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Received: 2019-01-09 ; Accepted: 2019-03-15

IDENTIFICATION AND QUANTIFICATION OF SELECTED FACTORS DETERMINING SOIL COMPRESSION BY TRACTORS OF WEIGHTS WITH SINGLE WHEELS AND DUAL WHEELS

Summary

Excessive soil compaction caused by agricultural tractors during plant production processes results in a considerable risk of reduced crop yields, increased erosion processes, greater input of energy in tillage and increased CO_2 emission to the atmosphere. As a consequence we observe a threat of degradation in Luvisols found over a considerable area in the Polish Plain and the North European Plain. In-situ studies made it possible to identify and quantify selected factors determining soil density in loamy sand at a depth of max. 0.4 m in wheel tracks of tractors weighing from 19 to 72 kN with single standard wheels and with dual wheels. Analyses were conducted during the first passage over soil loosened during ploughing. It was generally shown that at a lower initial soil density in the topsoil tractors with both driving systems cause greater density increments and lower soil density than in the hardpan. Tractors with dual wheels exert much lesser pressure and cause soil density by approx. 0.1 $g \cdot cm^{-3}$ lower in the topsoil and by approx. 0.06 $g \cdot cm^{-3}$ in the hardpan than it is the case for tractors with single wheels. Tractors varying in their weight cause similar soil densities in the topsoil, while in the hardpan heavier tractors cause greater soil densities than light tractors. Generally, tractors with single wheels compress the soil in the topsoil layer to 45 up to 65% of compressibility, while tractors with dual wheels do it to approx. 26 up to 49% of compressibility, respectively.

***Keywords**: tractor, weight, pressure, topsoil, hardpan, initial soil density, density increment*

IDENTYFIKACJA I KWANTYFIKACJA WYBRANYCH CZYNNIKÓW DETERMINUJĄCYCH ZGĘSZCZANIE GLEBY CIĄGNIKAMI O RÓŻNYCH CIĘŻARACH Z KOŁAMI POJEDYNCZYMI I Z KOŁAMI DODATKOWYMI

Streszczenie

Nadmierne zagęszczanie gleb ciągnikami rolniczymi w produkcji roślinnej powoduje znaczne ryzyko obniżenia plonowania roślin uprawnych, wzmożenia procesów erozyjnych, wzrostu energii na uprawę i zwiększenia emisji CO_2 do atmosfery. W konsekwencji występuje zagrożenie degradacją gleb Luvisol występujących na znacznym obszarze Niżu Środkowopolskiego i Niżu Środkowoeuropejskiego. W badaniach polowych dokonano identyfikacji i kwantyfikacji wybranych czynników determinujących gęstość gleby - piasek gliniasty - na głębokości do 0,4 m w koleinach ciągników o ciężarach od 19 do 72 kN z pojedynczymi kołami standardowymi i z kołami dodatkowymi. Badania wykonano podczas pierwszego przejazdu na glebie spulchnionej podczas orki. Wykazano ogólnie, że przy niższej początkowej gęstości gleby w warstwie ornej ciągniki z obydwoma systemami jezdnymi powodują wyższe przyrosty gęstości gleby i niższe gęstości gleby niż w podeszwie płużnej. Ciągniki z kołami dodatkowymi wywierają znacznie mniejsze naciski i powodują mniejsze gęstości gleby średnio o ok. 0,1 $g \cdot cm^{-3}$ w warstwie ornej i o ok. 0,06 $g \cdot cm^{-3}$ w podeszwie płużnej niż ciągniki z kołami pojedynczymi. Ciągniki o różnych ciężarach powodują podobne gęstości gleby w warstwie ornej, a w podeszwie płużnej ciągniki cięższe powodują większe gęstości gleby niż ciągniki lekkie. Ogólnie ciągniki z kołami pojedynczymi zgęszczają glebę w warstwie ornej od 45 do 65% potencjału zgęszczenia, a ciągniki z kołami dodatkowymi w ok. 26 do 49% tego potencjału.

***Słowa kluczowe**: ciągnik, ciężar, nacisk, warstwa orna, podeszwa płużna, początkowa gęstość gleby, przyrost gęstości*

1. Introduction and aim of the study

Adverse consequences of excessive soil compaction by agricultural tractors used in plant production processes include reduced crop yields, enhanced erosion processes, greater consumption of energy required for tillage and increased atmospheric CO_2 emissions [2, 7, 8]. Movement of agricultural tractors and machines in field operations results in increased soil compaction in the topsoil and below it, mainly in the so-called hardpan [1, 2, 3, 4, 5]. Increased soil compaction responsible for its degradation affects approx. 33 million hectares of arable land in Europe [6]. It is crucial to gain insight into the dependence of this risk on local soil and climatic conditions, applied equipment and tillage method [9]. Causes identified for the varied increase in soil density caused by tractors in experiments conducted under diverse conditions are diverse and frequently conflicting.

