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Soil considerations in cultivation of plants

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Abstract: *Soil considerations in cultivation of plants.* There are analyzed the results of investigations on the effect of tractor outfit traffic over the field on the plant growth conditions. Changes in soil compaction, density and porosity influenced by compacting by wheels are presented in relations to optimal values. The effect of excessive soil compaction on development of root system and absorption of nutrients are presented.

Key words: soil, compaction, plant growth conditions.

INTRODUCTION

The soil together with its properties is an important component of agricultural activity. On the one hand, it creates an environment for development and growth of cultivated plants; thus, preservation of its possibly best condition is one of the agro-technical operations' goals; on the other hand, it is continuously subjected to unfavourable changes, that result from the impact of natural processes as well as from application of field operations, performed with the use of agricultural implements, machines and tractors. It is estimated that word's area of soil degradation resulted from the vehicles' wheels compaction amounts to over 64 million ha [Van Ouwerkerk and Soane 1994], and half of this area is situated in Europe [Lipiec, Rejman 2007]. According to Van den Akker et al. [2003], the European soils are subjected to compaction-threat as never before. Changes in the soil state can be very extensive, both in respect of quality and quantity. These changes concern majority of basic soil properties, namely: density, firmness, porosity and also the related properties: susceptibility to compaction, wind and water erosion, hydraulic conductivity, pore arrangement, amount of water available for plants, etc. [Richard et al. 2001; Pagliai et al. 2004; Horn et al. 2000; Alaoui et al. 2011; Lipiec, Håkansson 2000]. These changes can be found not only in the arable layer, but also underneath this layer, where a hard subsoil is created that makes difficult water penetration and air exchange, as well as plant root penetration in soil [Lipiec and Stępniewski 1995; Radford et al. 2001]. The light soils of small organic matter and colloid particle contents are particularly susceptible to mechanical impacts. In Poland over 30% of agricultural lands involve V and VI soil valuation classes (determined as poor and very poor) with a trend towards decrease in organic matter content; additional deterioration of their quality resulted from compaction can make difficult carrying agricultural activity on these areas. Therefore, the knowledge of soil reaction to compacting and the changes in particular soil properties under various conditions of mechanical pressure application can be an important element in optimization of technological processes with the criterion of minimization of damage in the soil structure.

SOIL AS ENVIRONMENT FOR PLANT GROWTH AND DEVELOPMENT

In the structure of soil properly prepared for cultivation of plants, about 25% is taken by water, and 25% by air in the soil pores. The remaining 50% is taken by soil solid particles. This configuration is not constant, since traffic of vehicles over the field results in soil compaction that leads to substantial changes in the soil structure and properties [Powałka 2005; Śnieg et al. 2008]. As a result of soil compaction, the soil particles are compressed, the volume of pores decreases and their structure, configuration and continuity are changed [Defossez and Richard 2002; Teepe et al. 2004]. Changes in air-water relations affect indirectly development of the soil fauna and flora. Some crops (potatoes) and that with the taproots (sugar beet, rape, carrot) are especially sensitive to proper soil loosening during vegetation period. The soil porosity, bulk density and firmness are among basic properties that determine the soil density. According to some opinions [Alaoui et al. 2011], the changes in hydraulic conductivity and soil retention properties are more sensitive indices than the soil density and firmness to be used towards reduction of soil compaction, and they reflect functional soil properties. The share of biggest non-capillary pores that maintain the soil air should range from 20 to 40% of total porosity to create the advantageous conditions for growth of plants in heavy soils [Starczewski et al. 1995]. According to Gutmański [1991] in sugar beet cultivation the optimal level of total soil porosity should amount to 42–52%. Maintaining of porosity above the lower acceptable limit is particularly important, because the aeration minimum for majority of crops is regarded at the level of 10–15% [Kaźmierowski 2011]. Appropriate amount and structure of soil pores adjust the air-water relations in a layer of root system of plants, determining also the soil quality and enabling its biological activity. A decrease in water conductivity and soil porosity can reduce the soil gas diffusion and water availability; this can lead to yield reduction.

