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THE IDENTIFICATION AND QUANTIFICATION OF FACTORS DETERMINING SOIL COMPACTION CAUSED BY SINGLE AGRICULTURAL TYRES ON A FIELD

Summary

In field research, the influence of factors determining soil compaction in an arable layer caused by agricultural tyres during the first pass was determined. The factors were the following: a normal load of tyres resulting from a static load of a tractor axle, dimensions of tyres: diameter, and width as well as pressure determined by a simplified method. The research was conducted on soil cultivated with ploughing – Luvisol loamy sand. It was generally shown that tyre load was the main determinant of soil compressing. A bigger tyre load leads to higher soil density only in a deeper arable layer. Higher soil density caused by bigger tyres is the result of their higher load rather than their higher external diameter. Wider driving tyres of a similar diameter caused only slightly lower soil density mainly at a greater depth in an arable layer. Pressure determined by a simplified method is not correlated with soil density changed by tyres. A soil density increment caused by the investigated tyres was from approx. 30% to approx. 65% of the whole growth potential.
***Key words**: arable layer, soil density, tyres, diameter, width, load, pressure*

IDENTYFIKACJA I KWANTYFIKACJA CZYNNIKÓW DETERMINUJĄCYCH ZGĘSZCZANIE GLEBY W POLU *IN SITU* POJEDYNCZYMI OPONAMI CIĄGNIKOWYMI

Streszczenie

W badaniach polowych określono wpływ czynników determinujących zgęszczanie gleby powodowane w warstwie ornej oponami rolniczymi podczas pierwszego przejazdu. Czynnikami były: obciążenie normalne opon wynikające ze statycznych obciążeń osi ciągników, wymiary opon: średnica i szerokość oraz nacisk wyznaczony metodą uproszczoną. Badania dokonano na glebie Luvisol spulchnionej orką – piasek gliniasty. Wykazano ogólnie, że obciążenie opon jest głównym determinantem zgęszczania gleby. Wyższe obciążenia opon powodują większe gęstości gleby tylko na większej głębokości warstwy uprawnej. Większe gęstości gleby powodowane oponami większymi są rezultatem bardziej ich większego obciążenia niż większej średnicy zewnętrznej. Szersze opony napędowe o podobnej średnicy powodują tylko nieco mniejsze gęstości gleby głównie na większej głębokości warstwy uprawnej. Nacisk wyznaczany metodą uproszczoną nie jest skorelowany z gęstością gleby zmienianą oponami. Spowodowany przyrost gęstości gleby badanymi oponami wynosi od około 30 do około 65% całego potencjału wzrostu.
***Słowa kluczowe**: warstwa uprawna, gęstość gleby, opony, średnica, szerokość, obciążenie, nacisk*

1. Introduction and aim

Excessive soil compaction resulting from tyre movement of tractors and agricultural vehicles mainly reduces yield of cultivated plants, increases erosion processes, increases energy for cultivation and CO2 emission to the atmosphere [1, 2, 3]. The volume of such soil compaction depends on local soil, climate and technical conditions, which curbs application of the investigation results in agricultural practice [4].

Density is one of the most important parameters characterising the size of soil compressing under tyres. It is stated that the biggest increase in soil density is caused by the first pass of single tyres of a tractor on soil. The volume of that increase varies and depends on many factors [5, 6]. Research on factors determining soil compaction caused by single tyres is performed mainly in soil channels in laboratories and much more seldom on a field. Obtained results and reasons for soil compressing in ruts vary. The increase in a tyre load may lead to considerably high or very low increase in soil density [7, 8, 9, 10]. Some researchers associate an increase in soil density caused by tyres with their average pressure [10, 11, 12]. The influence of tyre size on soil compression is vague. It is generally presented that bigger tyres cause higher soil density [7, 13]. Ansorge and Godwin [14] claim that tyres of a bigger diameter may cause lower soil density. Generally, it is reported that recommended low-pressure tyres cause smaller soil density than tyres of standard sizes [12, 15]. Raper [16] shows that reducing soil density may be rather small but an area of compaction much bigger.

It is reported that initial soil properties affect the volume of soil compression caused by tyres. Higher initial soil density may favour higher compression and its influence varies [17, 13]. It is also shown that the growth of soil water content raises soil exposure to pressure and develops higher density in ruts [6, 18, 19]. However, Medvedew and Cybulko [20] show that such influence may be slight.