The volume of soil compression under wheel tires is typically described based on soil density. Becerra et al. [10] indicated that soils are considerably compacted in the topsoil and to a lesser extent in the subsoil. It is generally reported that a greater load of single wheels at the tractor axis in the first passage increase soil density primarily in the arable layer of soil [5, 11, 12, 13]. Other authors state that compaction of topsoil is dependent on the pressure of wheels [14, 15], while in the subsoil - on their load [15]. Horn et al. [5] suggested that soil compaction by tractors depends on the tire size. In turn, Canillas and Salokhe [13] reported that the volume of soil compression by tires is affected by the condition of soil during tractor passages. Also Soane et al. [11] and Soane [16] indicated that soil compaction after the first passage of tractors depends on the initial soil density, while they did not quantify this effect. In turn, Bakker and Davis [17] and Häkansson and Lipiec [18] pointed to the fact that an increase in moisture content increases soil deformation caused by tractors, whereas Medvedew and Cybulko [19] reported that this effect may be limited.

It is generally reported that the application of dual and triple wheels in tractors in the first passage causes smaller soil densities [7, 11, 20, 21]. Botta et al. [22] stated that this reduction in compaction for light soil is small.

The ambiguity of results recorded under various conditions limits their practical applicability. No comprehensive and general identification and quantification is available for basic factors determining soil density in wheel tracks of tractors varying in weight, used in field operations and equipped with different driving systems, assessed in experiments on sandy soils dominant in Poland and typical of the Polish Plain and partly for the North European Plain.

The primary aim of this study was to identify and quantify selected factors determining soil density in the topsoil and in the hardpan in wheel tracks during the first passage of tractors differing in weight and equipped with standard wheels or additional wheels.

The scope of this study included:

- the effect of initial soil density in the topsoil and in the hardpan on soil density increments and on soil density in wheel tracks caused by tractors with single wheels and with additional wheels,
- the effect of weight *L* and mean pressure *q* of tractors with both driving systems on soil density ρ in the analysed layers,
- relative soil compression was established, i.e. it was determined to what degree the tested tractors with the studied driving systems increase soil density in the topsoil in relation to the potential density increment (compressibility).

Results of studies concern tractors of various weights used in field operations, equipped in standard wheels, tires and equipment for field operations.

2. Material and methods

Analyses were conducted using agricultural tractors commonly used in tillage of Luvisol - loamy sand (IUSS Working Group WRB) [23]. The study objects are located near the city of Poznań in the Wielkopolska region (Poland) within the Leszno stadial of the Würm glaciation. The soil type represents soils commonly found in the Polish Plain and partly in the North European Plain. Analyses were conducted in the fields of the Poznań University of Life Sciences, loosened by ploughing to a depth of 0.25 m. In the years preceding the experiments conventional tillage to that depth was performed on the study objects. Specific gravity of the solid is 2.63 gcm^{-3}. Organic matter content in the topsoil ranged from approx. 1.3 to approx. 1.7%.

Testing results were recorded for loads of tractors with standard equipment for field operations. The recommended internal pressure was used in the tires. Parameters of tractors and used wheels and tires are presented in Table 1. The tractors were equipped with standard single wheels and standard tires. Tractors of 19 and 28 kN had dual wheels only on the back axle. The tractor of 62 kN had dual wheels both on the front and back axles. The tractor of 72 kN had two additional wheels only on the back axle. These extra wheels had identical dimensions as the standard wheels.

Within wheel tracks of the tractors soil density was determined in order to assess conditions for growth and development of crop plants. Soil density was recorded after passage of tractors in the wheel track rut at two depths in the topsoil and at one depth in the hardpan. Samples were collected in the longitudinal axis of the wheel tracks in the vertical plane of the greatest stresses under the wheels [24]. Soil was sampled using 100 cm^3 cylinders from the first depth of the topsoil located immediately below the impression of the tire tread and at the depth of 0.20-0.24 m as well as the hardpan at a depth of 0.3-0.35 m. Soil density was determined in the cylinders using the gravimetric method following drying at a temperature of 105-110°C. Soil density in the topsoil was the mean value from the two tested depths. In the tests of tractors with additional wheels soil samples were collected from the wheel tracks of standard wheels and from adjacent wheel tracks of additional wheels from similar depths. Compaction caused by these tractors was established based on the mean soil density from both wheel tracks.

