta} \ln \frac{q_d}{q_{xo}} \frac{A(\varepsilon_{max} - \varepsilon_{min})}{\varepsilon_{max} + 1} \tag{5}$$

where q_d– tire dynamic normal pressure during traffic in the soil layer nearest the wheel or track (*e.g.* 0.10 m), kPa; q_{xo} – compressive normal stress in the farthest soil layer during traffic relative to the tracks where no residual settlement is observed, kPa (usually q_{xo} = 20 kPa); β – coefficient of distribution of cone resistance in the vertical direction of depth of soil after traffic WTV, m^{-1} (Eq. 13); ε_{max} – maximum void ratio of soil before WTV traffic; ε_{min} – minimum feasible void ratio of soil after traffic of WTV (for example, traffic or laboratory tests of more than 50 times by oedometer); A – index (after traffic) of soil compaction when the soil void ratio ε_i is directly found in the field as a result of determining the dry bulk density, which is calculated as described by Troitskaya (1961):

$$A = \frac{(\varepsilon_{max} - \varepsilon_i)}{(\varepsilon_{max} - \varepsilon_{min})} \tag{6}$$

If specific density γ in ε (Eq. 6) is substituted by bulk density $\varepsilon = (\delta - \gamma)/\gamma$ then the index of soil compaction is calculated as:

$$A = \frac{(\gamma_i - \gamma_{min})\gamma_{max}}{(\gamma_{max} - \gamma_{min})\gamma_i} \tag{7}$$

where, γ_{min} – dry bulk density of soil in its loosened initial state, γ_i – current value of soil dry bulk density, γ_{max} – limit of soil dry bulk density in the state of compaction at which plants are not able to grow any more.

Table 1. ABC and index of soil volume trampling K_v (if the soil moisture ratio is equal to 0.8 FC), coefficient β distribution of normal compressive stresses in the depth of soil and appropriate soil bulk densities (γ_{min} and γ_{min}) including index A of soil compaction and field capacity of soil (for main Estonian soil samples).

Soil sample	Coefficient of soil volume trampling (K_v), kN m$^{3-1}$	Coefficient (β)m^{-1}	Soil dry bulk density initial state (γ_{min}), Mg m$^{3-1}$	Soil dry bulk density maximum state, (γ_{min}), Mg m$^{3-1}$	Index of soil com-paction (A)	Soil field capacity (FC), % g g^{-1}	Soil agro-technical bearing capability (ABC) or (q_{abc}), kPa
*Fragi-Stagnic Albeluvisol**	2050	2.5	0.98	1.79	0.81	16	470
Molli-Calcaric Cambisol	2900	3.3	1.11	1.78	0.82	17	390
Endoeutri-Mollic Cambisol	2900	3.1	1.07	1.68	0.79	18	380
Sceleti-Calcaric Regosol	2800	3.2	1.11	1.79	0.85	15	410
Epigleyi-Salic Fluvisol	3300	3.4	1.15	1.78	0.89	16	440
*Gleic Albeluvisol**	2600	3.3	0.98	1.73	0.71	15	520
*Mollic Gleysol**	2400	3.3	1.05	1.50	0.69	16	190

*determined during proximate period 2012–2014

Eq. 6 describes one of the more important characteristics for determining soil compaction A and could be used as the basis for determining the following indexes of soil structure: (B_{str}) and humidity C_w.

Accordingly, after transformation of Eq. 3 and substitution of the variable, the final expression for agroempirical bearing capability q_{abc} that describes the situation immediately after traffic can be written as:

$$q_{abc} = \frac{K_v}{\beta}\left\{\frac{1}{1-A\left(1-\frac{\gamma_{min}}{\gamma_{max}}\right)} - 1\right\} \tag{8}$$

where K_v – coefficient of soil trampling volume (kN m$^{3-1}$), which could be calculated if we have the value of soil resistance in the linear part of the beginning of the cone resistance diagram of (kN) and the value of cone nozzle (area in m^2) and at the same time have the depth (m) of soil penetration; γ_{min} – dry soil bulk density (Mg m$^{3-1}$) before WTV traffic and where the properties of soil are similar to those after spring cultivation and before sowing; γ_{max} – maximum feasible of soil dry bulk density (Mg m$^{3-1}$) after WTV traffic (for example, WTV traffic of more than 50 times).

The next important index needed is the index of soil structure B_{str}. First, the ratio of soil structure K_{str} is evaluated (Nugis, 2010; Nugis *et al.*, 2014) by the USA Standard Testing Sieve and also by the method of Swedish University of Agricultural Sciences (Kritz, 1983; Håkansson, 1983). For this determination, the soil is sieved under moist conditions.

The ratio of soil structure (structure ratio) K_{str} (soil moist sieving) is calculated with the following equation:

$$K_{str} = \frac{s_{ad}}{s_{un1}+s_{un2}} \tag{9}$$

where, s_{av} – percentage of soil particles with diameter between 2–4.75 mm (agronomically preferable structural aggregates – AVSA); s_{n1} – percentage of soil particles with diameter <2 mm (not-agronomically preferable structural aggregates – N-AVSA); and s_{n2} – percentage of soil particles with diameter >4.75 mm (also N-AVSA).

During long-term investigations, it has been found that if $s_{av} = s_{n1} + s_{n2}$ then the structure ratio K_{str} is equal to 1 (denoted by $K_{str(max)}$), which means that the soil structure is in the maximum preferred condition. Also, K_{str} at levels less than 0.50 are is a completely undesirable soil condition, For example, it has been observed that after potato harvesting in Estonia, soil compaction resulted in the structure ratio of $K_{str(min)} = 0.49$. Results indicate that it is possible to characterize the common structural condition of soil through a corresponding index B_{str} of soil structure measured directly in the field as described below:

$$B_{str} = \frac{\left(K_{str(\max)}-K_{str(i)}\right)}{\left(K_{str(\max)}-K_{str(min)}\right)} \tag{10}$$

where, $K_{str(i)}$ – the structure ratio of soil according to the current result of field measurements.