In the country, research on selected single tyres of small sizes and mainly in soil channels has been performed. The similarity of results obtained in that manner to results obtained in field research is questionable. Results obtained in more toilsome and costly research performed under production field conditions *in situ* can be directly and profitably applied in agricultural practice.

For these reasons, it is justified to perform a broader identification of factors determining soil density caused by tyres of tractors and agricultural machines in a field on sandy soil prevailing in the country of the Środkowopolskie Lowlands.

In this article, an identification and quantification of factors which may determine changes in soil density caused by the first pass of single tyres used for tractors of various standard weighs. The factors were: a load of tyres resulting from a load of tractor axles, tyre dimensions: diameter and width and average pressure of tyres determined by a simplified method. It was checked whether soil water content or soil initial density during research affected soil density altered by tyres.

Moreover, it was determined to which extent tyres compress soil in the first pass in reference to maximum compaction potential under research conditions.

2. Material and methods

The tyre research was performed in the production fields of the University of Life Sciences in Poznan located near Poznan in the Greater Poland region (Poland). The soil in the research subjects was Luvisol loamy sand (according to IUSS Working Group WRB, 2015) [21] and was representative for the region of the Środkowopolskie Lowlands. In the field prior to research, ploughing had been performed up to approx. 0.25 m deep. In the years before, in research fields, conventional ploughing at a similar depth had been made. The density of soil solid was 2.62 $g \cdot cm^{-3}$. Soil properties during the tyre research are presented in Table 1.

Tyres of various sizes used conventionally in front and rear axles of tractors of various power and load commonly used in soil cultivation and seed sowing were investigated. Some tyres of the same sizes were investigated under various conventional static loads of tractors of various weighs. More important parameters are presented in Table 1.

For each tyre, three passes were performed in various randomly selected places on a field chosen for research. Soil samples were collected from a rut after a pass of only an investigated tyre. Soil samples were collected from a rut created by only a front wheel after stopping a tractor moving forward. Soil samples were collected from a rut created only by a rear wheel after stopping a tractor moving rearward. Three such collections were made for each wheel during each of three tractor passes. 4 samples were taken from a rut longitude axis, in an axis of the biggest stress [22], from 2 depths using cylinders of 100 cm^3 capacity. Firstly, the samples were collected from the bottom of a rut – layer 1. From a rut of driving tyres from layer 1 placed directly beneath lug print in the soil. Then, the samples were taken from layer 2 at a depth of 0.20 – 0.24 m. The samples were also collected next to ruts from soil without wheel passes at at a depth of 0.05-0.1 m and 0.15 -0.20 m from 5 randomly selected places on the field in order to determine initial soil density. Soil density and water content were determined in the samples using a gravimetric method followed by drying at temperature of 105-110 °C. Average density values were shown in $g \cdot cm^{-3}$ and water content in % vol. ($cm^3 \cdot cm^3 \cdot 100$).

A tyre load *W* [in kN] was calculated while stationary using scales placed under wheels. Tyre pressure was determined by McKyes analytical method [23] modified by Grečenko [24]. Tyre pressure *q* [in kPa] is a tyre load vs. a soil contact area [23]. The contact area was determined by Grečenko method [24]. It is a quotient of tyre width, its diameter and an empirical coefficient 0.245 for deformable tyres and soft ground.

Correlations between soil density ρ at two depths and a tyre external diameter *D*, tyre width *B*, their load *L* and pressure *q* were investigated. Correlations between soil density in ruts of the investigated tyres and water content and initial soil density ρ_o were also determined.

Statistical research was performed using the statistical package STATISTICA 12. Correlation rates, regression equations and determination rates were stated for the investigated relations which were presented in Fig. 1-6 and in the article.

Table 1. Tyres and soil parameters during the investigation
Tab. 1. Parametry opon i gleby podczas badań

