Annals of Warsaw University of Life Sciences – SGGW
Agriculture No 68 (Agricultural and Forest Engineering) 2016: 21–30
(Ann. Warsaw Univ. Life Sci. – SGGW, Agricult. 68, 2016)

Impact of soil compaction by wheels of agricultural machinery in potato cultivation on physical properties of the soil and yield

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Abstract: *Impact of soil compaction by wheels of agricultural machinery in potato cultivation on physical properties of the soil and yield.* In a three year experimental research project, changes in soil density and water to air ratio in the soil were examined in wheel tracks and ridges after passage of agricultural machinery used for potato cultivation. A run-free plot was compared with a plot with runs along the run paths and the traditional system. Volumetric density of the soil increased significantly along the wheel runs already after the first treatments, and it was maintained on the same level until the end of the vegetation period. As a result of compaction, the share of air pores decreased to the minimum aeration level, while the share of pores filled with water, hardly accessible and non-accessible for the plants, increased. As a result of lateral impact of the wheels, significant changes in the parameters examined were found in ridges neighboring the run paths on a plot cultivated traditionally, which resulted in substantial reduction of the tuber yield.

Key words: potato, soil compaction, air and water characteristics, run paths, yield

INTRODUCTION

Intensification of modern farming and the associated progress in mechanization, apart from many benefits, brings threats and negative effects [Marks and Buczyński 2002]. The Commission of the European Communities [2006] has considered excessive compaction to be the main cause of soil degradation. One of the factors of excess compaction are multiple runs of heavy agricultural machines during cultivation, treatment and harvest [Carman 1994, Dawidowski 1995, Grečenko 2003, Nowowiejski et al. 2015]. The result of excessive soil compaction is a number of changes in its physical properties, such as: increase in volumetric density, humidity and firmness, decrease in porosity and air content even below the minimum aeration level [Buliński and Niemczyk 2007, Niemczyk 2007, Błażejczak et al. 2010, Buliński and Sergiel 2013]. There is a common belief that air content in the soil should be at least 10%. Excessive compactness of the soil increases the probability of root hypoxia. According to Lipiec [2002], even small increase in humidity of strongly compacted soil may lead to hypoxia and increased mechanical resistance of the soil.

The best effects in potato cultivation are achieved in well-aerated soil, characterized by low compaction (1.1––1.4 $g \cdot cm^{-3}$) and a good air to water ratio [Gruczek 2003]. In the case of intensive protection, which is required in tomato cultivation, the passing machines result in compacting of the ridge sides and the furrow bottom. The effect of lateral impact of the wheels on the soil reaches 40 cm outside the wheel track [Powałka and Buliński 2006]. Research conducted by Friessleben et al. [1988] indicates that the share of the roots in the ridge zones, exposed to the risk of compaction during treatment and protection activities is significantly reduced.

The aim of the research conducted is to assess the impact of soil compaction, caused by machine movement on the field during treatment on some physical properties of the soil on wheel tracks and in the zone of lateral compaction impact, and thus on potato yields. The research was aimed at comparison of soil parameters in traditional potato cultivation and on plots with run paths.

MATERIAL AND METHODS

Research was conducted on the experimental plot of the Department of Agronomy of Warsaw University of Life Sciences – SGGW in Chylice in years 2007–2009 degraded black soil, made of light glacial till. The soil was characterized by average humus content, regulated water ratio and neutral pH. The forecrop for potatoes in each year of research was winter triticale. The research years differed in terms of precipitation quantity and spread (Table 1).

The most beneficial precipitation spread was recorded in 2007. In 2008, June was very dry (15.1 mm of rainfall), while July was very humid (126.4 mm), while in 2009, the entire vegetation period was very humid, which was not advantageous for potato growth and yield, resulted in development of fungal diseases and the necessity to intensify chemical protection.

TABLE 1. Average precipitation sums during vegetation of potato 2007–2009

Month	Year		
	2007	2008	2009
Precipitation [mm]			
V	59.9	51.7	79.4
VI	74.0	15.1	114.5
VII	82.3	126.4	90.7
VIII	51.4	76.9	78.1
IX	48.5	57.4	17.4
Sum			
×	316.1	327.5	380.1

On the production field with Ditta potatoes spaced every 62.5 cm, row spacing of 30 cm, three plots were identified:

L – plots without passages (compact plants);
S – with passage paths;
T – traditional cultivation (machine runs during vegetation period between ridges along the bottom of the furrow).