Table 1. Characteristics of tractors
Tab. 1. Charakterystyka ciągników

Specification	Units	Tractors with weight, in kN						
		19 (2WD)	28 (2WD)	44(2WD)	50 (2WD)	52 (4WD)	63 (4WD)	72 (4WD)
Engine power	kW	22.4	38.2	57.0	78.0	67.1	82.0	114.0
Total weight of tractor	kN	19.4	27.6	44.2	50	52.1	62.8	71.8
Front axle load	kN	3..3	4.6	8.7	11	23.64	14	32.37
Rear axle load	kN	6.4	9.14	13.4	14	27.47	17.4	38.45
Tire of front wheels	-	6-16	6-16	16.9-34	7.5-20	13.6R24	14.9R24	14.9R24
Tire of rear wheels	-	12.4-28	14.9-28	7.5-20	18.4/15-34	16.9R34	18.4R34	18.4R34
Internal pressure in front tire	MPa	0.13	0.15	0.18	0.18	0.18	0.18	0.18
Internal pressure in rear tire	MPa	0.08	0.1	0.10	0.10	0.10	0.1	0.10
Pressure (mean) of tractors with single wheels	kPa	74.6	101.2	141.5	169.6	90.6	117.3	108.2
Pressure (mean) of tractors with additional wheels	kPa	37.8	51.5	-	-	45.3	-	47.7
Pressure of rear single wheel	kPa	61.8	67.3	74.0	74.2	79.0	84.6	91.3
Pressure of rear dual wheels	kPa	32.8	35.3	-	-	39.5	-	-
Pressure of rear triple wheels	kPa	-	-	-	-	-	-	34.0
Pressure of front single wheel	kPa	124.2	173.2	209	265	104.0	150.1	133.5
Pressure of front dual wheels		-	-	-	-	52.0	-	-
Fitting for additional wheels	kPa	Linked direct	Linked direct	-	-	MD-PLUS	-	AW-Quick

Source: the author's study / Źródło: opracowanie własne

Soil samples were also collected next to the wheel tracks from soil not exposed to the passage of wheels, from 5 randomly selected locations in the field in order to determine initial density of soil. In the case of topsoil samples were collected from a depth of 0.05-0.1 m and 0.15-0.20 m and from the hardpan from a depth of 0.3-0.35 m. Density was expressed in $g \cdot cm^{-3}$. Mean values of initial soil density for the topsoil and the hardpan during tractor tests are given in Table 2. Moreover, in soil samples collected from the field outside the tractor passage zone the moisture content was also determined by the gravimetric method. During tractor tests it ranged from approx. 7 to approx. 11% by volume.

Table 2. Initial soil density during tractor tests
Tab. 2. Początkowe gęstości gleby podczas badań ciągników

Tractor with weight, kN	Driving system of the tractors	Initial soil density in the arable layer	Initial soil density in the hardpan
19	Single and additional wheels	1.381	1.491
28	Single and additional wheels	1.381	1.491
45	Single wide wheels	1.450	1.580
44	Single standard wheels	1.362	1.602
50	Single wheels	1.391	1.631
52	Single and additional wheels	1.373	1.631
63	Single wheels	1.363	1.495
72	Single and additional wheels	1.384	1.648

Source: the author's study / Źródło: opracowanie własne

In the course of the study values of pressure were recorded for front and back wheels as well as the whole tractor applying generally known, simple and easy to use methods. Wheel pressure was determined using the method proposed by McKyes [25] as modified by Grečenko [26]. Pressure is the quotient of wheel load and the contact area with the soil [25]. In turn, the contact area is a quotient of the width and diameter of the tire and the empirical coefficient of 0.245 recommended for the deformable tire and soft soil [26]. Mean pressures of tractors q were determined using the method recommended by Wong [27]. Mean pressure of the tractor is a quotient of the weight of the tractor and the sum of contact area of its wheels. Loads transferred by wheels onto the subsoil were determined using a scale placed under individual tires. Established pressure values are presented in Table 1.

Results of tests were analysed statistically using the STATISTICA 12 package. Correlations (Pearson's linear correlation coefficient) were determined between means: weight of tractors, mean pressure as well as initial soil density and soil density in wheel tracks in the topsoil and separately in the hardpan. For the dependencies between the investigated variables regression equations were determined using the least square method and determination coefficients. Experimental and statistical results are presented in Figs. 1-6.

Increments in soil density $\Delta\rho$ analysed in this study is a difference between soil density ρ in the wheel tracks after tractor passage and initial soil density ρ.

A relative increase in soil density in the topsoil caused by tractors in the first passage was estimated using the Relative Compaction Index (RCI) proposed e.g. by Bennie [28]. This index is a ratio of increments of soil density in wheel tracks $\Delta\ \rho$ caused by tractor wheels to the value of potential increments in density $\Delta\ \rho_{max}$ possible in a given soil. The index was established from formula 1:

$$\mathrm{RCI} = \frac{\Delta\rho}{\Delta\rho_{\max}} = \frac{\rho - \rho_0}{\rho_{\max} - \rho_0}\ . \qquad (1)$$

Increments in soil density $\Delta\rho$ in formula 1 were expressed as: $\Delta\ \rho = \rho - \rho_o$. Maximum increments in soil density are a difference between maximum density ρ_{max} and initial soil density ρ_o: $\Delta\ \rho_{max} = \rho_{max} - \rho_o$. Maximum density of soil ρ_{max} was established empirically following the method proposed by Proctor [29], used to assess the volume of soil compression by tires e.g. by Raghavan et al. [14], Raghavan and Ohu [30] and Botta et al. [31]. For the investigated soil ρ_{max} is on average 1.842 $g \cdot cm^{-3}$.