Tire	Tyre diameter, cm	Tyre width, cm	Internal pressure, kPa	Normal static load, kN	Pressure, kPa	Initial soil density, $g \cdot cm^{-3}$	Soil water content, % vol.	Organic matter, %
6.0-16	71.1		0.13	3.2	120.8	1.4	11	1.3
6.0-16	71.1		0.15	4.6	173.7	1.4	11	1.3
6.0-16	71.1		0.2	3.2	120.8	1.395	10	1.5
7.5-20	88.6		0.2	11.04	266.8	1.39	15.9	1.64
7.5-20	88.6		0.24	8.5	205.4	1.395	10	1.5
10.0-15	88.9		0.1	11.04	199.5	1.37	15.75	1.6
12.8-18	108.7		0.2	8.5	101.3	1.41	14.6	1.4
12.4-24	123.9		0.14	14	146	1.4	15.4	1.3
12.4-28	134.1		0.08	6.2	60	1.395	10	1.3
14.9/13-28	137.2		0.1	9.15	82.5	1.39	10	1.3
16.9/14-34	157.5	42.9	0.1	13.4	80.9	1.31	9.9	1.5
16.9/14-34	157.5	42.9	0.1	14.8	89.4	1.34	9	1.05
23.1/18-26	157.5	58.7	0.05	14	61.8	1.39	10	1.0
23.1/18-26	157.5	58.7	0.1	13.8	60.9	1.37	15.9	1.64
23.1/18-26	157.5	58.7	0.06	14	61.8	1.39	10.6	1.0
13.6 R 36	160.5	34.5	0.1	14	103.2	1.445	14.7	1.6
13.6 R 36	160.5	34.5	0.1	14	103.2	1.43	11.05	1.05
18.4/15-34	162.5	46.7	98	13.8	60.9	1.37	15.9	1.64

Source: own work / Źródło: opracowanie własne

The extent of soil compaction caused by a tyre in relation to a maximum potential of that compaction was assessed using the Relative Compaction Index (RCI) applied in soil investigation [25]. The index is a relation of soil density increment $\Delta\rho$ in an arable layer to the maximum potential of that compression $\Delta\rho_{max}$ and is defined by the following formula:

$$RCI = \frac{\Delta\rho}{\Delta\rho_{\max}} = \frac{\rho - \rho_o}{\rho_{\max} - \rho_o}, \quad (1)$$

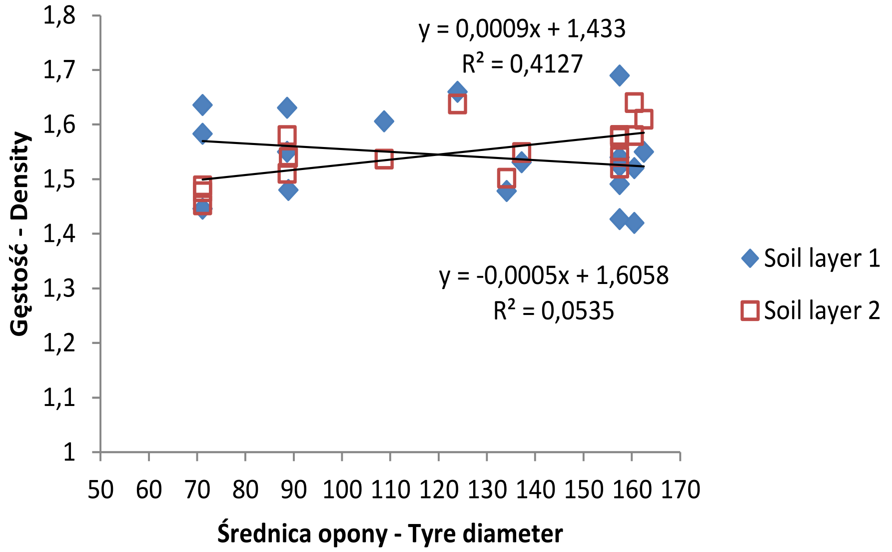
where $\Delta\rho$ is soil density increment caused by tyre passes: $\Delta\rho=\rho-\rho_o$. $\Delta\rho_{max}$ is a maximum potential of soil compression: $\Delta\rho_{max}= \rho_{max}-\rho_o$.

Maximum soil density ρ_{max} was determined empirically by Proctor method [26]. Soil density determined for research conditions is on average ρ_{max} = 1.842 g·cm^{-3}. The parameter ρ_{max} is used to assess the size of caused soil compaction under wheels [11, 27, 28]. Average soil density measured immediately after ploughing is on average ρ_o=1.31 g·cm^{-3} in an arable layer.

3. Results

The research results of soil density in two investigated layers assigned to the investigated tyre diameter are presented in Fig. 1. The correlation rate between soil density in layer 1 and a tyre diameter is only approx. r=0.23. The determination rate for the regression equation is R^2=0.05. It proves a slight influence of a tyre external diameter *D* on soil density in an outer layer. The correlation rate for the set of those variables but in the second layer is much bigger and amounts to r=0.64. The determination rate for the relation $\rho[D]$ is R^2=0.39 and indicates that tyres of bigger diameters can cause higher soil density in approx. 39% of cases but mainly in a deeper layer.