In each plot, five subplots were defined of length of 1 m and with of four plant rows. On plot “S”, each path was established in the place of a single unplanted row (Fig. 1a). In this manner, two internal rows and two external rows were established, situated at the paths. In the traditional cultivation plot (T), plant rows were situated similarly in relation to the traces of agricultural machine wheels, but much closer to the run paths. In the vegetation period, 5–7 runs with the same set of tractor aggregates for protection and treatment were performed. Tuber harvesting in each row was performed manually. Dry soil density samples were collected intact using experimental cylinders of volume of 50 cm^3. Samples were collected prior to planting and then five times in the vegetation period from ridges in the following time intervals: I – in mid-May, II – in the third decade of May or the first decade of June, III – in the third decade of June, IV – in the first decade of July, V – before harvest. These time intervals were correlated with protection treatments. Soil samples were collected from a layer of 1–6 cm from the following locations: A – in plots (L) from the furrow bottom, in plots S and T – from wheel tracks; B – in plots (L) from half of the height of the ridge side, in plots S and T, on the run side (Fig. 1b).

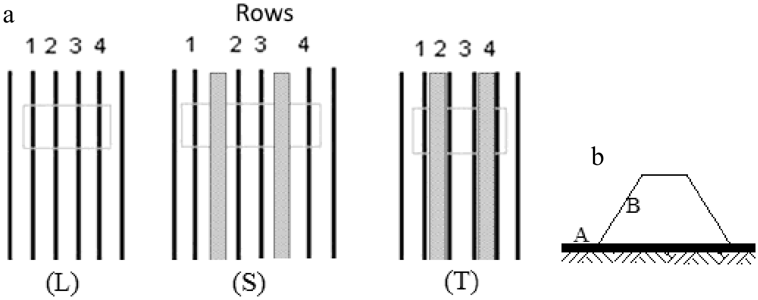

FIGURE 1. Diagram of experiment (a) and place of sample collection from ridge (b)

Before harvest, samples were collected from the same locations to determine the water-air characteristics. Capillary water capacity (CPC) was determined after capillary filling, water retention of the soil was determined for the following suction pressure ranges: 9.81 kPa (pF 2.0); 24.5 kPa (pF 2.4) and 98.1 kPa (pF 3.0). Water content at pF 2.0 is equivalent to field water capacity (FWC), and at pF 3.0 – humidity at initial plant growth retardation (IPGR).

On the basis of solid phase density and dry soil density, general soil porosity was determined, and the water content at individual values of suction pressure of the soil served as a basis for determination of the content of various pore groups of diameter >1,000, 1000–30, 3–12, 12–3 and <3 μm.

The results were processed statistically using the Statgraphics software.

RESULTS AND DISCUSSION

Physical soil properties

The average volumetric density of the soil upon potato planting in the research period was approximately 1.3 Mg·m^{-3}. At the beginning of the vegetation period with no runs (L) in the furrow between ridges, it was 1.46 Mg·m^{-3} and until the end of the vegetation period, it increased to 1.53 Mg·m^{-3}. In the plot with paths (S) and traditional paths (T), after ridge forming and the first herbicide treatment, the soil density in the wheel tracks increased significantly, reaching 1.65 to 1.68 Mg·m^{-3} and remained at a similar level until the end of the vegetation period (Fig. 2).

The compacting effect of wheels of agricultural machines was recorded partially in the ridge. On the plot with no runs (L), after forming of the ridge, density in its lateral part amounted to