Soil density is regarded as one of more important environmental factors that influence soil functionality and the plants' growth conditions and development. Optimal soil density amounts to 1.51–1.53 $g\cdot cm^{-3}$ for sandy soils, and to 1.41 $g\cdot cm^{-3}$ – 1.46 $g\cdot cm^{-3}$ for heavy and clay soils [Sommer and Petelkau 1990]. The authors found that an increase in soil density by 0.2 $g\cdot cm^{-3}$ caused reduction of barley yield by 18%. In maize cultivation an increase in soil density by 1 $kg\cdot m^{-3}$ resulted in a decrease of grain yield by 13 kg ha^{-1} [Canarche et al. 1984], while according to Czyż and Tomaszewska [1993] the optimal soil density in sugar beet cultivation should amount to about 1.3 $g\cdot cm^{-3}$ and an increase in soil density from 8 to 27% resulted in reduction of root yield in the range from 33.5% to 43.2%. Nasr and Selles [1995] found the quickest plant germination and sprouting at soil density lower than 1.2 $g\cdot cm^{-3}$.

Botta et al. [2002; 2007] reported that at clay soil density 1.6 $g \cdot cm^{-3}$ and sandy soil density over 1.8 $g \cdot cm^{-3}$, the development of plants' root system was slowed down. Pabin et al. [1998] determined the limit soil density for pea as 1.55–1.77 $g \cdot cm^{-3}$ depending on soil moisture content, while Reeves et al. [1984] found the lower spring wheat root growth at soil density 1.52 $g \cdot cm^{-3}$ than at soil density 1.32 $g \cdot cm^{-3}$. Chan et al. [2006] reported that the rape root density determined within the wheel track 85 days after sowing was threefold lower than that in the area without traffic. Decreased volume of plant roots cultivated in the compacted soil leads to a decrease in area, from which nutrients are taken up; Czyż [2004] found positive correlation between spring barley grain yield and the mass of its roots. The soil compaction that directly affect the air-water relations can limit denitrification and N_2O emission processes. According to Ahmad et al. [2009], an increase in soil density in wheat cultivation led to reduction in taking up of nitrogen, phosphorus and potassium by 7–26%, 11–54% and 11––28%, respectively, in relation to control plots. It can also be an important factor that decreases the growth and development rate of plants and their root system. The most favourable soil density values depend on the soil type. Grečenko [2003] reported that the critical dry soil density and porosity amounted respectively to 1350 $kg \cdot m^{-3}$ and < 48% for clay soil, 1550 $kg \cdot m^{-3}$ and < 42% for sandy clay soil, 1600 $kg \cdot m^{-3}$ and < 40% clayish sand, 1700 $kg \cdot m^{-3}$ and < 38% for sand.

The mentioned optimal soil density values are not constant, since they depend on the remaining factors, e.g. moisture content. One can distinguish the notion of soil moisture content that is optimal for the plants, however, this can vary also, since it is connected to soil structure, especially to structure of pores. Elongation of pores, that is characteristic for strongly compacted soils, leads to a decrease in water content in soil, resulted from limited possibilities of water storage.

The plant response to soil compaction is strongly related with dynamic changes in moisture content conditions during vegetation period [Hakansson and Lipiec 2000]. The strongest soil compaction results from traffic of tractor outfits directly after rainfall, especially on heavy clay soils of big water capacity [Buliński and Niemczyk 2007]. Bearing capacity of the ground of small moisture content is higher than that at big water content. The limit for highest susceptibility to compaction is moisture content close to field water capacity. Defossez et al. [2003] maintain, that besides soil moisture content, the specification of agricultural vehicle traction system and its loading are the main factors that shape the soil compacting intensity.

