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Effects of Soil Compaction on Cereal Yield

A Review

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This paper reviews the works related to the effect of soil compaction on cereal yield and focuses on research of field experiments. The reasons for compaction formation are usually a combination of several types of interactions. Therefore one of the most researched topics all over the world is the changes in the soil's physical and chemical properties to achieve sustainable cereal production conditions. Whether we are talking about soil bulk density, physical soil properties, water conductivity or electrical conductivity, or based on the results of measurements of on-line or point of soil sampling resistance testing, the fact is more and more information is at our disposal to find answers to the challenges.

Thanks to precision plant production technologies (PA) these challenges can be overcome in a much more efficient way than earlier as instruments are available (geospatial technologies such as GIS, remote sensing, GPS with integrated sensors and steering systems; plant physiological models, such Decision Support System for Agrotechnology Transfer (DSSAT), which includes models for cereals etc.). The tests were carried out first of all on alteration clay and sand content in loam, sandy loam and silt loam soils. In the study we examined especially the change in natural soil compaction conditions and its effect on cereal yields.

Both the literature and our own investigations have shown that the soil moisture content changes have the opposite effect in natural compaction in clay and sand content related to cereal yield. These skills would contribute to the spreading of environmental, sustainable fertilizing devoid of nitrate leaching planning and cereal yield prediction within the framework of the PA to eliminate seasonal effects.

Keywords: cereals growth, cereal yield prediction, soil compaction effects, moisture content, precision crop production

Introduction

Soil is one of the most important elements of plant production, determining the cereal yield and quality. Changes in the soil (physical, chemical, biological) cannot be achieved without sustainable biomass production follow-up. Sustainable biomass production cannot be achieved without follow-up of changes in the soil during the vegetation period. In

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this paper, first of all the effect of change on soil natural compaction with different soil textures on cereal yield is discussed. To know more about this phenomenon is very important in order to enhance the yield prediction accuracy.

In this research, we concluded that soil compaction as an influencing factor does not appear in the direct form listed above. However, we came to the conclusion that natural changes in soil compaction at moisture content level (precipitation) for different soil types (first of all for different clay content %), in some cases can result in significantly divergent cereal yield (Nyéki et al. 2013).

The up-to-date decision support models use different meteorological data as well. It is common knowledge precipitation influences soil compaction, which is a changing property. At the same time, the direction of change on compaction can vary in different soil textures as a function of soil moisture content.

Consequently, the amount of water influences (generates more frequently extreme effects) in different forms, according to soil texture, the development of a root system of cereals, too.

These differences, mainly in maize and wheat yield, occur primarily in the extreme meteorological seasons (drought, waterlogging). Review articles in this context: cereal yield, soil texture – clay content, soil moisture content and soil compaction at a given nutrient supplement: Orrben and Thorp (1931); Raghavan et al. (1979); Håkansson and Lipiec (2000); Grzesiak et al. (2002); Lipiec et al. (2003a); Chen et al. (2005); Filipovic et al. (2006); Chen and Weil (2011); Salem et al. (2015).

Birkás et al. (2008) give a general review about the environmentally friendly tillage systems and research.

Soil compaction effects on cereal yield

The development of the plants at a given genotype includes physical (physiological), chemical, biological, biochemical and biophysical processes.

We can differentiate between two basic factors influencing the crop production: the effects of the soil and the effects of the atmosphere.

The maximum yield is achieved when these conditions are optimal for the plant growing stage, when there is coherence in the temporal development of the maize, the weather conditions and the soil conditions (Raghavan et al. 1990).

Neményi and Milics (2010) in their analysis argue that from the point of view of optimum cereal yield production technology, it is not the maximum of energy yield function, but rather the maximum of net energy function ($E_{out} – E_{inp}$).

The soil resistance effects on cereals growth depend on several factors: the depth of the compacted layer, the genotype, characteristics of root and root growth of the crop, soil type (susceptibility to compaction) (Nawaz et al. 2013), and the moisture content (Raghavan et al. 1979; Mouazen et al. 2003b; Szőllősi 2003; Parent et al. 2008; Nawaz et al. 2013) and last but not least the climatic factors (Jones et al. 1995).

Based on studies, in the case of natural compacted (uncompressed) silt loam soil there was an expected 21% reduction in maize yield, while in loam and in fine sandy loam this value is 10%. The soil resistance has influence on the cereals root (Czyž et al. 2001; Wolkowski and Lowery 2008; Lipiec et al. 2012) in turn on the whole plant's physiological maturation, growth and yield, and additionally affects the nutrient intake, independent of the culture. In spite of that, in the deeper soil layer subsoil compaction is not present; the surface compaction affects the root exploration and growth Taboada and Alvarez (2008). Maize seedlings were affected significantly by compaction treatments in Taser and Kara (2005) and the shoot ratio in Wolfe et al. (1995), respectively.

Kristoffersen and Riley (2005) investigated spring barley for three soil types with varying degrees of soil resistance. This was confirmed by Ishaq et al. (2001) in cereal culture who observed that yield reduction was 12–38% under natural soil compactness. These clearly show that the penetration resistance is negatively correlated with root length and root mass and there is a significant relationship between soil types, soil compaction (loam, clay loam and silty loam) and the usage of water. In other experiments the water consumption of wheat at continuous water supply was higher on silt loam and sandy loam soils (Lipiec et al. 2002; Vetsch and Randall 2002).

In individual years, maize yield varied according to the soil water content. Lindstrom and Voorhees (1994) found a positive maize response to compaction during the dry years and a negative response in the wetter seasons.