3. Investigation results

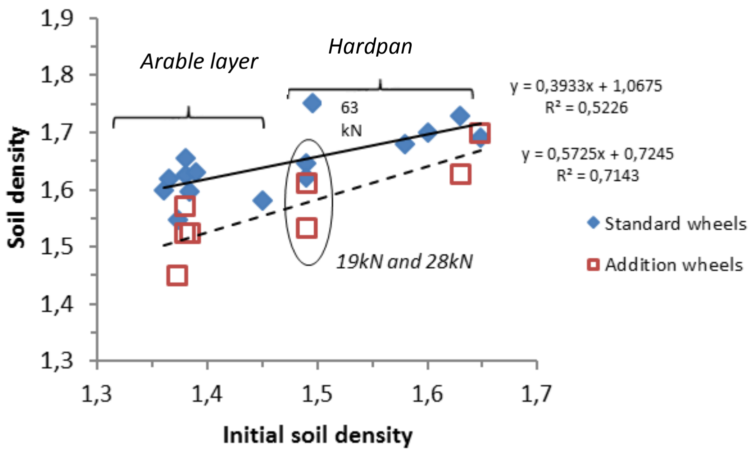
3.1. Soil density in wheel tracks of tractors

It results from data presented in Fig. 1 that with an increase in initial soil density a linear increase is observed for the density of soil in wheel tracks of tractors with single wheels and those with additional wheels. The established correlation between initial density of soil and the density of soil in wheel tracks of tractors for both types of driving systems is very high and strong at r > 0.72. The coefficient of determination R^2 for linearly increasing regression equations for both dependencies $\rho[\rho_o]$ exceed $R^2>0.52$ (Fig. 1). The value of $R^2=0.71$ shows a strong effect of initial soil density on the density of soil in wheel tracks produced by tractors with additional wheels, while $R^2=0.52$ confirms a medium scale effect of ρ_o on this density caused by tractors with standard wheels.

It generally results from Fig. 1 that tractors with single wheels at initial soil density from approx. 1.38 $g \cdot cm^{-3}$ in the topsoil cause in their wheel tracks soil density on average approx. 1.6 $g \cdot cm^{-3}$, while in the hardpan at initial density of approx. 1.6 $g \cdot cm^{-3}$ cause density in wheel tracks of approx. 1.70 $g \cdot cm^{-3}$.

Tractors with additional wheels at a low initial soil density in the topsoil amounting on average to approx. 1.38 $g \cdot cm^{-3}$ cause mean density of soil in wheel tracks of approx. 1.5 $g \cdot cm^{-3}$. At a high initial density of approx. 1.64 $g \cdot cm^{-3}$ found in the hardpan tractors heavier than 52 and 72 kN, equipped with additional wheels cause very small changes in soil density, in their wheel tracks amounting to approx. 1.65 $g \cdot cm^{-3}$. At a medium initial soil density of approx. 1.49 $g \cdot cm^{-3}$ in that layer light tractors of 19 and 28 kN with additional wheels cause density of soil in wheel tracks of approx. 1.64 $g \cdot cm^{-3}$, while a heavier tractor of 63 kN leads to soil density of approx. 1.75 $g \cdot cm^{-3}$.

It may generally be concluded that with an increase in the initial soil density tested tractors cause greater density of soil in wheel tracks. Tractors with additional wheels cause soil density by approx. 0.1 $g \cdot cm^{-3}$ lower in the topsoil and by approx. 0.06 $g \cdot cm^{-3}$ lower in the hardpan than tractors with single wheels.



Source: the author's study / Źródło: opracowanie własne

Fig. 1. Soil density in the topsoil and in the hardpan in wheel tracks of tractors with single wheels and tractors with additional wheels depending on initial soil density

Rys. 1. Gęstość gleby w warstwie ornej i w podeszwie płużnej w koleinach ciągników z kołami pojedynczymi i ciągników z kołami dodatkowymi w zależności od początkowej gęstości gleby

3.2. Increments in soil density in tractor wheel tracks

It generally results from Figs. 1 and 2 that with an increase in initial soil density the increments in density caused by tractors with single wheels and those with additional wheels decrease linearly. Generally tractors with additional wheels cause increments by approx. 50% smaller than tractors with single wheels.

A considerable effect of initial soil density on an increment in its density is confirmed by the linear correlation coefficient, for tractors with single wheels amounting to r = -0.88, while for tractors with additional wheels r= -0.76. A considerable effect is confirmed by relatively high coefficients of determination of R^2=0.58 and R^2= 0.78, respectively, for linearly decreasing regression equations describing these dependencies (Fig. 2).