The soil firmness is an important factor that determines soil compaction. In agricultural practice the soil firmness is most often measured with the use of cone penetrometers and it can provide information on conditions to be overcome by the roots of growing plant. A series of investigations point out at some constraints in the growth of root mass and development rate in strongly compacted soils, especially during drought, when availability of water and nutrients from soil deeper layer is poor [Raper et al. 2005]. For majority of cultivated crops and the soil fauna, the soil compaction that exceeds 1.7–2.0 MPa [Beylich et al. 2010; Buchter et al. 2004], and on clay soils 1.0 MPa [Farias 1994], is the limit, above which the plant development stops rapidly or entirely. It is evident from investigations [Copas et al. 2009], that under field conditions the soil firmness exceeded 1.5 MPa at depth 0.25–0.30 m and 3.0 MPa at depth 0.3–0.4 m, depending on operations applied. The roots that meet the strongly compacted soil layer have to input more energy to overcome the resistance, it slows down and weakens their growth. Under such conditions a decrease in the root mass growth can exceeds even 50% [Atwell 1993; Lipiec et al. 2003] and the root deformation can occur.

IMPACT OF VEHICLE WHEELS ON SOIL

The wheel running over loosened soil creates a rut with strongly compacted bottom layer. The subsequent running over the same track increase the rut depth and the stress values in the subsurface layer. After two – four running of wheel, the contact wheel-ground area and the specific pressure values are similar to the ones on the hard surface [Grečenko 2003]. The soil stresses are a function of the stresses created on tyre-soil contact area; they depend on tyre inflation pressure, wheel loading, tyre parameters and soil properties. The soils of bigger clay particles are more resistant to stresses [Sánchez-Girón et al. 1998]. The investigation results point out that stress values created in soil under the wheel and the rut depth increased with an increase in tractor mass [Way et al. 1998]. According to Dawidowski et al. [2001], Canillas and Salokhe [2002], the load on wheel axle, number of runs over the same track, the soil state during traffic (especially soil moisture content) affect significantly the soil compaction in the zone of running.

The highest increase in soil compaction was found at depth from 4 to 12 cm [Powałka 2005; Sweeney et al. 2006]. Abu-Hamdeh [2003] in his investigations, carried out on clay soil at the axle load 6 and 16 t and inflation pressure 120 and 359 kPa, found an increase in soil density to a depth of 48 cm. Becerra et al. [2010] reported that even a single run of heavy tractor (50 kN) increase the soil density and CI index value at the subsoil layers. At axle load of 100 kN the range of soil compaction amounted to 0.5 m [Håkansson, Reeder 1994]. The zone of soil properties changed by the wheel pressure can cover strap of width 0.9–1.0 m along the rut axis [Powałka 2005], and in places of double overlapping of tracks the aeration porosity at depth to 150 m can amount to 15%. Assuming that in traditional cultivation 70–90% of soil area is compacted annually [Buliński 1998; Nogtikov 2004], the wheel tracks in some places can overlapped over 25 times [Buliński 1998], while the total wheel tracks area can exceed 3–7 times the field area [Walczyk 1995]. Although in reduced tillage (zero tillage) the number of runs is decreased [Tullberg et al. 2007], the problem of heavy machinery for sawing and harvesting is still unsolved; they compact over half of cultivated field area. Investigations of [Pagliai et al. 2003] showed a significant decrease in porosity of superficial layer already after single run of tractor, with growing tendency along with the increased number of runs. Many authors

[Buliński 2000; Pytka 2005; Jurga 2008; Walczyk 1995; Bell 1994] pointed out, that the first 2–4 runs over loosened soil (according to Canillas and Salokhe [2001] – the first three runs) led to the highest changes in soil properties, and activity towards reduction of wheel pressures are among main tasks for agricultural practice. In typical plant cultivation technologies, in places of multiple wheel track overlapping the total pressure values can exceed 2000 kPa [Buliński 1998] and the soil properties can exceed values admissible for the plants. Van den Akker et al. [2003] investigated large axle loading of vehicle on the light soil (50 kN) and found a decrease in maize yield by 38% and the reduced reach of root to depth 0.35 m, i.e. to the zone of performing the loosening operations. [Radford et al. 2001] reported that an increase in tractor axle loading to 100 kN combined with big soil moisture content resulted in the reduced maize yield by 48%. The effects of changes in soil can be sustained and noticeable even during 17 years [Alakukku 2000].