The same principle was used for estimation of soil moisture properties characterized by a corresponding index of humidity "C_w", but with the difference that this index was subtracted from one. For example:

$$C_w = \left[\frac{\left(1-F_{c(\max)}-F_{c(\mathrm{i})}\right)}{\left(F_{c(\max)}-F_{c(\min)}\right)}\right] \tag{11}$$

where, $F_{c(\max)}$ – soil water content (g/g%), which is equal to field capacity (FC),

$F_{c(\min)}$ – soil water content (g/g%), which is equal to plant fading.

Since for the optimization of WTV assessment is use for corresponding tillage equipment, there is a need to know that the structure of the soil is good when it is ready for cultivation, *i.e.*, if soil humidity is in the FC range of 0.7–0.9 (or 70–90% field capacity) (Nugis, 1997; Heinonen, 1979; Revut, 1960).

Finally, a suitable model for the theoretical description of changes for the previously discussed indexes (A, B_{str}, C_w) can be developed for each index separately using the same computer simulation model (Figs. 2 and 3) with the POWERSIM system (www.powersim.no). Index C_w can be determined using the same model (Fig. 4) as indexes A and B_{str}. After substitution we can write Eq. 11 as follows:

$$C_w = \frac{1-(\text{Maximum\_level\_of\_MR}-\text{Moisture\_ratio\_MR})}{(\text{Maximum\_level\_of\_MR}-\text{Minimum\_level\_of\_MR})} \tag{12}$$

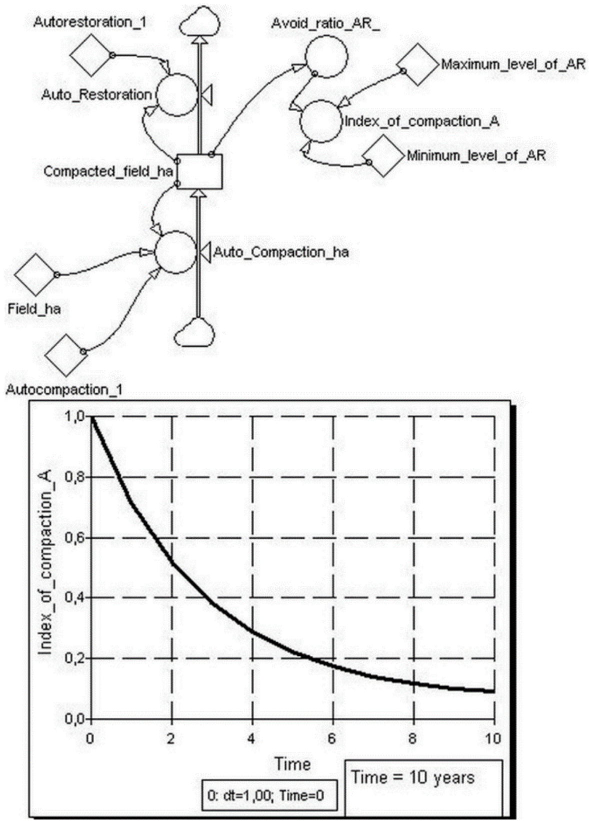

Figure 2. Relationship between index of soil compaction (*A*) and time (year) when soil compaction and start of spontaneous autorestoration related to changes in soil dry bulk density

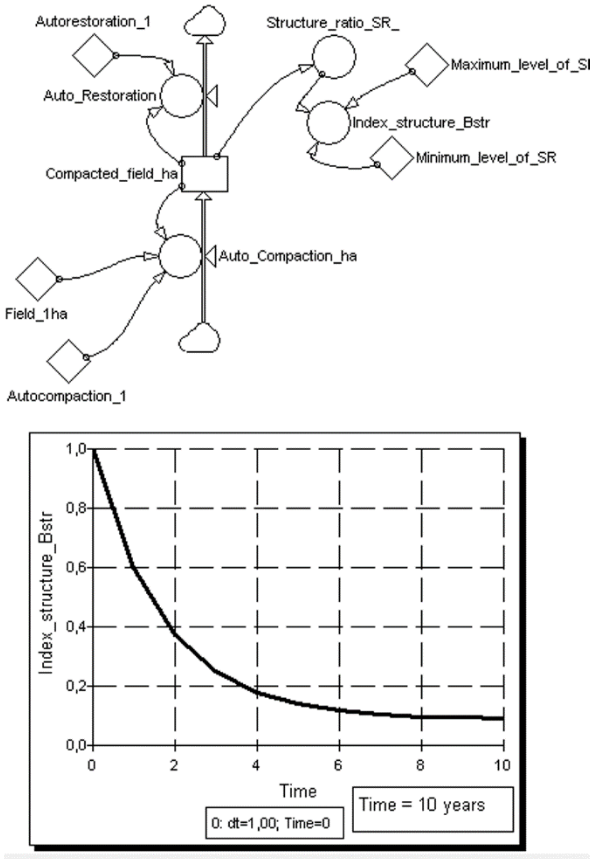

Figure 3. Relationship between index of soil structure (B_{str}) and time (up to 10 years) when MTM started spontaneous autorestoration related to changes in soil structure ratio