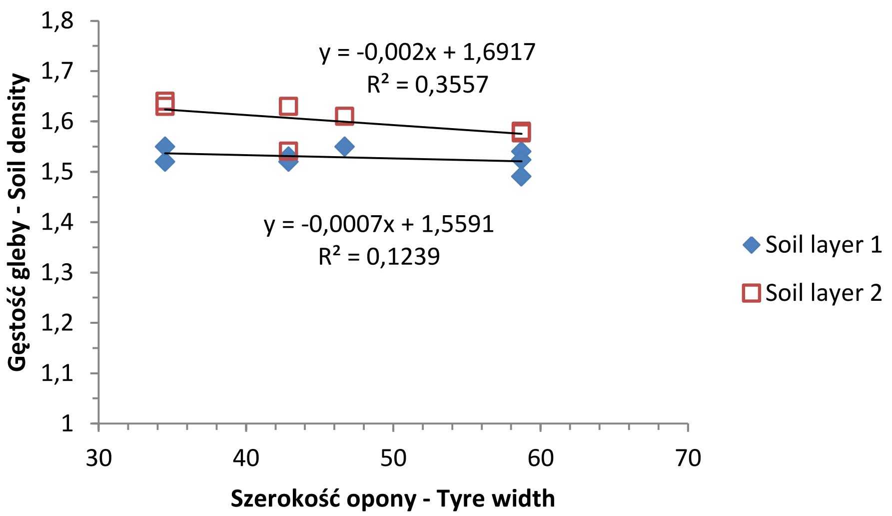
The relation of soil density at two depths of an arable layer to driving tyre width is presented in Fig. 2.



Source: own work / Źródło: opracowanie własne

Fig. 1. The relation of soil density in an arable layer to an external tyre diameter (in cm)

Rys. 1. Zależność gęstości gleby w warstwie uprawnej od średnicy zewnętrznej opon



Source: own work / Źródło: opracowanie własne

Fig. 2. The relation of soil density in an arable layer to driving tyre width (in cm)

Rys. 2. Zależność gęstości gleby w warstwie uprawnej od szerokości opon napędowych

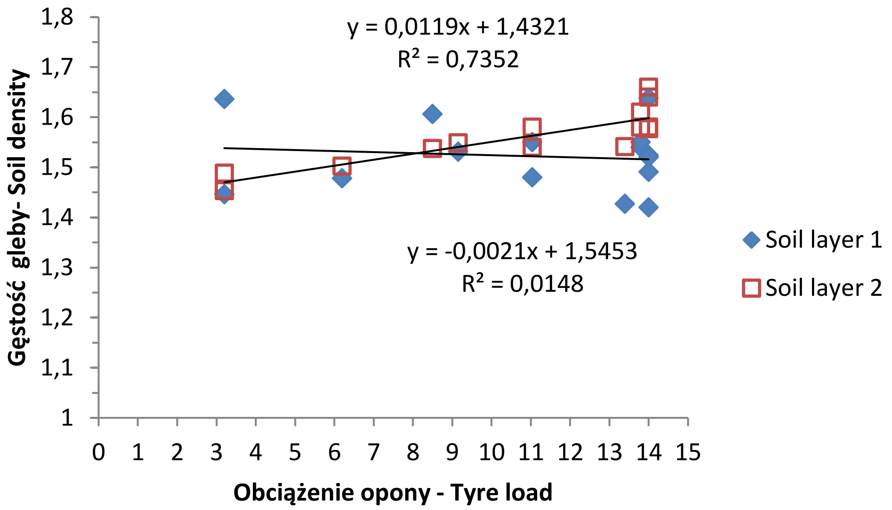
The research was performed only for driving tyres of a similar big external diameter: 13.6 R36, 16.9/14–34, 18.4/15-34 and 23.1/18-26 (Table 1). An external tyre diameter varied up to approx. 5 cm, ranged from 157.5 cm to approx. 162.5 cm. Tyres were under a similar static load from approx. 13.4 to 14.8 kN, the differences were smaller than 10%. The correlation rate for the relation $\rho[B]$ in layer 1 is r=0.35 and indicates a slight influence of tyre width on soil density in a soil outer layer 1. The determination rate R^2=0.12 indicates that tyre width determined soil density in that layer in only approx. 12% of cases.

An influence of tyre width on soil density in a deeper layer is bigger, correlation between variables is average and amounts to r=0.59. The determination rate R^2=0.35 indicates that tyre width determines soil density in that layer in only approx. 35% of cases.