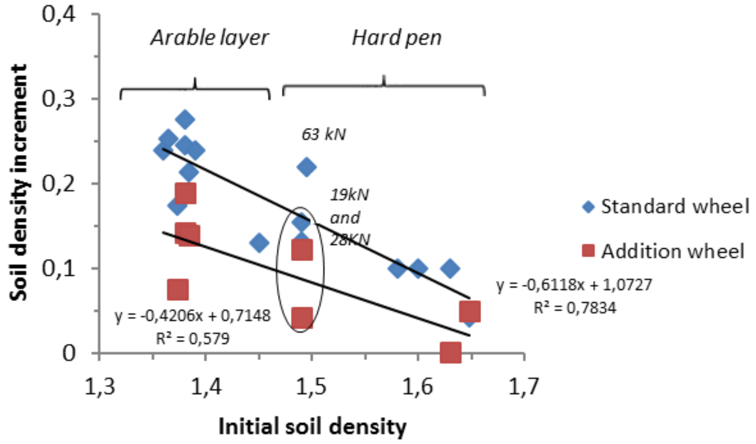
At a low initial soil density of approx. 1.38 g·cm^{-3} tractors with single wheels cause increments in soil density in the topsoil amounting on average to approx. 0.23 g·cm^{-3}, while tractors with additional wheels cause increments by approx. 50% smaller, approx. 0.125 g·cm^{-3}. At a high initial soil density in the hardpan of approx. 1.6 g·cm^{-3} tractors with single wheels cause an increment in soil density of approx. 0.098 g·cm^{-3} and those with additional wheels lead to much smaller increments of approx. 0.014 g·cm^{-3}.

3.3. Relative soil compression caused by tractors

The relative compression index RCI established in this study for the topsoil is as follows:

- for tractors with single wheels 0.45-0.65,
- for tractors with additional wheels 0.26-0.49.

This indicates that tractors with single wheels compress soil in the topsoil within 45 to approx. 65% total compressibility. In turn, tractors with additional wheels may compress soil in that layer to a much lesser extent, from approx. 26 to approx. 49% total compressibility, typically to approx. 40%.



Source: the author's study / Źródło: opracowanie własne

Fig. 2. Increments in soil density caused by tractors with single wheels and tractors with additional wheels depending on initial soil density

Rys. 2. Przyrosty gęstości gleby powodowane ciągnikami z kołami pojedynczymi oraz ciągnikami z kołami dodatkowymi w zależności od początkowej gęstości gleby

3.4. The effect of tractor weight on soil density

3.4.1. Tractors with standard wheels

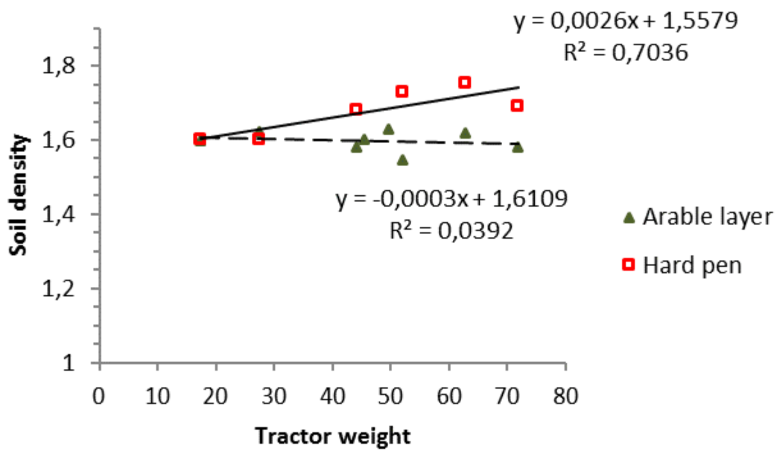
It results from Fig. 3 that an increase in weight in tractors with single wheels causes slightly smaller density of soil in the topsoil and much greater density of soil in the hardpan. In the topsoil the correlation of soil density with tractor weight is very weak, at r=-0.2. The limited effect of weight of those tractors on soil density in that layer is confirmed by the very low coefficient of determination for the linear regression equation at R^2=0.04 (Fig. 3). At an increase in tractor weight from approx. 17 kN to approx. 71 kN soil density in that layer decreases on average only by approx. 1.6 to approx. 1.57 g·cm^{-3}.

In the hardpan the density of soil increases linearly and relatively strongly with an increase in weight of tractors with single wheels. The correlation between these variables is strong and high at r=0.84. A considerable effect of weight of these tractors on soil density is confirmed by the very high coefficient of determination for linear regression equation amounting to R^2=0.70 (Fig. 3).

3.4.2. Tractors with additional wheels

It results from Fig. 4 that an increase in weight of tractors with additional wheels slightly reduces soil density in the topsoil, but it considerably increases it in the hardpan. In the topsoil the correlation between soil density and weight of tractors with such wheels is of medium strength, r=-0.54. A small effect of tractor weight on soil density is confirmed by the low coefficient of determination, R^2=0.30 (Fig. 2). Tractor weight only in 30% cases causes a linear decrease in soil density in the topsoil.