In the case of silt loam soils, maize yield reductions were observed in wet years (because of poor drainage), based on a standard meteorology year, but in dry years, yield was increased (Orrben and Thorp 1931). Kirkegaard et al. (1992) observed higher reductions on pigeonpea yield resulting from compaction varied from 100% in a very dry season to 0% in a wetter season in clay soil.

Franke et al. (2008) found 4.9 and 4.4 t/ha maize yield, with an average 4.65 t/ha, in loam soil with 25% clay content (2002 and 2003: rainy years), while the dry season in 2004 produced 3.9 t/ha maize yield. In contrast to this, the plant did not respond to fertilizer, fertilizer response was absent. On the other hand, Ijoyah et al. (2012) reported 34% yield reductions in dry season on sandy loam soil (7–20% clay content), in relation to the wet yield offer. Poincelot (1986) suggests 50% or more maize yield limitating effect on natural compacted soils. Chen and Weil (2011) likewise examined the effects of compaction on maize yields in two experiment sites under wet and dry growing conditions. They established less compactness with higher percentage clay (loam soil) under wet conditions than in soil with lower clay content. It is important to note that on the first occasion the maize has bigger root mass.

The decrease in yields (8–33%) in direct drilling and shallow, spring cultivated treatments, despite the higher water content available, can be explained partly by the compacted status of the 15–25 cm soil layer (Rátonyi et al. 2005).

So the soil strength is heavily dependent on water content (soil moisture content), wet soils with higher clay content are more susceptible to compaction that drier soils.

Nawaz et al. (2013) emphasize the importance of colloid content of soils; they suggest that silt loam soils with lower colloid are more susceptible to soil compaction than the medium or fine textured loam and clay soils under lower moisture content in contrast to sandy soils.

Table 1. Description of literature database of soil types, textures and cereal yield

Author(s)	Soil type(s)	Clay content (%)	Cultivar
Aflazinia and Zabihi 2014	silty clay loam	40.94	maize
Chen and Weil 2011	loam loamy sand	18.2 5.1	maize
Chen et al. 2005	clay	60	canary seed
Czyž et al. 2001	loamy sand	16	spring barley
Filipovic et al. 2006	silty loam	21.4–24.8	maize
Franke et al. 2008	sandy loam loam	–	maize
Gameda et al. 1987	clay	35	maize
Håkansson and Lipiec 2000	various soil types	0–60	spring barley
He et al. 2014	silt loam clay	18.2 59	wheat
Ijoyah et al. 2012	sandy loam	–	maize
Ishaq et al. 2001	sandy clay loam	–	wheat, sorghum
Lipiec et al. 2012	silt loam	–	wheat, barley, rye, maize, triticale
McKyes 1985	clay	–	silage maize
Nyéki et al. 2013	loam silt loam	15.6 8.3	maize
Parent et al. 2008	clay	20.3–77.3	maize
Salem et al. 2015	loam	21	maize
Taboada and Alvarez 2008	various soil types	6.7–58.4	maize
Taser and Kara 2005	clay loam	39.10	silage maize
Vetsch and Randall 2004	clay loam	–	maize
Wilkins et al. 2002	silt loam	–	wheat
Wolfe et al. 1995	silt loam	–	sweet maize

Brathwaite and Brathwaite (2002) focused on a maize hybrid experiment under wet and dry years. It was concluded that maize achieved significantly higher yield in dry conditions than in wet seasons with higher precipitation. Thus the effect of soil compaction and measurement can play a leading role in the selection of genetic types because of the impact of climate change and drying.

Triticale varieties root development was carried out under dry, water-saturated and compacted conditions (Grzesiak et al. 2002). The majority of cereal hybrids do not indicate any specific differences in either waterlogged or drought soils. They support findings on maize plants, hence the development and morphological characteristics are similar to triticale.

Birkás et al. (2004) found a significant connection between soil compaction and earthworm activity on sandy loam and loam soils in the winter wheat and maize experiments. Birkás et al. (2009a) found a correlation between compaction stress in terms of weakened emergence, deficient nutrient and water uptake, root deformation, and low yield.

Birkás et al. (2009b) examined the soil compaction effect of soil tillage practices on winter wheat, spring barley, maize yield, among others. Hungarian and Croatian long-term field monitoring and experimental work have proved a correlation between subsoil compaction and the degree of climatic damage.

Table 1 summarizes literature database with soil types and cereal yield data taking the data with the response of different crops to trafficked and non-trafficked conditions on different soil types. The clay content of soils is highly variable but provides an indication of the robustness of the trends.

Measurements and modelling

To determine the soil compactness, the models use bulk density and water content value and penetration resistance (Lipiec et al. 2003b), soil compactness stresses the impact of topsoil and subsoil compaction importance and complexity. For the determination of soil compaction there are various possibilities for on-the-go (real-time measurement; horizontal, continuous field measurements) (Mouazen and Neményi 1999a, b; Mouazen et al., 1999; Mouazen et al., 2003a, b; Neményi et al. 2006, 2008; Hemmat et al. 2009; Mouazen and Ramon 2009; Abbaspour-Gilandeh and Rahimi-Ajdadi 2016) and points measurements (vertical) (Raper et al. 2000; Lapen et al. 2002; Szőllősi 2003; Kristoffersen and Riley 2005; Taser and Kara 2005; Taboada and Alvarez 2008; Tracy and Zhang 2008; Afzalinia and Zabihi 2014) measurements in precision, site-specific crop production. Hemmat and Adamchuk (2008) considered the current sensors for soil resistance measurements: soil strength sensors, fluid permeability sensors, water content sensors or combinations of them to determine soil physical and chemical properties, such as texture, organic matter, salinity, moisture content etc.