Fig. 3 presents soil density for two investigated depths in a rut depending on a tyre load ranging from approx. 3 to approx. 15 kN (Table 1). The correlation of soil density with a load in an outer layer 1 is weak and amounts to only r=0.12, in a deeper layer is very strong with the correlation rate being as strong as r=0.84. The relation $\rho[W]$ for layer 2 is very well described by an increasing linear regression equation characterised by the determination rate R^2 = 0.74. The rate shows that soil density is very strongly determined by a tyre load at a greater depth in an arable layer.

Fig. 4 presents soil density in two investigated depths in a rut assigned to tyre pressure in a very wide range from approx. 50 to approx. 250 kPa (Table 1). The correlation rates for those two variable sets do not exceed 0.06, which indicates expressly that soil density in two soil layers is not correlated with tyre pressure.

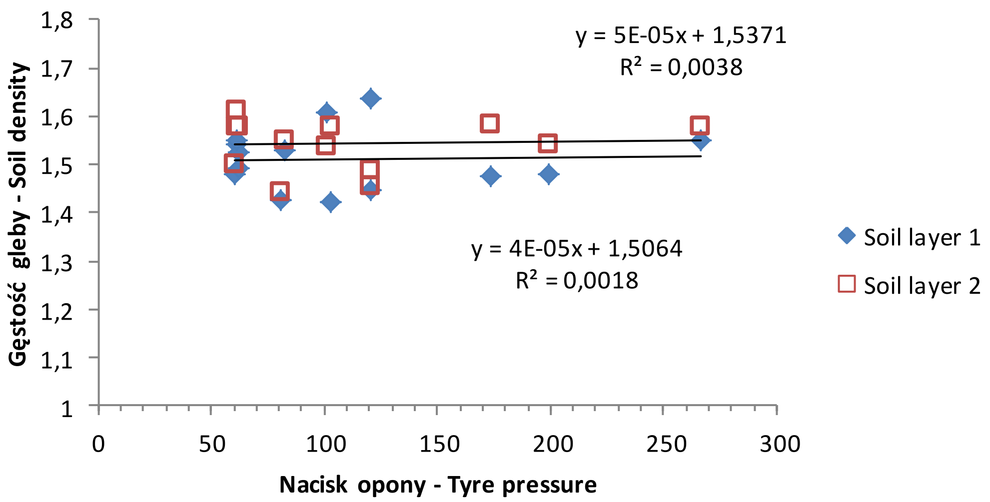
The relation of soil density in ruts of the investigated tyres to initial soil density, average in an arable layer variable during research ranging from approx. 1.3 to approx. 1.5 $g \cdot cm^{-3}$ is presented in Fig. 5. The correlation rate amounting to r = 0.48 indicates an average influence of initial soil density on soil density.



Source: own work / Źródło: opracowanie własne

Fig. 3. The relation of soil density in a rut to a tyre static load

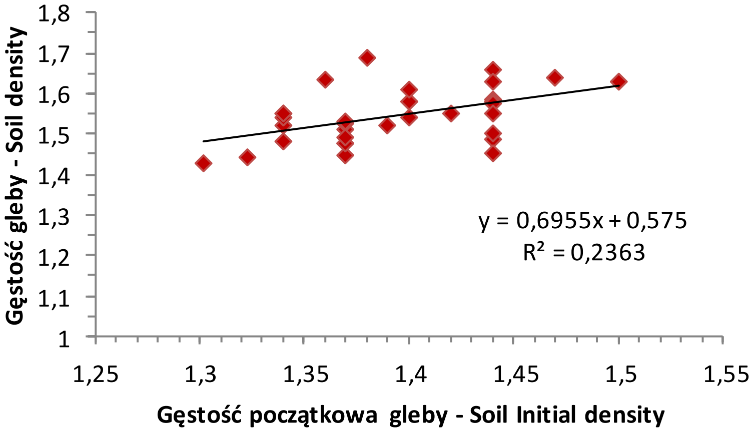
Rys. 3. Zależność gęstości gleby w koleinie od obciążeń statycznych opon



Source: own work / Źródło: opracowanie własne

Fig. 4. Relation of soil density to tyre pressure in a rut

Rys. 4. Zależność gęstości gleby w koleinie od nacisku opon



Source: own work / Źródło: opracowanie własne

Fig. 5. The influence of initial soil density on soil density caused by the investigated tyres in ruts