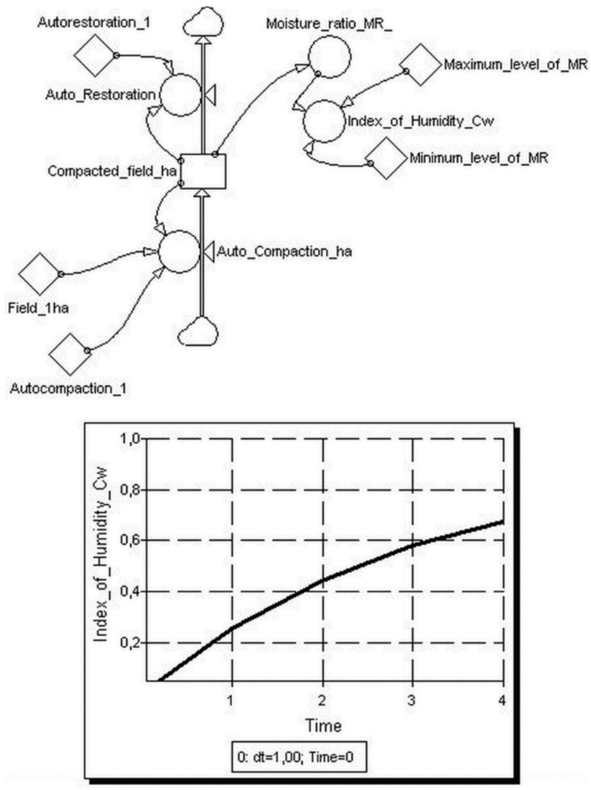

Figure 4. Relationship between index of soil humidity (C_w) and time (up to 3 years) when MTM started spontaneous autorestoration related to changes of soil moisture ratio

Concerning models (Figs. 2, 3, and 4), it should be noted that the starting-point for all of the indexes was the same, *i.e*. a compacted field 10000 m^2 (filled into the box "*Field_1ha*") and ratio 0.26 (filled into the box "*Autorestoration_1*") between width of double tracks after tractor traffic (1.31 m) and working with drill (5 m). With controlled traffic farming (CTF), to divide the distance between the two tramlines for the width of double tracks, the corresponding ratio is filled into the box "*Autorestoration_1*" (Fig. 2).

However, the model process for Figs. 2 and 3 for soil spontaneous autorestoration runs for a much longer period (about 10 years) compared to the related soil humidity (Fig. 4). Since examining the process of moisture ratio due to weather conditions of Estonia would not be appropriate without precipitations during the same period, a 4 year period (2012–2014) corresponding to the field experiments was used.

Results

Soil agroempirical bearing capability

Generally, the ratio between minimum (initial state of soil) and maximum dry bulk density, Eq. 6 and 7, varied according to soil type (Mouazen, Ramon, 2009; Nugis, 1988). On average, the minimum dry bulk density (γ_{min}) for relatively light soils of Estonia (by WRB – *Gleic Albeluvisol* including *Fragi-Stagnic Albeluvisol*) were observed to be 0.98 Mg m^{3-1} (ε_{max} = 1.65). For *MollicGleysol* (WRB) – γ_{min} = 1.05 Mg m^{3-1} (ε_{max} = 1.50). The data for maximum dry bulk density for several soil types were quite different (Table 1). For example, experiments during 2012–2014 resulted in γ_{max} = 1.73 Mg m^{3-1} (ε_{min} = 0.50) for *Gleic Albeluvisol* (South-Viljandi County) and γ_{max} = 1.79 Mg m^{3-1} (ε_{min} = 0.45) for *Fragi-Stagnic Albeluvisol* (Valga County) and for *Mollic Gleysol* (Pärnu County).

To determine the coefficient of volume trampling of soil (kN m^{3-1}), it was sufficient to have a chart of penetration or cone resistance (Fig. 5). In the diagrams shown in Figure 5, a dot corresponding to the linear part could be marked which represents each trial (h_{co} = 0.4 m; h_{cok} = 0.3 m; h_k = 0.3 m). This was necessary for calculation of the coefficient of trampling volume of soil K_v (kN m^{3-1}). Also, for each trial it was possible to fix the suitable level of penetration resistance (MPa) for each soil layer (p_{ro} = 1.17 MPa (117 kN m^{-2}); p_{rok} = 0.80 MPa (80 kN m^{-2}); p_{rk} = 0.77 MPa (77 kN m^{-2}).

The hypothesis concerning the coefficient β (Eq. 5) for distribution of cone resistance in the soil depth layer h_{ci} after traffic of WTV was defined as:

$$\beta = 1/h_{ci} \tag{13}$$

This coefficient mostly depends on soil type and moisture ratio level. It is a well-known that if soil humidity decreases then the coefficient β level will increase. Coefficient of trampling volume K_v (Eq. 6) also depends on soil humidity and at the same time soil texture classification. Because the Estonian soils are relatively light, the soil humidity plays a more important role.

In order to evaluate the soil agroempirical bearing capability q_{abc} (ABC), the corresponding results are shown in Table 1 for the most common soils of Estonia (Nugis, 1988) and for the soils evaluated in the field experiments (Tamm *et al.*, 2015). Table 1 includes the agroempirical bearing capability results of previously ploughed plots. Direct drilling increases agroempirical bearing capability, thus allowing bigger equipment usage with direct drilling technology without harmful effects to soil. However, such effects were not observed on the heavier soils of Pärnu County, (*i.e. Mollic Gleysol).*