To reduce deep soil compaction there are undertaken activities towards decreasing of axle loading to 6 t (Sweden) [Danfors 1974], development of standards that determine the admissible soil stress to a depth 0.5 m with consideration to soil conditions during wheel running [Rusanov 1994], or limiting the vehicle wheel loading and application of proper inflation pressure in tyres that fit to soil conditions [Van den Akker 1994]. According to Schjønninga et al. [2006], the stress created under the wheel to a depth of 50 cm should not exceed 50 kPa. The researchers determined dependences to select wheel parameters (loading, tyre inflation pressure) to meet the conditions. Bakken et al. [2009] used these dependences to determine this depth (34–38 cm) for light tractors and (40–44 cm) for heavy tractors used in their investigations.

Some researchers [Walczyk 1995] introduce various indices to determine intensity of vehicle wheel impact in soil, e.g. the product of wheel loading mass and the length of vehicle related to the field area ($\text{Mg}\cdot\text{km}\cdot\text{ha}^{-1}$). The applique importance of such index was shown by Botta et al. [2004], who reported that intensity of running 60, 120 and 180 $\text{Mg}\cdot\text{km}\cdot\text{ha}^{-1}$ was accompanied by yield reduction by 9.8, 22.6 and 38%, respectively. Powałka and Buliński [2005] introduced a dimensionless coefficient Wp to express the share of active part of tyre thread cooperating with ground, with consideration to ground state and wheel design parameters. This parameter enables to compare tyres in respect to the track area on soils of different compaction, (that is common in agricultural practice), thus, it enables to determine the specific pressure of wheels on soil. Evaluation of soil compaction reduction in the field operations technologies is possible with the use of compaction intensity index (W_i) proposed by Buliński [2001], that enables to characterize various outfits used in plant cultivation. Grečenko and Prikner [2009] developed a compaction capacity index (CC), that enables to evaluate the risk of soil compacting by tyre in the profile of depth 0.5 m, with consideration to tyre loading and inflation pressure, therefore, allowing for proper selection tyres in agricultural vehicles under given operational conditions. The authors introduced a scale of soil compaction risk, ranging from 0,0 (tyre and its loading conditions

„friendly" for soil) to 200 (extreme risk of compaction).

Some possibilities of reducing compaction can be provided by proper shaping of technical and exploitation parameters of the vehicle (mass distribution, ground speed) or its traction system (tyre size and type, inflation pressure, dual wheels, track-laying mechanisms). Ansorge and Godwin [2007] in investigations carried out in a soil bin on track-laying and wheel systems found, that a tyre loaded with 4.5 t caused similar soil deformations as a track-laying mechanism under the load of 12 t; a decrease in tyre inflation pressure from 2.5 bar to 1.25 bar caused significant decrease in soil compaction (cone resistance), rut depth and an increase in bulk density by 6%. The researchers maintain that in respect of soil compaction, better results can be achieved by increasing the tyre diameter, than its width. Putting on the special track on wide-profile tandem wheels enabled to reduce the rut depth by 40% and soil compaction in the rut expressed with the cone index (*CI*) by 10%, in spite of higher mass of vehicle [Bygdéna et al. 2003]. These findings are important, since an increase in tractor power and mass is not accompanied by appropriate increase in the wheel-ground contact area. According to Botta et al. [2002], the considerable decrease in soil compaction (thus, decrease in specific pressures) can be achieved by application of dual wheels. It is important, since during last 30 years the tractor power and mass increased by 60–80%, while the wheel-ground contact are increased by only 20%. The increased pressure values on the tyre-ground contact area increases the deep-reaching permanent soil deformations [Nosalewicz 2005.] An increase in wheel load from 3 Mg to 5 Mg increased by over five times the area of deformations and the range of changes was connected with tyre inflation pressure. According to Diserens [2009], the tyre-ground contact area depends on tyre elasticity. At a given wheel load and tyre inflation pressure, the tyre is subjected to greater deformation and the contact area will increase, until spaces between the tyre tread get in full contact with soil.