Rys. 5. Wpływ początkowej gęstości gleby na gęstości gleby w koleinach powodowany badanymi oponami

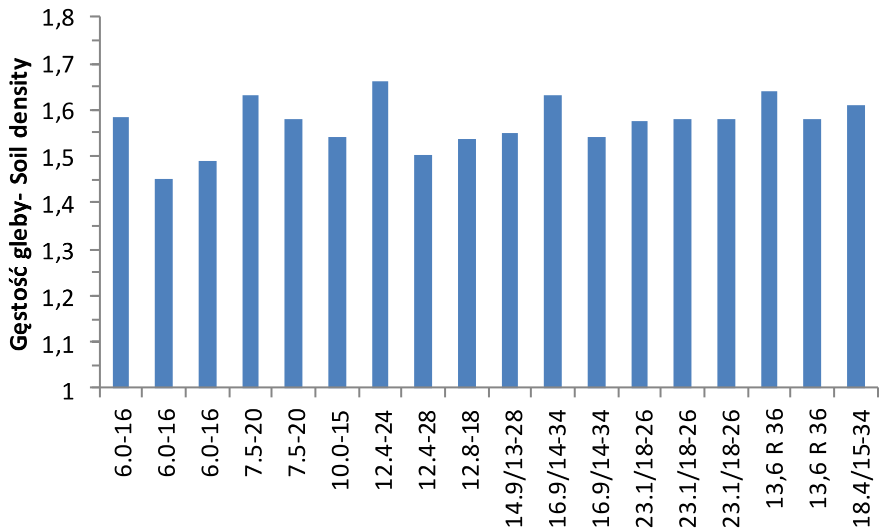
The relation is described by a slowly growing regression linear function of the determination rate: $R^2 = 0.23$, which shows that higher initial soil density may strengthen an increase in soil density caused by the investigated tyres only in 24% of cases.

It was studied whether variable soil water content during researching tyres in an arable layer ranging from approx. 8 to approx. 16% of volume affects results of soil density caused by tyres. The correlation rate between soil density in tyre ruts and water content in an arable layer is only approx. r = 0.24, whereas the determination rate for a regression equation $\rho[w]$ is meagre and amounts to below 0.07. Generally, the results indicate that soil water content during the research determined soil density caused by the investigated tyres to very slight effect.

4. Discussion

Tyre size

It is reported in literature that tyres of bigger widths lead to lower soil density [12, 15]. The research results in this article presented in Fig. 2 and 6 prove that driving tyres of various widths, a similar diameter and load do not diversify soil density much and diversify it differently at an arable layer depth. At the small depth, a width tyre influence is feeble, whereas in a deeper layer is average. An increase in tyre width by about 70% from approx. 34.5 cm to approx. 60 cm results in decreasing soil density in a deeper layer only by approx. 0.06 $g \cdot cm^{-3}$ and may occur only in approx. 35% of cases, which indicates that it is not reasonable to recommend in practice wider driving tyres under research conditions due to the above. Their use, as other research and observations show, may be justified by smaller unevenness of a surface left, which is more beneficial in soil cultivation.



Source: own work / Źródło: opracowanie własne

Fig. 6. Soil density in a deeper arable layer assigned to tyres of various sizes organized according to increasing external diameters

Rys. 6. Gęstości gleby na większej głębokości warstwy uprawnej przyporządkowane oponom o różnych wymiarach uporządkowanych według wzrastających średnic zewnętrznych

In general, Fig. 1 suggests that bigger tyres of bigger external diameters being under a standard load in tractors cause higher soil density in most cases but only in deeper arable layer (Fig. 1 and 6). It is a consequence of the above average correlation for that relation r=0.62 and quite a significant determination rate for a regression equation R^2=0.39 (Fig. 1). But the relation of soil density to a tyre diameter is equivocal as bigger tyres are more loaded. Higher soil density in ruts left by bigger tyres was pointed also by other researchers [7, 12].