Abja-Paluoja 2013–2014

No Till		K+No Till		Ploughing	
Cone res.	LSD	Cone res.	LSD	Cone res.	LSD
MPa	<0.05	MPa	<0.05	MPa	<0.05
0.56	0.17	0.49	0.15	0.47	0.14
0.73	0.24	0.61	0.16	0.57	0.17
0.98	0.24	0.80	0.19	0.77	0.20
1.17	0.27	0.92	0.21	0.89	0.21
1.35	0.28	1.00	0.21	0.99	0.22
1.49	0.29	1.07	0.22	1.07	0.21
1.63	0.27	1.15	0.22	1.13	0.23
1.78	0.27	1.22	0.22	1.21	0.25
1.90	0.25	1.34	0.23	1.21	0.26
1.93	0.23	1.51	0.26	1.15	0.26
1.98	0.19	1.61	0.27	1.17	0.27
2.08	0.17	1.65	0.27	1.20	0.28
2.06	0.18	1.67	0.27	1.18	0.28
2.11	0.17	1.71	0.28	1.20	0.28
2.09	0.19	1.68	0.30	1.18	0.30
2.12	0.19	1.63	0.32	1.22	0.32
2.13	0.22	1.64	0.34	1.26	0.32
2.15	0.24	1.63	0.35	1.32	0.34
2.14	0.25	1.64	0.34	1.46	0.39
2.16	0.29	1.82	0.40	1.52	0.41
2.31	0.32	1.88	0.36	1.60	0.45
2.35	0.33	1.97	0.37	1.90	0.50
2.34	0.36	2.20	0.39	2.12	0.53
2.47	0.38	2.46	0.36	2.44	0.52
2.61	0.41	2.65	0.32	2.65	0.51
2.85	0.42	2.91	0.31	2.90	0.54
3.16	0.44	3.14	0.32	3.12	0.55
3.37	0.49	3.39	0.35	3.44	0.54
3.50	0.51	3.51	0.32	3.74	0.50
3.51	0.48	3.57	0.33	3.99	0.50
3.52	0.49	3.80	0.36	4.40	0.59
3.56	0.50	3.92	0.43	4.58	0.59
3.61	0.49	3.97	0.38	4.72	0.56
3.65	0.53	4.07	0.43	4.93	0.53
3.69	0.45	4.27	0.50	5.20	0.58
3.83	0.44	4.43	0.49	5.26	0.54
4.08	0.50	4.47	0.47	5.41	0.57
4.02	0.51	4.50	0.48	5.40	0.58
3.97	0.45	4.58	0.48	5.44	0.55
4.11	0.69	4.88	0.42	5.55	0.55
O2		**OK2**		**K2**	

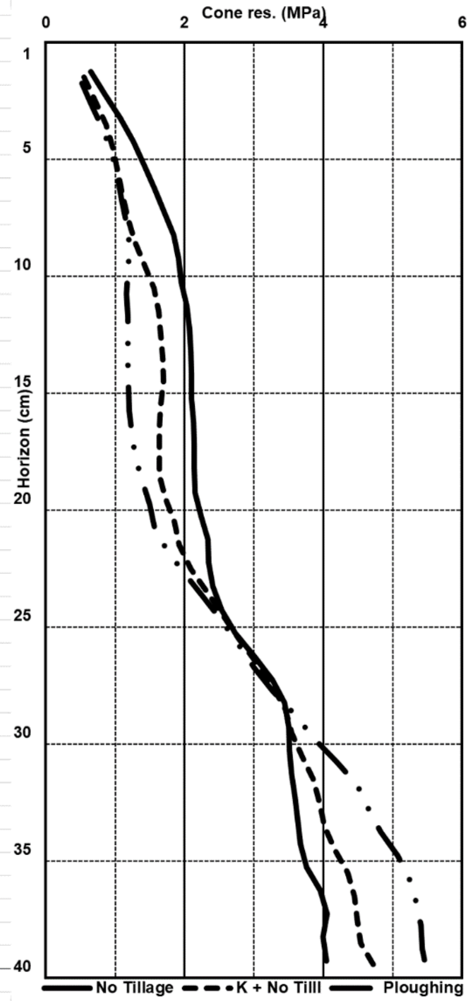

Figure 5. Example changes of average penetration or cone resistance (MPa) depending on depth (cm) of soil layer (O2 – direct drilling or no tilled; OK2 – one time is ploughing and after that every time is direct drilling; K2 – ploughing) which were measured during field experiments (2013–2014) in South-Viljandi County at Abja-Paluoja (58º7´39´´N, 25º15´32´´E) – trial No 2 (WRB – Gleic Albeluvisol)

Indexes of soil compaction, soil structure and soil humidity

In Table 2, the average values for structure ratio ($K_{str(i)}$) and for index values of soil compaction (A), soil structure (B_{str}) and soil humidity (C_w) are shown. In this table (according to equations 4, 7, 8, and 9), the minimum and maximum values are: 1) $K_{str(min)} = 0.10$, $K_{str(max)} = 1.00$; 2) $\varepsilon_{min} = 0.45$, $\varepsilon_{max} = 1.65$; 3) $B_{str(min)} = 0.01$, $B_{str(max)} = 0.99$; and4) $F_{c(min)} = 0.19$, $F_{c(max)} = 1.00$. Accordingly, it was observed that for the assessment of the best and worst structure and humidity characteristics corresponding to soil compaction, $\varepsilon_{min} = 0.45$, $K_{str(max)} = 1.0$, $B_{str(min)} = 0.01$ and $F_{c(min)} = 0.19$ are worst and other characteristics were inversely better. It is very important for the formation of suitable POVERSIM models that the above mentioned characteristics be filled into the related ring boxes of "Avoid_ratio_AR", "Structure_ratio_SR" and "Moisture_ratio_MR", respectively (Figs. 2–4).