Nowadays on-the-go sensors are widely used in precision crop research, which are able to provide and predict accurate database whereby a heterogeneous field could be shared in relatively homogeneous areas: management zones (Halcro et al. 2013).

The electrical conductivity maps are generally in accord with the yield maps, too (Adamchuk et al. 2004). Neményi et al. (2006) developed a tillage force monitoring system using a shank subsoiler as a strength sensor, so it was associated with the tillage force maps and maize yield maps.

To characterize the interaction of soil and medium subsoiler on sandy loam and silty clay loam soils Mouazen et al. (2003a, b) used the finite element method. Measurements revealed that with a relatively high clay content (30%), an increasing moisture content decreases the traction. The indicated Equation (1) refers to this:

$$D = -0.2136\,w + 73.9313\,d^2 + 1.6734\,p_d^3 \quad (1)$$

This equation includes the traction (D), soil moisture content (w), the working depth (d) and dry bulk density (p_d). This context – further developing their model – is described in Mouazen and Ramon (2009), which was developed for high bulk density values and established that with increasing soil moisture content it is necessary to reduce draught force (Equation 2).

$$BD=\left(\sqrt{\frac{D+21.36\,MC-73.9313\,d^2}{1.6734}}\right)\times\left(1.240-0.592\,MC\right). \tag{2}$$

Hemmat et al. (2009) found the effect of moisture content and preload stress on soil bulk density highly significant ($P<0.01$). However, with increasing preload stress (kPa) the bulk density only grows to a certain degree on sandy soils with 10 percent clay content, with higher moisture content (19% vis-à-vis 17%). On the other hand, Parent et al. (2008) found a negative close correlation between the bulk density and maize grain yield, as with the clay content.

Determination of the soil bulk density is not only important because of the moisture content but also in respect of optimal root development (plant growth): Czyž et al. (2001) found 1.43 g/cm^3 bulk density value in loamy sand soil optimal for spring barley (Table 2).

Table 2. General relationship of soil bulk density to root growth based on soil texture (USDA 1987)

Soil texture	Ideal bulk densities for plant growth (g/cm^3)	Bulk densities that affect root growth (g/cm^3)	Bulk densities that restrict root growth (g/cm^3)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.40	1.60	>1.75
Silt loams, silty clay loams	<1.40	1.55	>1.65
Sandy clays, silty clays, clay loams	<1.10	1.49	>1.58
Clay (>45% clay)	<1.10	1.39	>1.47

Contrary to some research, a reverse relationship was determined between the bulk density and the draft force (Lapen et al. 2002): at higher bulk density low values were measured for draught force. Liu et al. (2016) concluded that above 1.55 g/cm^3 bulk density of silt loam soil the plant development is restricted, but the authors highlighted: this effect depends on agrotechnology, too.

The following Equation (3) was confirmed by Håkansson and Lipiec (2000) at difference dry bulk density of the same soil. It was defined as an optimal degree of compactness in 4–25 cm soil layer for grain yield (D_{opt} = optimal degree of compactness in 4–25 cm soil layer for cereal grain yield), as stated:

$$D_{opt} = 90.3 - 0.216\,C + 0.0038\,C^2 - 0.214\,H$$
$$\left(2<C<60;\ 1<H<11;\ n=102;\ r^2=0.07\right), \qquad (3)$$

where C indicates the content of the clay and H is the organic matter content.

The point (vertical) compaction measurement is also the analysis of the penetration resistance. Nowadays the soil strength is measured by cone penetrometers which are available in various types of instruments for researchers. The majority of these devices can determine the soil compaction and the soil moisture content down to 90 cm as well. The cone penetrometer is one of the most widely used tools and indicators of soil compaction, cone index (CI) is used to determine the compactness of soil (soil strength).

Szőllősi (2003) measured the soil resistance with penetrometer (Hungarian 3T SYSTEM Instrument) in an open measuring system. A large number of measurements was elaborated under the growing period in 60 cm depth to determine the correlations between soil resistance (*MPa*) and the soil moisture content (*vol%*), $R^2 = 0.5921$, and soil bulk density (*g/cm*^{3}), $R^2 = 0.9531$. Furthermore, a functional relationship was determined between soil compaction and moisture values at the same bulk density values for loam textured soil which could convert resistance values at the same moisture content.

Afzalinia and Zabihi (2014) concluded that the penetration measurements do not give adequate opportunity to set up connections while the measurements at the end of the growing season provide more accurate values. Karmakar and Kushwaha (2007) examined the gravimetric soil moisture content (10%, 13%, 17% and 20% dry basis) on clay loam soil (29% clay, 24% silt and 47% sand) on five soil compaction levels (100, 150, 200, 300 and 400 kPa). Lapen et al. (2002) found a strong positive correlation among the penetration resistance (cone index), the mouldboard plow draft force measurements and clay content of soil. Chung and Sudduth (2004) reported that the compaction level, which was measured by plow tillage draft with depth, texture and water content of the soil, all significantly affected CI. According to Bogunovic et al. (2015) the values of penetration resistance in the tillage practices should be changed if we consider improved conditions for plant root's development.

Machinery compaction and maize yield

Experiment treatments of machinery traffic and soil compaction were reported from the aspect of precipitation (Raghavan et al. 1979). They noted that under dry and wet conditions in consecutive years, compaction vehicles caused opposite effects on maize yield. In the case of heavy clay soil in wet years the reduction in yield could be up to 40–50%.

Further analysis of crop response to soil compaction, both in compressed and uncompressed experiments was conducted by Lipiec et al. (2012). They analysed several plants including maize root development and anatomy. In comparison to compacted soils the maize had 50% yield and root length reduction (bulk density 1.21 g/cm^3) in contrast to uncompacted soils (bulk density 1.21 g/cm^3). This bulk density value is shown in Table 2, which is ideal on silty loam soil.