In the hardpan with an increase in the load of tractors with additional wheels the density of soil markedly increases linearly. The correlation between these variables is very strong, r=0.94. The coefficient of determination for the linearly increasing regression equation is R^2=0.89. These results confirm the very high effect of weight of tractors with additional wheels on soil density in the hardpan.



Source: the author's study / Źródło: opracowanie własne

Fig. 3. A dependence of soil density in wheel tracks on weight of tractors with single wheels
Rys. 3. Zależność gęstości gleby w koleinach od ciężaru ciągników z kołami pojedynczymi

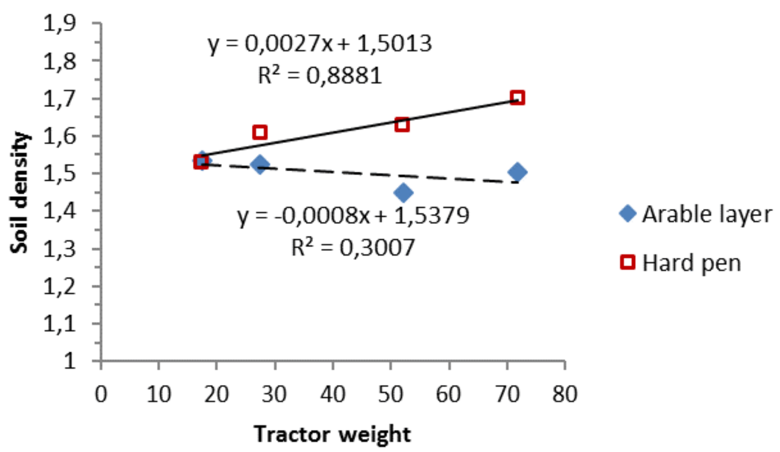


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Fig. 4. A dependence of soil density in wheel tracks on weight of tractors with additional wheels
Rys. 4. Zależność gęstości gleby w koleinach od ciężaru ciągników z kołami dodatkowymi

3.5. The effect of tractor pressure on soil density

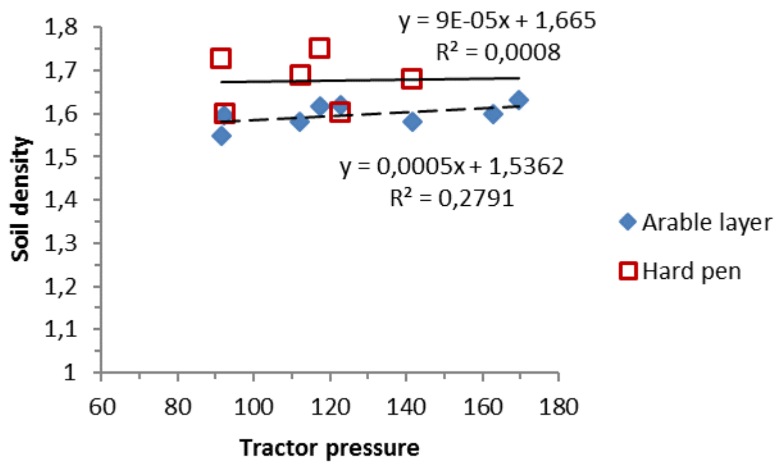
It results from Fig. 5 that the varying mean pressure of tractors with single wheels ranging from approx. 70 to 170 kPa does not cause considerable changes in soil density in the topsoil or in the hardpan. The correlation between mean pressure and soil density in the topsoil is medium, r=0.53. The limited determination of soil density by mean pressure of tractors with single wheels is confirmed by the low coefficient of determination for the linear regression equation R^2=0.28. In the hardpan the correlation of tractor pressure and soil density is slight at r=0.03, which confirms a lack of effect of mean pressure of tractors with single wheels on soil density.

The general dependence of soil density in the topsoil and in the hardpan on the mean pressure of tested tractors with single wheels and those with additional wheels is presented in Fig. 6. This figure shows a relatively strong effect of pressure of tested tractors on soil density in the topsoil. The linear correlation between tractor pressure and soil density in both these layers is medium, r>0.62. However, these dependencies are best expressed by involution regression equations (Fig. 6), relatively well describing dependencies of $\rho[q]$. The coefficient of determination for the regression equation for the topsoil is R^2=0.69, while for the hardpan it is R^2=0.44. It results from Fig. 6 that this mean effect is determined mainly by a lower pressure of tractors resulting from the use of additional wheels increasing contact area with the soil surface.