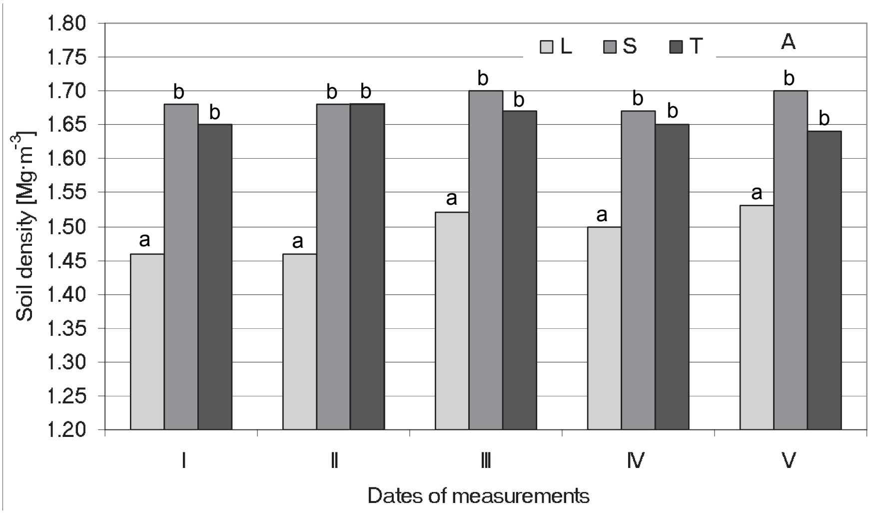

FIGURE 2. Soil density at the furrow bottom in the examined plots (marking with the same letter – no statistically significant differences at significance level $p = 0.05$)

1.28 Mg·m^{-3}, in the period of two months (interval I–IV), it increased to 1.35 Mg·m^{-3}, and until the end of the vegetation period – to 1.42 Mg·m^{-3} (Fig. 3). This density increase on the plots without passages (L) resulted both from natural soil settling after forming of the ridge and substantial rainfall in June and July in the subsequent years (Table 1). In the plot with paths (S), soil density in the lateral ridge zone, on the side of run of machine wheels, at the three recording intervals was higher by 0.06–0.08 Mg·m^{-3} in comparison with the canopy (a statistically significant difference); however, from July until the end of the vegetation period, it decreased substantially. In the plot with traditional runs (T), volumetric soil density in the lateral ridge zone on the side of the runs increased substantially already after the first run, and it increased systematically in the vegetation period to reach 1.55 Mg·m^{-3} before harvest, and it was statistically significant in relation to the respective values in the plots (L) and with paths (S). Increase in soil compaction after machine runs led to changes in overall porosity and pore distribution in the soil. In plots (L), total soil porosity was on the average equal to 0.42 m^3·m^{-3}. In the run tracks in the plot with paths (S), total porosity was lower, reaching 0.353 m^3·m^{-3}, respectively, and in the plot with traditional runs (T) – up to 0.37 m^3·m^{-3}, which corresponded with percentage changes by 16 and 12%, respectively.

Along with increase in soil compaction, the volume of non-capillary pores of diameter above 1,000 μm decreased by 57% in the plot with paths (S) and by 42% in the plot with traditional runs (T). The volume of capillary pores of diameter of 1,000–30 μm decreased in these plots by 36% (S) and 39.5% (T), respectively. In the place of passage of agricultural machines in the traditional manner (T), the total share of pores of diameter above 30 μm decreased from 0.191 to 0.113 m^3·m^{-3}, while in the

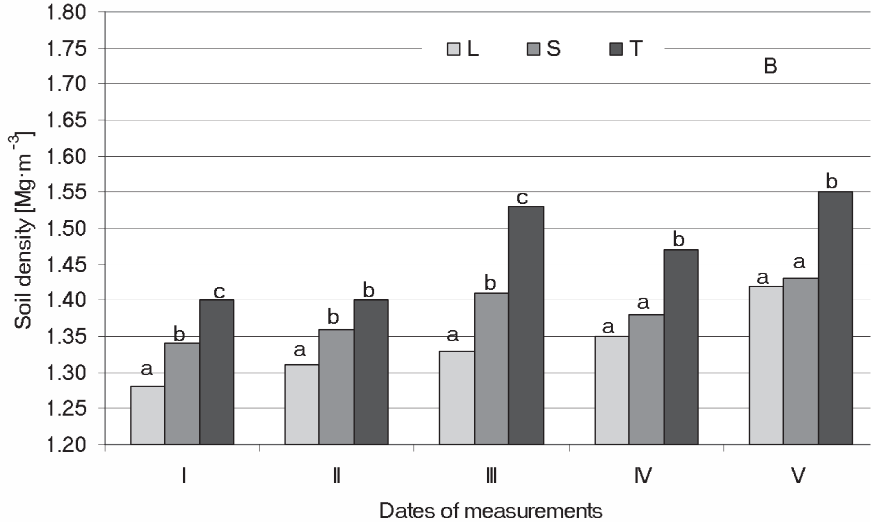

FIGURE 3. Soil density in the lateral ridge zone in the examined plots (marking with the same letter – no statistically significant differences at significance level $p = 0.05$)