The compaction effects influence the maize yield in sandy loam soil less than on clay soils. This phenomenon confirms the fact that the compactness is a lower influencing factor in the case of sandy loam soils than on clay soils. In this case the average density of soils correlates with the compaction significantly.

Gameda et al. (1987) also examined the compaction stresses in maize culture under wet and dry conditions (clay content: 35%). Dry years' results revealed 26% cereal yield reductions, while under wet conditions there was ~55% maize yield reduction. McKyes (1985) came to a similar conclusion: in the case of silage maize, in years of divergent precipitation a higher yield was measured in the dry season (precipitation in growing period: 33 mm) than in the wet season (215–220 mm).

Control and compacted treatments were tested in 21 experimental trials (Arvidsson and Håkansson 1996). All fields' (both compacted and controls) results showed that with increasing clay content the average yield significantly decreases in the case of clay content >40% for the heavier soils. The average reduction (11.4%) was caused by compaction stress in the long time experiments. The penetration resistance did not change up to 20 cm. The compaction differences appeared with inflation of 100–150 kPa at 50 cm.

The short-time effects of tillage systems are less presented in the literature than the long-time effects. However, better short time results contribute to the increase in the decision support systems and to the accuracy of the extension for farmers.

Based on literature data, 5–6-textured soil types were investigated, from which it was established that increasing sand and silt fraction content increases the penetration resistance in no-tillage and conventional-tillage trials, too. This was also in all cases between cone index and clay fraction linear connection. A positive function was determined between the cone index data and bulk density values (Kumar et al. 2012).

Filipovic et al. (2006) report effects of 4-year soil cultivation (conventional, conservation and no-tillage practice) on silt loam soil. In 1997 and 1999 the average soil moisture content was 19.43% at maize seeding, in 1999: 21.2%. In April at sowing time the precipitation amount was almost double in 1999 (92.8 mm; in 1997: 53.4 mm). Comparing the two years there were no significant differences in precipitation and in temperature. During three cultivation operations there was lower yield in 1999 with wetter conditions. The average penetration resistance of 40 cm depth (10, 20, 30 and 40 cm average) was 21.2 MPa in 1997 and 3.4 MPa in 1999. Maize yield decreased by as much as 20% under conventional and conservation tillages in wetter maize growing season in 1999.

In soil moisture content above 15%, in the case of loam soil with high clay content the bulk density decreases. This operation can reduce the soil compaction values (Smith et al. 1997).

With agrotechnological processes (tillages systems) Vetsch and Randall (2002) found significant correlation in maize yield. But they also suggest that these methods caused minimal impact on maize production and have no effect on the tested N-treatments concerning the treatment time. Afzalinia and Zabihi (2014) concluded that between the cone index and tillage systems there are significant correlations in maize growing seasons. Salem et al. (2015) also came to this conclusion, measuring the highest maize yield, the longest kernel and the highest thousand-kernel weight in the conventional tillage sytem.

The maize yield produced higher values in the case of environmentally friendly agricultural cultivation methods (conservation agriculture practices) with lower annual rainfall (<600 mm), while lower values were produced by rainfall above 1,000 mm (Rusinamhodzi et al. 2011).

Cid et al. (2014) investigated the bed planting with irrigation treatments: they measured higher maize yield on loamy soils (14% clay content) at higher soil moisture content (bed planting with irrigation treatments), this moisture value was measured at the highest cone index value (1.8 MPa).

The experiments of Taboada and Alvarez (2008) resulted in no diffence between conventionally-tilled and zerotilled systems in levels of soil (soil profiles), and maize root systems of distribution and frequency (maize root abundance and distribution). In contrast, Salem et al. (2015) attributed soil compaction and a potential reduction in maize yield to the tillage method, although the greatest bulk density reduction was observed under conventional tillage and measured cone index was the largest in zero tillage.

Wilkins et al. (2002) also reported that a short-term no-tilled soil had higher soil strengths than tilled ones.

Soil compaction and soil electrical conductivity versus maize yield

Several publications, including Alimardani et al. (2007) analysed the bulk density, the soil apparent electrical conductivity (EC_a) and soil texture. Soil EC_a (mS/m) increased with soil clay content ($R^2 = 0.916$), the draft force was highly correlated with soil EC_a (over $R^2 = 0.9$). The soil properties influence the soil electrical conductivity (Carrol and Oliver 2005), such as the soil moisture content, cation exchange capacity, salt content, the depth of sensing and the clay content (Payne 2008). Both Payne (2008) and Kerry and Oliver (2003) emphasize the importance of aerial imaging. A large amount of soil parameters

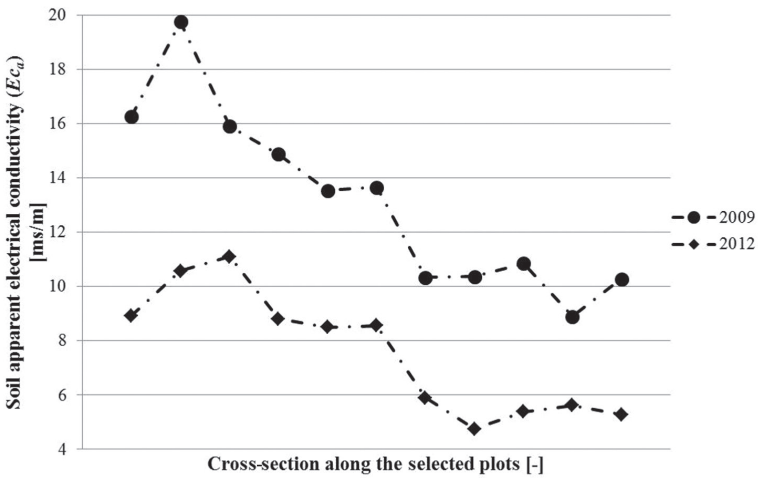

Figure 1. Change of EC_a values in the experiment field (2009 a wet year and 2012 a dry year; Nyéki et al. 2013).