Tyre load

In an outer layer, an increase in a tyre load does not lead to changes in soil density. In a deeper layer, soil density is strongly determined by a tyre load (Fig. 3), which results from high values of a correlation rate r=0.84 and determination rate R^2=0.73 for the relation $\rho[L]$. Soil density in deeper arable layer grows linearly along with a standard tyre load (Fig. 3). Soil density may be higher even by approx. 0.2 $g\cdot cm^{-3}$ at the load growth from 3 to approx. 14 kN (at an axle load to approx. 28 kN). Apart from a load, also a tyre diameter affects an increase in soil density in a lower layer (Fig. 1). Generally, Table 1 shows that a tyre load increases along with an increase in a tyre diameter. Following correlation and determination rate analyses for relation $\rho[L]$ and $\rho[D]$ for layer 2 it has been stated that the relation of soil density to a tyre load is much stronger than to their diameter. It indicates prevailing influence of a tyre load and much smaller influence of their diameter on changes in soil density. The higher influence of a tyre load is confirmed by the fact that tyres of small diameters, e.g. 6-16 and 7.5-20 as well as 12.4-24 (Fig. 6) under an increased load (Table 1 and Fig. 6) lead to soil density values similar to that caused by tyres of big sizes.

Tyre pressure

Tyre pressure is an indicator used also for resulted soil compaction volume. The applied simple analytical method enables determination of pressure in practice in a very easy manner [23, 24]. A research analysis shows that pressure resulting methodologically from a tyre size and their load is not correlated with soil density in the whole arable layer (Fig. 4), which proves that pressure determined by that method cannot be an indicator of tyre assessment as far as presented soil compression changes are concerned.

Initial soil density and soil water content

Soil water content during the tyre research on the experimental fields was rather differentiated and ranged from approx. 9 to approx. 16% (vol./vol.) and fitted in water content range at which cultivation procedures are performed as well as tractor wheels pass [28]. The low correlation rate: 0.24 and the determination rate: 0.07 for $\rho[w]$ relation generally indicate that water content in the investigated range is a factor which did not affect significantly results of soil density research changed with tyres.

Initial soil density immediately after ploughing during the research was quite differentiated and ranged from approx 1.3 to approx. 1.5 $g\cdot cm^{-3}$. Increasing the soil density during a research period resulted from water influence from precipitation, air and dew. Mere correlation rate: 0.48 and low determination rate: 0.23 for the $\rho[\rho_o]$ relation indicate that initial soil density did not influence much soil density volume changed by the investigated single tyres (Fig. 5).

Relative soil compression

As it results from the research, tyres may increase soil density in an arable layer on average to values ranging from approx. 1.45 to approx. 1.65 $g\cdot cm^{-3}$ (Fig. 1, 3 and 5). Maximum soil density increment potential $\Delta\rho_{max}$ immediately after ploughing is 0.531 $g\cdot cm^{-3}$. Determined relative compaction index may amount to on average RCI=0.3-0.65. This means that the investigated tyres lead to soil density increment from approx. 30 to approx. 65% of the whole density growth potential in an arable layer, mainly due to their various load.

The research results of this article may be applied to forecasting soil compression (soil density) caused by single tyres used also in cultivation tools or seeders, etc.

5. Conclusions

The presented conclusions concern the field research results of single agricultural tyres used in front and rear tractor axles obtained under field conditions.

– Load is the main factor determining soil compaction caused by tyres. A bigger tyre load leads to higher soil density only at a greater depth in an arable layer.

– An increase in soil density in deeper arable layer resulted from bigger tyres is more the result of their bigger load than their bigger external diameter.

– An increase in driving tyre width results in slight decrease in soil density mainly in deeper arable layer.

– Tyre pressure determined by a simplified method is not correlated with soil density in tyre ruts.

– Tyres after the first pass on a field cultivated with ploughing increase soil density in an arable layer to a value ranging from approx. 1.45 to approx. 1.65 $g\cdot cm^{-3}$. A resulted soil density increment is from approx. 30 to approx. 65% of the whole growth potential.

6. References

[1] Soane B.D., Van Ouverkerk C.: Soil compaction in crop production. Elsevier Science, 1994.

[2] Hamza M.A., Anderson W.K.: Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil & Till. Res., 2005, 82, 121–145.

[3] Mordhorst A., Peth S., Horn R.: Influence of mechanical loading on static and dynamic C02 efflux on differently textured and managed Luvisol. Geoderma, 2014, 219-220, 1-13.

[4] Oskoui K.E., Voorhees W.B.: Economic consequences of soil compaction. Transactions of the ASAE, 1991, 34, 6, 2317-2323.

[5] Soane B.D.: The role of field traffic studies in soil management research. Soil & Till. Res., 1980, 1, 205–237.

[6] Bakker D.M., Davis R.J.: Soil deformation observations in a Vertisol under field traffic. Aust. J. Soil Res., 1995, 33, 817–832.