Table 2. Average values of ratio structure ($K_{str(i)}$), soil compaction (A), soil structure (B_{str}) and soil humidity (C_w) in results usage of several agro-technologies (no till and ploughing, *i.e*. O2 and K2; O3 and K3; O8 and K8; ploughing+no till, *i.e*. OK2) during three years (2012–2014)

Characteristics	Trial plots						
	O2	K2	OK2	O3	K3	O8	K8
K_{str}[1)]	0.33	0.47	0.24	0.16	0.23	0.31	0.38
A[2)]	0.71	0.59	0.74	0.81	0.90	0.69	0.61
B_{str}[3)]	0.74	0.59	0.84	0.93	0.86	0.77	0.69
C_w[4)]	0.13	0.21	0.13	0.12	0.36	0.05	0.09

Data in Table 2 regarding trial plots showed that the indexes of soil compaction (A) and soil structure (B_{str}) for no till versus ploughing changed quite logically in South-Viljandi County for *Gleic Albeluvisol*, but the change was not logical for the Valga County trial. This was likely due to the fact that in the Valga County trial involved a different type of soil and that shallow tillage was used instead of ploughing. The index of humidity (C_w) changed predictably at both study trials. The results of moist soil sieving ratios for the South-Viljandi County, Valga County trial shown in Table 2 indicate that the preferred (in agronomical sense) soil particles K_{str} in conventionally tilled (ploughing – K2; K3) fields were significantly better compared to no-tilled (O2; O3) fields in the trial plots.

Computer simulation in comparison with data of field experiments

Figures 6–8 show the experimental data, also data of the laboratory tests (by guttation method) and theoretical SIM curve (the same as Figs. 2–4) of the computer simulation. In 2014, the index of compaction A in comparison with SIM curve for trial plots O3 and K3 are considerably different (Fig. 6). At the same time the curve of guttation tests is located quite near with SIM curve. The same tendency (Figs. 7, 8) was observed related to the index of soil structure B_{str} and soil humidity C_w for the same trial plots in 2013 and 2014, including OK2, O8 and K8 (Fig. 7). A more careful study of several similar variants is needed and selection of other input parameters for the POWERSIM model and guttation method should be done in future research.

Fig. 8 shows a shorter modelling period because the index of humidity is mostly dependent on weather conditions. In comparison to the SIM curve (the same as Fig. 4) and to the curve of laboratory tests (by guttation method), most of the trial plots are considerably different in 2014. At the same time, trial plot K3 is not very different. Therefore, it is likely that the initial data needs to be changed for the left part of the POWERSIM model (in boxes "Autocompaction_1" and "Autoresoration_1"), but after that, changes are not needed to set the same initial conditions for the above mentioned indexes: A, B_{str} and C_w. Further investigations are planned to verify this conclusion.

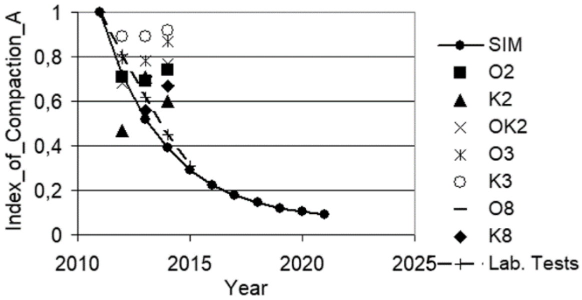

Figure 6. Results of modelling by POWERSIM system (SIM curve), curve of laboratory tests (by method of guttation) and data of indexes of soil compaction A related to different trial plots in 2012–2014.

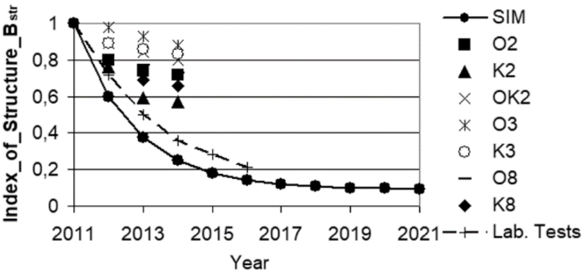

Figure 7. Results of modelling by POWERSIM system (SIM curve), curve of laboratory tests (by method of guttation) and data of indexes of soil structure B_{str} related to different trial plots in 2012–2014

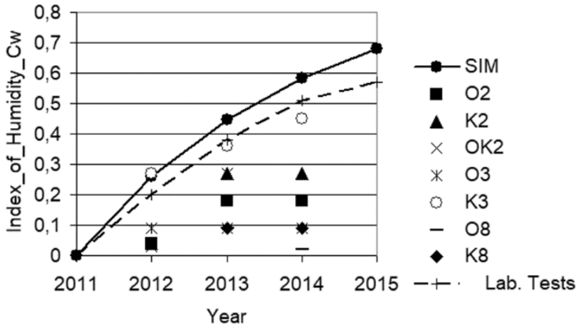

Figure 8. Results of modelling by POWERSIM system (SIM curve), curve of laboratory tests (by method of guttation) and data of indexes of soil humidity C_w related to different trial plots in 2012–2014

The comparison of all experimentally determined volumetric water content values of soil computed from E_r measurements according to different formulas (Experimental Graph – Eq. 1, (Topp *et al.*, 1980) and ln formula – Eq. 2) are presented in Figure 9. The Y-axis value – W_v of each point of "Cylinder Sampling and drying/weighing" series represents the average value of W_v of soil samples taken from the field at the same depths. The X-axis value – E_r is the average of 15 percometer measurements at the same depth as the samples were taken.