The effect of wheel load (11, 15 and 33 kN) and tyre inflation pressure (70, 100 and 150 kPa) was investigated by Arvidsson and Keller [2007]. It was found that tyre inflation pressure had biggest effect on the stress under wheel to a depth 10 cm and small effect at depth 30 cm and more, in contract to load that changed significantly the stress in deeper layers. At depth 10 cm the soil stress values exceeded considerably the tyre inflation pressures. Similar findings were reported by Carman [2008]; the load was a main soil compaction factor, when compared to tyre type and wheel running speed. The highest soil compaction expressed with density and compaction index occurred at depth 70 mm. It is evident from investigations of Buliński [2000] carried out under field conditions on clayish sand, the speed and type of tractor outfit, together with wheel load distribution, affected the soil compaction and the rut depth more distinctly, than the soil density. An increase in speed from 0.2 to 4.0 $km \cdot h^{-1}$ decreased soil compaction by 6.2–7.8%, while at speed 8.0 $km \cdot h^{-1}$ the compaction decreased by 14.6–16.5%, and at speed 12 $km \cdot h^{-1}$ it was lower by about 23%. The decreased compaction at higher speed of wheel run is connected with the time of tyre-ground contact. The additional changes in tyre inflation pressure recommended by tyre manufacturers for field conditions (deformable surfaces), from one hand lead to a smaller sinking in soil and making the shallower rut, from the other hand increase the rolling resistance [Wong 2001]. Decreasing the tyre inflation pressure by 28 kPa in relations to manufacturer's recommendations increase rolling resistance by 5.01%, and after further decrease by 55 kPa the resistance increased by 9.96% [Elwaleed et al. 2006]. The investigations of Kurjenluoma et al. [2009] pointed out that a decrease in radial-ply tyre inflation pressure decreased rolling resistance by 20% and the rut depth by 15% when compared to diagonal tyre, but on the soft and loosened soil only.

The activity of organizational nature cannot be neglected; it involves e.g. more and more common application of so called traffic paths system, where running over the field is performed at precisely determined parts of the field, combined with proper selection of machines' working widths. This system is highly appreciated, especially due to possibility of application of computer aided organization of vehicle traffic over the field (GPS and DGPS); it allows for vehicle traffic optimization and precise positioning of machinery in the field (with accuracy of several cm). The similar advantageous effects towards reduction of field compacted areas can be achieved by the reduced cultivation and direct drilling methods. However, some results of investigations point out that reduced cultivation methods can increase e.g. soil density, when compared to traditional tillage [Pabin et al. 2008].

SUMMARY

The investigations carried out hitherto on determination of most favourable solutions towards reduction of adverse effects of soil compaction give the fragmentary knowledge only, limited due to restricted technical potential of researchers, the scope of undertaken project and the specified environmental conditions (field, laboratory) of performing the experiments and their implications (number of repetitions, soil condition variability). Possibility of predicting the soil compaction is essential also for agricultural engineering. Therefore, determination of the effect of particular factors that influence the wheel exploitation parameters on the changes in soil basic physical properties at various moisture content is important. Knowledge of these problems can be a premise for better management of mechanized field operations with the use of heavy agricultural machinery; it will allow for better identification of processes responsible for the adverse effects of soil compaction and for minimization of the risk of deterioration of agricultural production effectiveness. As it is evident from an official document: "Thematic Strategy for Soil Protection. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions", the problem of soil compaction is not limited to a single phenomenon, but concerns the entire group of effects connected with physical, chemical and biological properties and processes proceeded in soil and distinctly associated with environmental and cultivation aspects [Keller and Lamandé 2010].

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Streszczenie: *Glebowe uwarunkowania w uprawie roślin*. Praca analizuje wyniki badań nad kształtowaniem optymalnych warunków dla wzrostu i rozwoju roślin. Jednym z głównych czynników wpływających na niekorzystne zmiany stanu gleby jest nadmierne jej zagęszczenie przejazdami agregatów ciągnikowych. Przedstawiono zmiany zachodzące w glebie pod wpływem ugniatania, krytyczne (dla roślin) wartości takich parametrów, jak: zwięzłość, gęstość porowatość gleby, naprężenia w strefie rozwoju korzeni. Omówiono niektóre działania natury technicznej, eksploatacyjnej i organizacyjne zmierzające do ograniczenia niekorzystnych skutków związanych z przejazdami agregatów ciągnikowych.

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