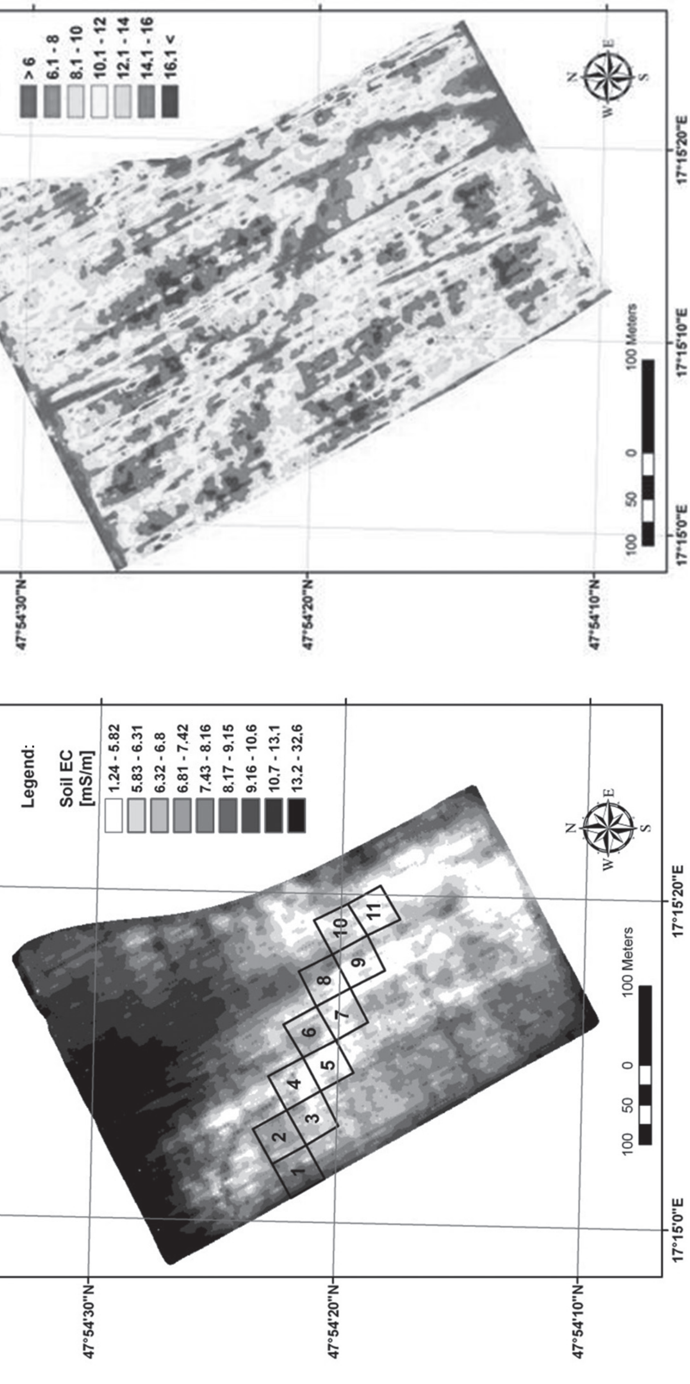

Figure 2. Soil electrical conductivity (a) and maize yield map (b) in the experiment field with the investigated 11 plots (2013)

were obtained and the higher soil moisture content results in higher soil electrical conductivity values (Al-Gaadi 2012), which Fig. 1 also shows well. The author concluded that EC_a measurements can be a relevant indicator to detect the soil compaction (R^2 value of the relationship between EC_a and soil compaction was 0.66), which is overwhelmingly influenced by the soil moisture content.

The precision, site-specific measurements were carried out in the 23.9 hectare experimental field of the Faculty of Agricultural and Food Sciences, Széchenyi István University in the vicinity of Mosonmagyaróvár, Hungary [N47°54'20.00"; E17°15'10.00"].

Figure 2a shows the investigated grids, too. Figure 2b pictures maize yield map (2013). Figure 3 shows the strong correlation between soil electrical conductivity and cone index measurements on site-specific management units with changing clay content.

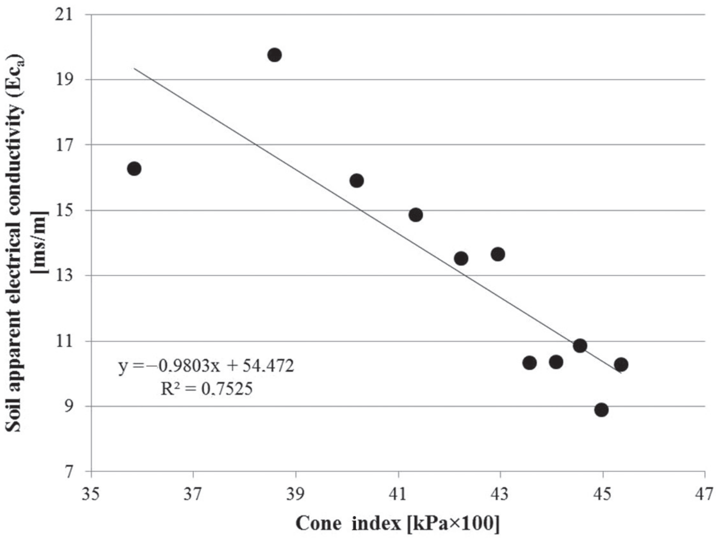

Figure 3. EC_a versus CI under wet conditions in the experiment field

Fig. 4 demonstrates that the results that use soil electrical conductivity to predict volumetric soil moisture content from clay content of test field were very successful ($R^2 = 0.87$) (Nagy et al. 2013). The establishment of the connection between EC_a and moisture content was proved in a previous article by Balla et al. (2013) for the same field.