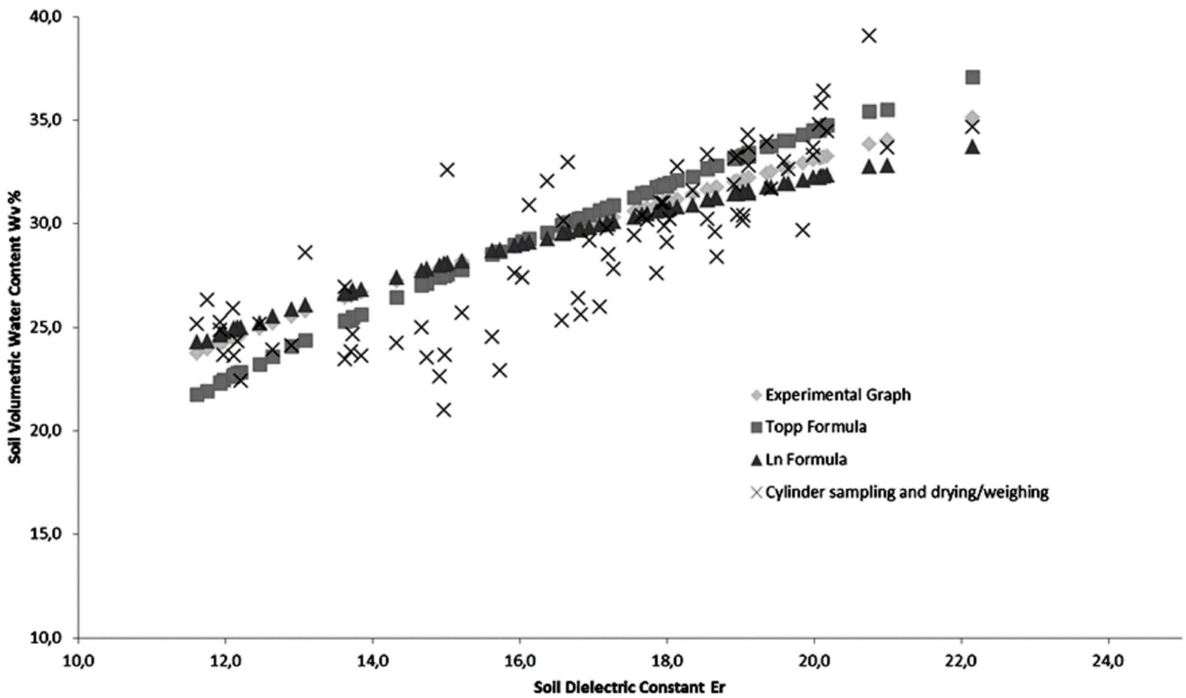

Figure 9. Comparison of experimentally determined and computed soil dielectric constant volumetric moisture values

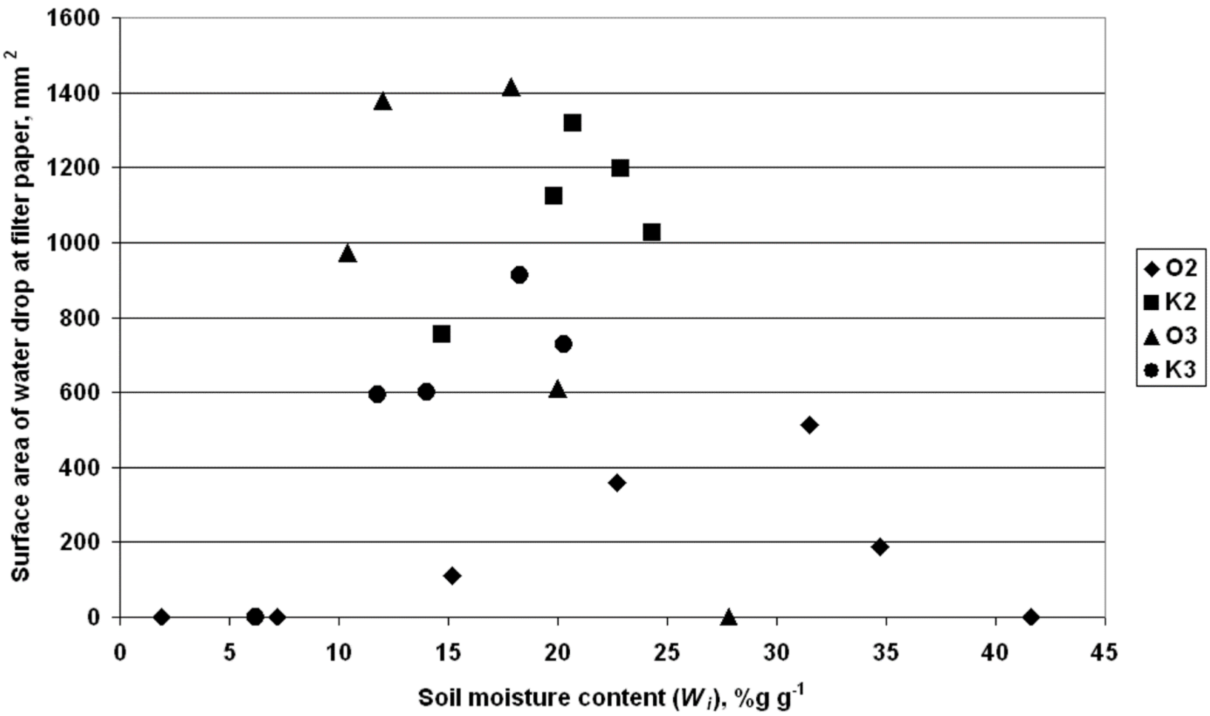

Figure 10. Results of humidity test simulation by vegetation miniatures (guttation method by Reppo (SU 866471 A1), of soils which were extracted from farmer's fields (2012–2013). Each diagram point (maximum LSD_{05} = 257 mm^2 of guttated liquid) connected with current cylinder (253.5 cm^3; diameter 62 mm and height 84 mm) was filled with the corresponding soil (middle dry bulk density 1.10±0.04 Mg m^{3-1})

The dispersion of sampled W_v values is predictable since the samples are taken at only two places and the electrical parameters are not measured at exactly the same sample, but from the nearby soil. The natural variance of soil water content can be as high as 3 to 4% on the 2.5 m scale (Famiglietti *et al.*, 2008). The measurements at ECRI on Estonian fields resulted in a standard deviation for soil volumetric water content of 1 to 2%. The average deviation between experimental and computed W_v values given in the Figure 9 was less than 1%, which represents the natural soil variation in the field. All three means of W_v calculation from E_r data gave reasonably accurate results and the difference between the formulas used in this study were in the same order as the natural soil moisture variability.