[7] Koger J.L., Burt C.E., Trouse A.C.: Multiple Pass Effects of Skidder Tires on Soil Compaction. Transaction of the ASAE, 1985, 28, 1, 11-16.

[8] Smith D.L.O., Dickson J.W.: Contribution of vehicle weight and ground pressure to soil compaction. J. Agric. Engn. Res., 1990, 46, 13-29.

[9] Błaszkiewicz Z.: Wpływ obciążenia trójpunktowego układu zawieszenia wybranych ciągników rolniczych i ciśnienia wewnętrznego w ogumieniu na zagęszczenie gleby lekkiej w koleinach. Problemy Inżynierii Rolniczej, 2000, 1/27, 49-56.

[10] Fekete A.: Some observations on the contact pressure of tires, Zeszyty Problemowe Postępów Nauk Rolniczych, 1977, 183, 145-157.

[11] Raghavan G.S.V., McKyes E., Chassé M.: Soil compaction patterns caused by off-road vehicles in Eastern Canadian agricultural soils. J. of Terramechanics, 1976, 13, 107-115.
[12] Ridge R.: Trends in sugar cane mechanization. Int. Sugar J., 2002, 104, 164–166.
[13] Soane B.D., Blackwell P.S., Dickson J.W., Painter D.J.: Compaction by agricultural vehicles, A review II, Compaction under tires and other running gear, Soil & Tillage Research, 1, 1980/81, 373-400.
[14] Ansorge D., Godwin R.J.: The effect of tyres and a rubber track at high axle loads on soil compaction: Part 1: Single Axle Studies. Biosystems Engineering, 2007, 98 (1), 115–126.
[15] Murosky D.L, Hassan A.E.: Impact of tracked and rubber-tired skidders traffic on a wetland side in Mississippi. Trans ASAE, 1991, 34(1), 322–7.
[16] Raper R.L.: Agricultural traffic impacts on soil. Journal of Terramechanics, 2005, Vol. 42 (3-4), 259-280.
[17] Ljungars A.: Olika factorers betydelse för tractorernas jordpackningsverkan. Mätningar Agricultural College Sweden Dep. Soil Sci., 1977, 43.
[18] Défosses P., Richard G., Boizard H., O`Sullivan M.F.: Modelling change in soil compaction due to agricultural traffic as function of soil water content. Geoderma, 2003, 116, 89–105.
[19] Buliński J., Sergiel J.: Wpływ wilgotności gleby na jej zagęszczenie kołem ciągnika. Inżynieria rolnicza, 2011, 8(133), 45.
[20] Medvedev V.V., Cybulko W.G.: Soil criteria for assessing the maximum permissible ground pressure of agricultural vehicles on Chernozem soils. Soil Tillage Res., 1995, 36, 153–164.
[21] IUSS Working Group WRB. World Reference Base for Soil Resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. Food and Agriculture Organization of the United Nations. Rome, 2015, 190.
[22] Söhne W.: Druckverteilung im Boden und Bodenverformung unter Schlepperreifen. Grundl. der Landtech., 1953, 5, 49-63.
[23] McKyes E.: Soil cutting and tillage. Developments in Agricultural Science. Elsevier, Amsterdam. 1985, Vol. 7, 217.
[24] Grecenko A.: Tyre footprint area on hard surface computed from catalogue. J. Terramech., 1995, 32(6), 325-333.
[25] Bennie A.T.P.: Growth and mechanical impedance. In: Waisel Y., Eshel A.A., Kafkafi U. (Eds.), Plant Roots, The Hidden Half. Marcel Dekker, New York, 1991, 393–414.
[26] Proctor R.: Fundamental principles of soil compaction. Eng. News Rec., 1933, 111, 245-248, 286-289, 348-351.
[27] Raghavan G.S.V., Ohu J.O.: Prediction of Static equivalent pressure of Proctor compaction blows. Transaction of the ASAE, 1985, Vol. 28(5), September-October.1398-1400.
[28] Botta G.F., Tolon Becerra A., Bellora Tourn F.: Effect of the number of tractor passes on soil rut depth and compaction in two tillage regimes. Soil & Till. Res., 2009, 103, 381–386.
[29] Petelkau H., Seidel K.: Bearbeitbarkeit und Befahrbarkeit von Ackerboden in Abhängigkeit von Bodenfeuchte. (Workability and traficability of arable soils as influenced by soil water). Tag-Ber., Akad. Landwirtsch. Wiss. D.D.R. Berlin. 1986, 246. 46-54.

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