The results of EC_a measurement show a great pattern with soil compaction maps (Corwin and Lesch 2005) and there are also some impacts on soil salinity and water content level. Motavalli et al. (2003) observed significantly higher EC_a values for compacted versus non-compacted soils by the electrical conductivity sensing and penetrometer.

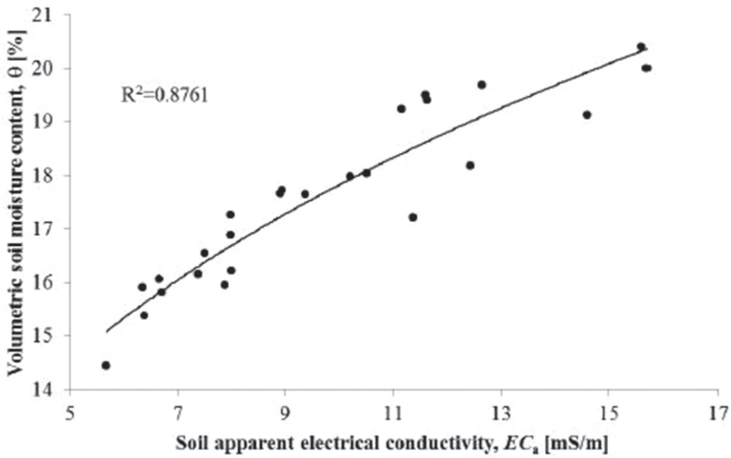

Figure 4. EC_a and volumetric soil moisture content in the experiment field (Nagy et al. 2013)

Soil compaction and moisture content

On different compactness levels Fig. 5 shows the water tension matrix of soils (Håkansson and Lipiec 2000). Almost always the tension increases if soil compaction stress increases. Figure 5 establishes a connection between soil compaction and soil moisture content in relation to differing clay content. We can conclude from the study that in the case of higher clay content the soil compactness increases to a certain water tension matrix value and then decreases. In lower clay content soils the compactness is continuously declining in relation to moisture content (except lower compactness).

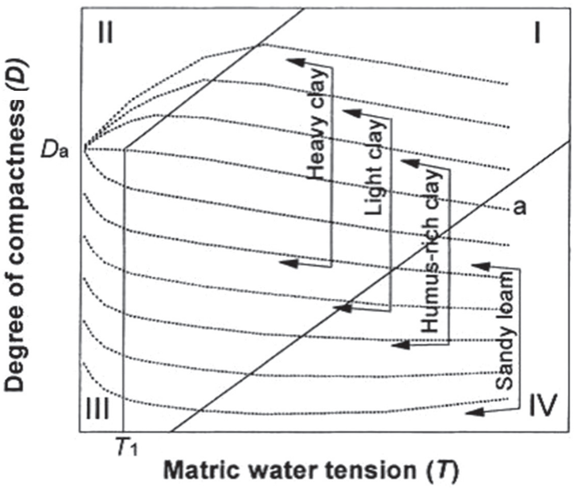

Figure 5. Matric water tension vs. compactness degree for different soil types (Håkansson and Lipiec 2000)

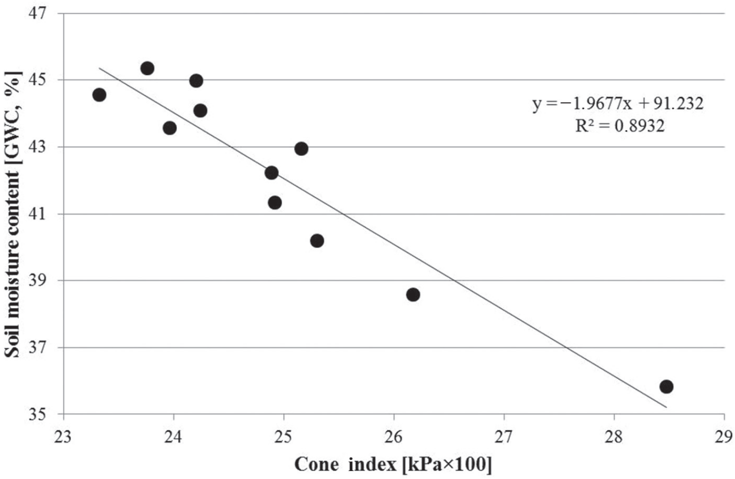

Figure 6. Correlation between soil moisture content and cone index under wet conditions in the experiment field

Hartmann et al. (2012) suggest that drought and water logging are important risk factors for soil compaction because they could increase the compaction sites of soils in spring. The authors note that climate change impacts – droughts, extreme rainfalls and their intensity can contribute to the compacted zones, which could affect the accuracy of yield forecast (less predictable yield and plant growth).

Wilkins et al. (2002) concluded that there is a positive relationship between the CI (kPa) and the soil moisture content in measured depth layers on silt loam soil.

According to Glinski and Lipiec (1990), under wet conditions, soils with high organic matter content could be more resistant to compaction than soils with low organic matter. Lapen et al. (2002) describe positive associations between soil draft force measurements and soil water content.

Based on research a highly significant correlation was discovered between CI 0–40 cm soil layer depth and the GWC (gravimetric soil moisture content) taking into consideration management units in experiment field (Fig. 6, $R^2 = 0.89$).