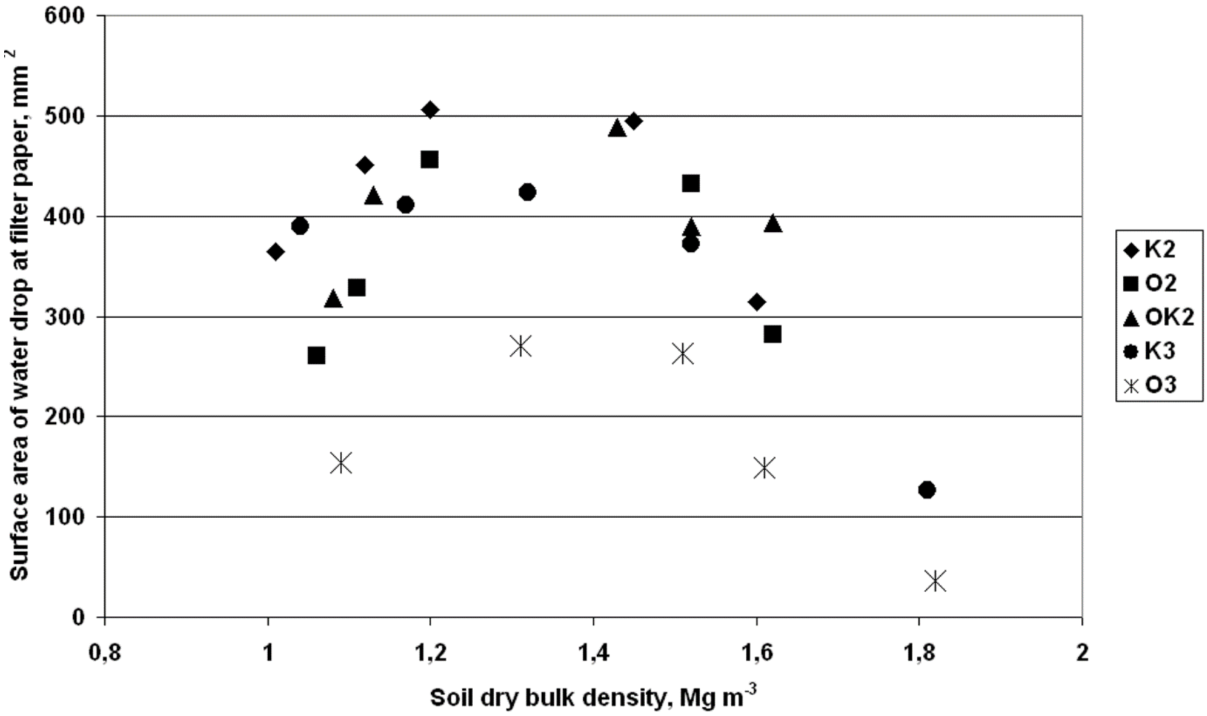

Figure 11. Results of bulk density simulation by vegetation miniatures (guttation method, SU 1018013 A1; EE 05682 B1), of soils which were extracted from farmer's fields (2012–2013) where middle soil moisture content was 20.1±1.7 % g g^{-1} (the maximum LSD_{05} = 281 mm^2 concerning the guttated liquid or water drop at filter paper)

Figures 8 and 9 show that the tendency for changes in the index for humidity (C_w), W_v,and E_r are similar. This is quite logical because the dependence between C_w and the moisture ratio (MR) or W_{MR} is linear. Therefore, from the field experiments (2012–2014), the relationship between moisture ratio W_{MR} (calculated from soil field capacity (FC)) and the index of humidity C_w can be described by the equation: $C_w = -0.599\ W_{MR} + 0.89$ ($R^2 = 0.89$).

Simulation by vegetation miniatures

Figures 10 and 11 show the results of the laboratory test with vegetation miniatures of soil humidity and soil bulk density, respectively. In Figure 10, the soil water content, smallest field capacity (SFC) is shown while Figure 11 indicates the limits of dry bulk density concerning Estonian Gleic Albeluvisol (South-Viljandi County) and *Fragi-Stagnic Albeluvisol* (Valga County). These limits are the most favourable conditions for growing cereals. Based on the dependences shown in Figures 10 and 11, the corresponding minimum and maximum limits of characteristics could be selected for computer simulation modelling of the soil physical properties.

Discussion

Our main goal was to develop an express-diagnostics method to describe the relationships between q_d (WTV) and q_{abc} (soil) in such a way that the functions of the machine-soil-crop system could be predicted. The study determined that the complex estimation of soil compaction, soil structure, and humidity could be characterize by indexes "*A*" (Fig. 6, Eq. 6), B_{str} (Fig. 7, Eq. 10), and C_w (Fig. 8, Eq. 11). Accordingly, it was determined that the main diagnostic level could be summarized for Estonian soils. It should be noted that similar results have been reported by others (Mouazen, Ramon, 2009; Mueller *et al.*, 2009; Troitskaya, 1961).