4. Discussion

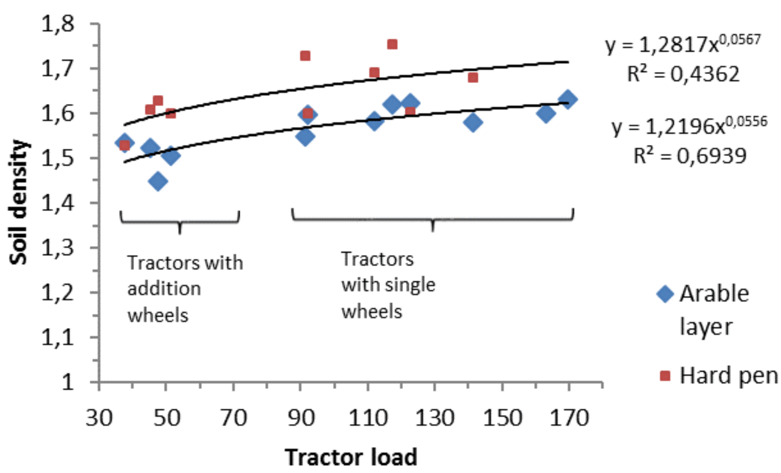
4.1. The effect of initial soil density on soil compression and on soil density in wheel tracks

It was generally shown in this study that the tested tractors cause greater soil compression, i.e. its greater density increments in the topsoil than in the hardpan. These results are consistent with those presented earlier by Soane et al. [11] and Beccera et al. [10]. It was also generally shown that light tractors of max. 30 kN both with single wheels and with additional wheels cause similar soil density values in both these layers (Figs. 3 and 4), while heavier tractors with both the driving systems cause lesser soil density in the topsoil than in the hardpan.



Source: the author's study / Źródło: opracowanie własne

Fig. 5. A dependence of soil density on mean load of tractors with single wheels
Rys. 5. Zależność gęstości gleby od średniego nacisku ciągników z kołami pojedynczymi



Source: the author's study / Źródło: opracowanie własne

Fig. 6. The general dependence of soil density on mean pressure of tractors with single wheels and tractors with additional wheels
Rys. 6. Ogólna zależność gęstości gleby od średniego nacisku ciągników z kołami pojedynczymi i ciągników z kołami dodatkowymi

Soane [16] and Soane et al. [11] generally indicated effect of soil hardness on the density of soil in wheel tracks of tractors with single wheels. In this study quantification was performed for the effect of initial soil density on increments in soil density and on its density in wheel tracks of tractors with different driving systems (Figs. 1 and 2). The effect of this density is strong, as evidenced by the high absolute values of correlation coefficients and high values of coefficients of determination for the linearly determined regression equations for dependencies $\rho[\rho_o]$ and $\Delta\rho[\rho_o]$ concerning tractors with single wheels. They also refer to tractors with additional wheels, which is a significant extension of the statements presented by Soane [16] and Soane et al. [11].

Soil density at a specific depth in wheel tracks may be analysed as a sum of initial soil density and the increment in its density caused by tractor wheels. Data from Figs. 1 and 2 indicate that at a high initial soil density observed mainly in the hardpan the analysed tractors cause lesser increments in soil density, but the density of soil in tractor wheel tracks is very high. In the topsoil soil density after tractor passage is generally lower than in the hardpan as a result of lower initial soil density, despite high increments in density generated by the analysed tractors (Figs. 1 and 2). The presented general dependencies concern tractors with single wheels and those with additional wheels. However, tractors with additional wheels cause smaller increments in soil density, as a result leading to lesser soil density in wheel tracks in both the soil layers.

4.2. The effect of tractor weight in soil density

Soane et al. [11], Lebert et al. [12], Horn et al. [5] and Canillas and Salokhe [13] stated that in the topsoil heavier tractors with single wheels in their passage compress the soil to a greater extent than light tractors. Results recorded in this study are different. In the topsoil both heavy and light tractors cause similar soil density (Figs. 3 and 4) or we may even observe a slightly lesser soil density in wheel tracks of heavier tractors. In turn, in the hardpan heavier tractors cause greater soil density than light tractors. The considerable effect of weight shown in this study for tractors with single wheels on soil density in the hardpan is consistent with the results presented by Botta et al. [15]. Findings in this study confirm a large and similar effect to the one specified above also for tractors with additional wheels (Fig. 4), which is found within a smaller soil density range.

The high soil density recorded in this study in wheel tracks, amounting to mean approx. 1.7 $g \cdot cm^{-3}$ in wheel tracks of heavy tractors is mainly the result of high initial soil density of approx. 1.6 $g \cdot cm^{-3}$ at relatively small increments in soil density (Figs. 1 and 2). The small increments in soil density result from the greater strength of the hardpan not subjected to high stresses, according to Söhne [24] propagated to greater depths under wheels of heavier tractors. When the initial soil density is approx. 1.5 $g \cdot cm^{-3}$ we observe a smaller strength of the hardpan and high stresses exerted by the large wheels of the heavier tractor of 63 kN, causing a considerable increment in soil density evident in Fig. 2. As a consequence soil density is high, exceeding 1.7 $g \cdot cm^{-3}$ (Figs. 1, 3 and 4). Wheels of smaller light tractors under smaller loads concentrate stresses, according to Söhne [24] mainly in the topsoil [24] causing in this layer a considerable increment in soil density (Fig. 2). It may be seen in Figs. 3 and 4 that the considerably increased soil density in that layer is similar to that in the hardpan subjected to a lesser increment in density (Fig. 2) due to the small stresses generated by smaller wheels.