Modelling of soil compaction impact on yield

Today to gain an accurate description of the soil-plant-atmosphere, several decision support models are at the disposal of research. For a more accurate determination of the relationship between the three factors above (soil compaction, electrical conductivity and moisture content), only the PA tools may provide the solution.

Mechanical impedance and rainfall during the growing period are particularly important in predicting the crop yield of sandy soils where strength problems are aggravated by low available soil water content and velocity of the soil water movement down the soil profile (Lipiec and Hatano 2003).

The most widely used plant physiological models (e.g. DSSAT, Ceres-Maize for maize and Ceres-Wheat for wheat and barley) need the following input data (Hoogenboom et al. 2010):

- Site soil profile and soil surface data,
- Desired soil data includes soil classification (SCS), surface slope, colour, permeability and drainage class. Soil profile data by soil horizons include:
  - upper and lower horizon depths (cm),
  - percentage sand, silt, and clay content,
  - 1/3 bar bulk density,
  - organic carbon,
  - pH in water,
  - aluminum saturation and
  - root abundance information.
- Site weather data for the duration of the growing season.
- The minimum required weather data includes:
  - Latitude and longitude of the weather station,
  - Daily values of incoming solar radiation (MJ/m^2-day),
  - Maximum and minimum daily air temperature (°C) and
  - Daily total rainfall (mm).
- Crop management data from the experiment:
  - Management data includes information on planting date, dates when soil conditions were measured prior to planting, planting density, row spacing, planting depth, crop variety, irrigation, and fertilizer practices. These data are needed for both model evaluation and strategy analysis.
- Observed experimental data from the experiment.

In addition to site, soil and weather data, experimental data is utilized including crop growth data, soil water and fertility measurements. These are the observed data that are needed for model use.

There are numerous papers that describe the numerical modelling of soil resistance including Raghavan and McKyes (1978); Larson et al. (1980); Gupta and Larson (1982); and Smith (1985); Bailey et al. (1986). The idea that the bulk density values are valid for defining soil compaction in decision support models, can also lead to inaccurate results (e.g. yield prediction), because this conception is not clearly established in most cases. In some studies contradictions are presented between the bulk density and compaction (Lapen et al. 2002; Taboada and Alvarez 2008), while other references found positive correlation (Smith et al. 1997; Szőllősi 2003; Kumar et al. 2012; Lipiec et al. 2012).

DSSAT Ceres-Wheat was calibrated and validated by He et al. (2014), who investigated two soil types using 30-year data: silt loam and clay soils. The effectiveness of inaccurate wheat yield predictions has been caused by the soil texture (soil physical properties) and the model predicted –39% yield compared to the actual measured ones (Fig. 7).

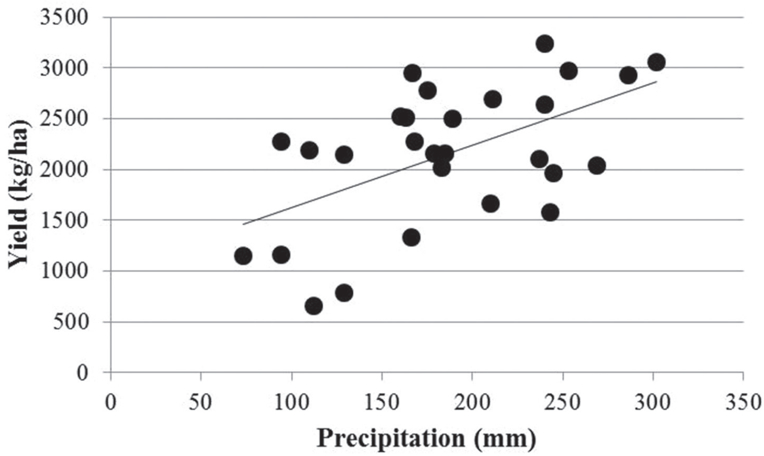

Figure 7. Correlation of wheat yield and growing season precipitation in soil with clay content >50% (He et al. 2014)

Nyéki et al. (2013) published that the DSSAT Ceres-Maize model was in the wet season (2010) over-predicted, the maize yield was under-predicted in the dry years (2011) in the investigated area (Fig. 8). We stress repeatedly that this paper aims fundamentally to clarify this contradiction.

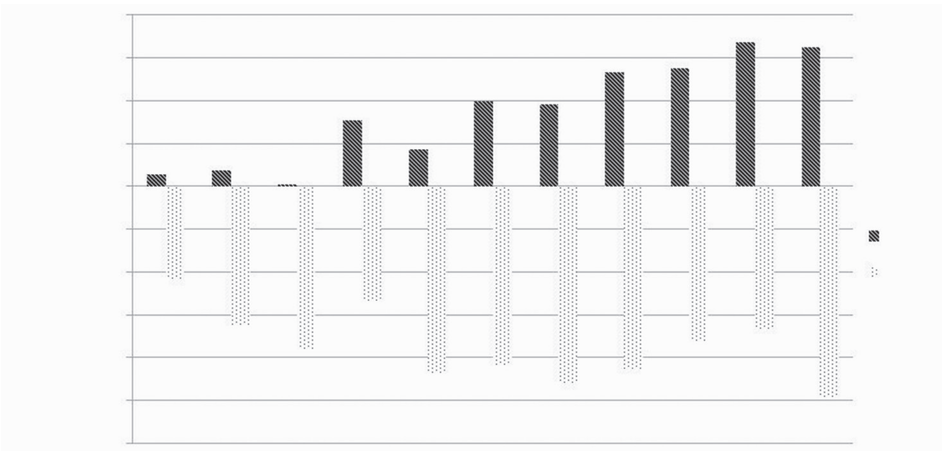

Figure 8. Difference between simulated (DSSAT) and measured maize yield in the selected plots in research field (2010, 2011) (Nyéki et al. 2013)
The change of content of organic matter: 1.5 → 1.9%.
Characteristics of selected plots

Clay (%)	16.8	12.5	11.9	10.8	10.1	10.9	10.1	10.3	9.3	9.7	8.6
Sand (%)	30.6	44.2	48.4	50.5	52.7	50.7	54.6	53.6	57.8	51.3	54.7

These differences occur significantly in silt loam soil (sand content is 54.7%, clay content is 8.6%) and the lowest level in the loam zones (sand content is 30.6%, clay content is 16.8%) in both years.