The main focus of the study was characterizing the ABC (agroempirical bearing capability, Eq. 8) with practical results that could be used by farmers. For farmers, it is necessary to immediately know the level of soil compaction for a given tractor under the specific Estonian soil conditions. Many studies report that they have solved this urgent problem (Söhne, 1953; Arvidsson, Håkansson, 1991; Richards *et al.*, 1997; Koolen, van den Akker, 2000; Dawidowski *et al.*, 2000; Tarkiewicz, Lipiec, 2000; Tullberg, 2000), but none of the publications consider the issues related to ABC.

Most of the agronomically preferable structural aggregates (macrostructure) are formed as a result of soil tillage (Soane, Bonne, 1986) in conditions of mature soil. Nevertheless, it should be noted that according to Revut (1960), in general agronomically preferable aggregates of soil are deemed to be those with a diameter between 0.25 to 10 mm, which are determined by means of dry screening in a laboratory.

In Nordic countries, an evaluation method (as described by Kritz (1983) and Håkansson (1983) is used that differs from the above widely used methods. In this method, soil aggregates between 2 to 5 mm (in our case was 2 to 4.75 mm) in diameter are deemed agronomically preferable structural aggregates and are assessed in the field by means of moist soil screening. The soil structural aggregates with diameters larger than 5 mm and less than 2 mm are considered as not agronomically preferable. Because we have evaluated soil structural elements by both the USA Standard

Testing Sieve and also by the Swedish University of Agricultural Sciences method (Kritz, 1983; Håkansson, 1983) where moist soil is sieved, it is believed that the differences between corresponding soil particle size of 2–5 mm or 2–4.75 mm are not important.

It is well established that soil is compacted by WTV during agricultural farming operations. Modern WTV are commonly very powerful units, which must be properly ballasted for maximum trailing capacity. A >50 kW unit can weigh about 4 Mg (1.8 Mg in front axle and 2.2 Mg rear axle) and carry about its own weight. Modern high power WTV can weight considerably more. For example, a typical New Holland T8.260 with 168 kW, weighs 7.2 Mg (2.7 Mg front axle and 4.5 Mg rear axle) and can carry 10 Mg on rear linkage and 3.7 Mg on the front. Total weight with all ballasts can be more than 20 Mg (>6 Mg in front axle and >14 Mg in rear axle). This type of machinery generates a considerably higher load to soil and results from this research agrees with the well-known opinion that an axle load above 10 Mg should never be used in agriculture soils (Håkansson *et al.*, 1987).

It should also be noted that the advantage of express-diagnostics method discussed in this scientific work is that it enables the specific "machine-soil-crop" functioning system to be determined without complicated laboratory and field experiments. The influence of tractor actions (and corresponding tools) on soil is passed on to the functioning of the plant, which influences crop yields either positively or negatively. Therefore, it is very important to understand the relationships between machine, soil, and crop (Pidgeon, Soane, 1977). The main question is how are changes in dry bulk density, penetration or cone resistance, soil water content, and structural composition of soil resulting from machine operations. The results of this study have indicated that information regarding the soil penetrologger including TDR (Mueller *et al.*, 2009; Bejarano *et al.*, 2010; Botta *et al.*, 2010) and data from a guttation method (simulation by vegetation miniatures (from PhD of Enno Reppo (SU 866471 A1; SU 1018013 A1) is sufficient for express-diagnostics assessment. However, the impact on soil from field ploughing for the tramline strips and in the middle of the field (both immediately during the motion of WTV and later) remain less understood. In spite of the large amount of information that has been reported about this topic (*i.e.* McHugh *et al.*, 2009; Leiaru, 2015) more research is required.

For assessment of soil compaction, it is very important to obtain adequate soil condition information. Because weather conditions are usually very variable under field conditions, long-term field experiments are required to obtain reliable results. However, results from this study have indicated that the guttation method or simulation by vegetation miniatures during a short period (only 2 days and 7 determinations of water droplets (guttate) from plant sprouts) can be used to obtain suitable results for soil compaction assessment. Thereby, if to compare the results of laboratory experiments obtained by guttation method with a theoretical curve we could be noted that we gave an encouraging result, which confirms the correctness of the theoretical approach. It is believed that difference in these methods and long term studies would be negligible, while providing easily available soil condition characteristics for yield estimation.

If the surface area of water drop on filter paper shown on the vertical axis of Figure 11 was converted into relative data then it could be compared with relative crop yield data. Results of several field studies of machines have indicated that relative guttation and relative yield did not vary more than 5%, calculated from the best (maximum) result (100%). We have found that our results were correlated with crop response curves which has been supported by many authors (Semionov *et al.*, 1980; Håkansson, 2001).

Conclusions

In this research, the soil agroempirical bearing capability for the main Estonian soil types was determined.

Indexes of soil compaction, soil structure, and soil humidity were determined and by using POWERSIM system changes to these indexes were simulated.

Results of simulation by vegetation miniatures (guttation method) could be used to determine the minimum, maximum, and limit levels of dry bulk density, and the limits of smallest field capacity (SFC).

Field experiments determined soil bulk density (in 0–10, 11–20 and 21–30 cm layers) for three field pairs. Result showed that at the deepest layer the bulk density was higher for tilled soil compared to no-tilled soil. Soil bulk density in no-tilled soil after 2 years in the deepest layer was 0.11 Mg $m^{3\,-1}$ less than tilled soil. The bulk density of no-tilled soil after 3 years in the deepest layer was 0.12 Mg $m^{3\,-1}$ less compared to the tilled field soil.

Also, the amount of agronomically preferable aggregates (2–4.75mm) was major in tilled soil compared to no-tilled soil.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publications of this paper.

Author contributions

EN, KT, TV, TP, VP – study conception and design.
EN, KT, TV, TP – acquisition of data.
EN, KT, TV, TP, VP – analysis and interpretation of data.
EN, TP, VP – drafting of the manuscript.
EN, KT, TV, TP, VP – critical revision and approved the final manuscript.

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