It may thus be generally observed that only in the hardpan heavier tractors cause greater soil density than light tractors.

4.3. The effect of tractor pressure on soil density

In earlier studies by Raghavan et al. [14] and Botta et al. [15] it was shown that the effect of tractor pressure on soil density in the topsoil is considerable. It results from this study that a change in pressure exerted by tractors with single wheels within a large range from approx. 70 kPa to approx. 170 kPa does not lead to considerable changes in soil density in wheel tracks in the topsoil or in the hardpan (Fig. 3).

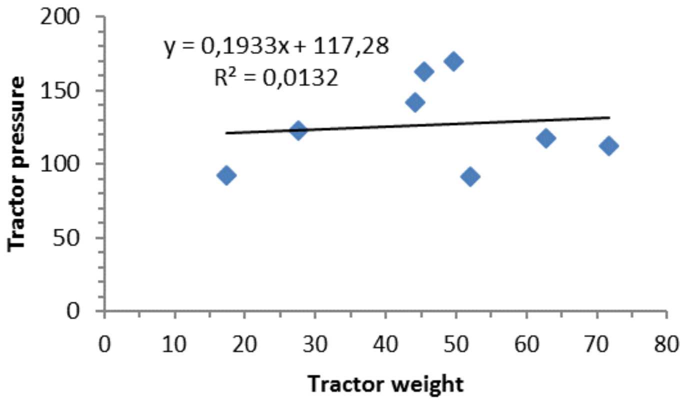
Studies by Soane et al. [11], Hamza and Anderson [7], Arvidsson et al. [21] and Botta et al. [22] indicate that tractors equipped with additional wheels cause smaller soil density changes both in the topsoil and in the hardpan. Testing results recorded in this study are generally consistent with those findings. Tested tractors with additional wheels cause soil density on average by approx. 0.1 $g \cdot cm^{-3}$ lower in the topsoil and by approx. 0.6 $g \cdot cm^{-3}$ smaller in the hardpan than tractors with single wheels. Analysis of Figs. 3, 4 and 6 generally shows that smaller soil density in wheel tracks of tractors with additional wheels are a consequence of smaller pressure resulting from the larger number of wheels. Tractors with single wheels exert pressure ranging from 90 to approx. 170 kN, while tractors with additional wheels - from approx. 38 to approx. 52 kPa. A large dependence of soil density in both analysed layers on pressure is confirmed by relatively high values of coefficients of determination for regression equations describing dependencies $\rho_o[q]$ presented in Fig. 6.

The differing effect of weight and mean pressure of tractors with single wheels on soil density shown in this study is determined, among other things, by the fact that the correlation between pressure and weight of tested tractors is slight (Fig. 7).

5. Conclusions

Results of this study concern the first passage of tractors weighing from 19 to 72 kN used in field plant production equipped with standard wheels and equipment for field operations.

1. It was generally shown that at an increase in initial soil density increments in its density decrease, while a linear increase is observed for soil density in wheel tracks caused by passage of tested tractors with single wheels and tractors with additional wheels.
2. Tractors of different weights, equipped with single wheels and with additional wheels do not differ markedly in terms of the changes they cause in soil density in the topsoil. In the hardpan heavier tractors cause greater soil density than light tractors.
3. Generally soil density caused by wheels of heavier tractors is lower in the topsoil than in the hardpan mainly due to the lower initial soil density at greater increments in this density in the topsoil.



Source: the author's study / Źródło: opracowanie własne

Fig. 7. A dependence of pressure of tractors with single wheels on their weight
Rys. 7. Zależność nacisku ciągników z kołami pojedynczymi od ich ciężaru

4. The varying pressures exerted by tested tractors with single wheels ranging from 90 to approx. 170 kPa cause no major differences in soil density either in the topsoil or the hardpan.
5. Tested tractors of different weights, equipped with additional wheels exert much lesser pressures than tractors with single wheels and lead to smaller soil density in both examined soil layers as a result of smaller increments in density they generate.
6. Tractors with additional wheels cause increments in soil density amounting on average to approx. 1.0 $g \cdot cm^{-3}$ in the topsoil and approx. 0.06 $g \cdot cm^{-3}$ in the hardpan, which are by approx. 50% smaller than increments caused by tractors with single wheels.
7. Generally tractors with single wheels compress soil in the topsoil at 45 to 65% total compressibility, while for tractors with additional wheels it is from approx. 26 to 49% total compressibility.

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Acknowledgements
The study was financed by the Ministry of Science and Higher Education.
The author would like to thank the technical staff of the Institute of Biosystem Engineering for their assistance in the preparation and execution of field experiments.