Lapen et al. (2002) conducted some plant and draft force measurements in experiments: in the case of maize the highest correlation value was found. Lipiec et al. (2003) account for sensitivity of model predictions with the spatial and temporal variability in the input parameters. A wide range of these parameters is influenced by compaction, and several models' sensitivity has more limited sensibility of spatial variabilty in the topsoil than in the subsoil.

Nowadays, remote sensing is widespread and a recent trend is the use of the hyperspectral method (Ge et al. 2011) which also provides an opportunity to record the large database of soil parameters and to adapt and validate the decision support models. We emphasize that the EC_a measurements could contribute to the increase in accuracy of decision support models (Nagy et al. 2013).

Discussion

The trends, presented by Gameda et al. (1987), suggest that our analysis on sandy and silt loam soils, and the findings are true in the case of the results from Kumar et al. (2012), as well. In experiments (McKyes 1985) maize production in the dry season contrasted sharply with the wet season.

However, the moisture content was not determined, but Arvidsson and Håkansson (1996) reported that with increasing clay content the yield significantly fell. Taking into consideration the moisture content and the penetration resistance, (Filipovic et al. 2006) strengthen our hypothesis.

Soil compaction measurements of Taboada and Alvarez (2008) and Nyéki et al. (2013) synchronize in the case of sandy loam and silty loam soils. Several authors proved that soil compaction effects on cereal yields taking into account the clay content change (Filipovic et al. 2006; Franke et al. 2008; Chen and Weil 2011; Ijoyah et al. 2012; Nyéki et al. 2013).

The results among Lapen et al. (2002) and Neményi et al. (2006) correspond with the draft force and cereal yields. The above-mentioned EC_a measurements (Nagy et al. 2013; Nyéki et al. 2013) describe the relationship between maize yield, soil moisture content and tillage draft force with soil physical properties. Maize yield cannot complete the plant emergence and plant height in the growing season because of soil compaction in the case of silt loam soil maize. Maize is the plant most sensitive to soil compaction (Wolkowski and Lowery 2008).

Hartmann et al. (2012)'s findings proved Nyéki et al. (2013)'s observation, namely the differences in measured and simulated maize yield, as well. This phenomenon can be explained by the fact – which this study would like to emphasize – that the moisture content changes on different textured soils, can react in different ways. Higher cereal yields can be realized in wetter time on soil with higher clay content compared to management zones with lower clay content. This phenomenon will appear reversed in a drier period.

He et al. (2014) calculated 40% cereal yield reductions: the simulated yields of wheat were very sensitive because of soil texture.

Afzalinia and Zabihi (2014) raised the problem of when to carry out the soil physical measurements. The measurements must be carried out under soil circumstances characterized by growing conditions of cereals. Particularly in the case of cereals, points measurements should be applied with sufficient frequency to be able to correctly validate the soil–plant relationships.

Several times it may occur that the measurements were accomplished with completely different circumstances during the sowing and harvesting than when the crop was characterized by the growing period's conditions. If this is not the case, false correlations may be obtained with regard to the texture, surface compactness, soil moisture content and cereal yield context.

Field site-specific measurements of the above-mentioned parameters can estimate a wide range of connections and the clarification of relationships can provide research plant conditions. Of course, the modelling of root water absorption and utilization belong to other research areas.

Conclusions

Despite the fact that there are numerous publications related to soil compaction, the definition of soil is inaccurate in the absence of additional factors (cereal yield, soil moisture, etc.). Using precision, site-specific technologies for sustainability, or reducing the effects of climate change, it is important that we know the soil texture combination from the smallest homogenity management zone in the field that we can identify. We presented the results as to what effect soil compaction has on cereal yield. Not only the soil hydraulic conductivity, soil aeration, soil temperature, root growth, root density, plant types (hybrid), soil moisture potential, depth of water table, diseases, but also the soil compaction and soil moisture content can influence the cereal yield under extreme weather conditions.

It is important to close this discrepancy between models to predict the final effects of compaction on cereals – in relation to growth and environment, too, such as nitrogen leaching – in short term, seasonal processes rather than long-term experiments. Especially under extreme weather conditions a significant natural change in soil moisture content can be experienced before and during the growing season of cereals. The results and measurements of these soil textured types confirm the hypothesis that the moisture content changes cause different natural physical conditions in soil layers. Variable soil compactness was caused by different soil moisture content – depending on clay content - which is closely related to cereal yield.

An accurate cereal yield prediction requires the quantification of soil compactness, at the same time precision approach defines this as a way towards healthy, high quality food production, and food security, clean water and sustainable environment (Várallyay 2010). Many researchers fully or partly emphasize this phenomenon. We summarize the most interesting general consensus of literature in this analysis. The aim is to achieve sustainability and to increase the dependability and accuracy of the decision support models. In other words, to bolster expectations of the second green revolution. Tilman (1998) highlighted the fact that it cannot be achieved without the precision, site-specific crop production technologies.

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