place of run paths (S) – to 0.1 $m^3 \cdot m^{-3}$, that is, to the critical air capacity value [Cockroft and Olsson 1997]. Volume of pores of diameter between 30 and 3 μm changed little, and in the case of the smallest pores of diameter above 3 μm, it increased by about 14%. In the plot with traditional runs (T), in the direct vicinity of the ridges, near the end of the vegetation period, general porosity of soil in the ridge decreased from 0.464 to 0.415 $m^3 \cdot m^{-3}$ (by 10.6%), while in the plot with paths (S), situated further away from the ridges, these changes were much less visible.

Increase in soil density led to changes in the pore structure. In the plot with traditional runs (T), the share of pores of diameter above 30 μm, amounting to 0.257 $m^3 \cdot m^{-3}$ in the ridge, decreased to 0.181 $m^3 \cdot m^{-3}$, and in the ridge next to the path established, the share of this group of pores was small. Pores with diameter above 30 μm are usually filled with soil air, and they are filled with free water. Air capacity of the soil in the ridge on the side of wheel passage in both plots (S and T) was above the critical level. The share of the pore group of diameter 30–3 μm, filled with water easily accessible for the plants, in the plot with traditional runs (T) increased by about 10%, and the share of pores of diameter below 3 μm containing hardly accessible and non-accessible water – by 14.2%. In the plot with paths (S), these changes were reduced to a minimum. Pore distribution in the canopy and its changes due to machine runs on the wheel tracks (A) and in the lateral ridge zone (B) have been presented in Figure 4.

Before harvest, water characteristics of the soil were recorded in the plot with no runs (L) and on the wheel tracks in the plot with paths (S) and with traditional runs (T). Water content in the soil at capillary water content (CPC) did not change significantly under the influence

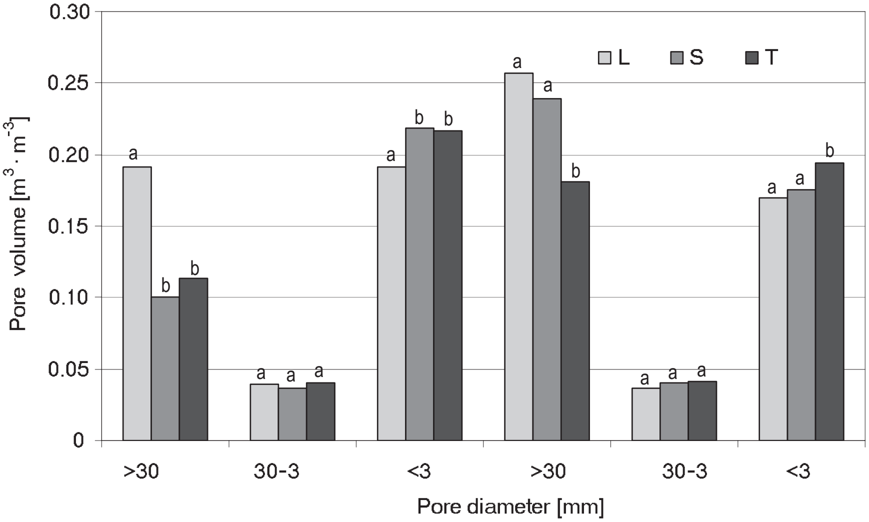

FIGURE 4. Pore distribution in the soil in the plots examined (marking with the same letter – no statistically significant differences at significance level p = 0.05)

of compaction caused by the wheels, and in the case of FWC and IPGR, a significant increase in the water content was observed (by about 13%) in both lad plots with runs. In the lateral ridge zone, no significant changes in the water content were recorded in the plot with paths (S), while in the plot with traditional runs (T), water content changes at CPC, FWC and IPGR, referred to the respective values in the canopy, were statistically significant (Table 2). On the basis of the data obtained, effective water retention was calculated (EWR). This term refers to water content in the soil ranging between pF 2.0 and pF 3.0, which corresponds with the quantity of water very easily accessible and easily accessible for the plants [Olszta and Zawadzki 1991].

TABLE 2. Water properties of the soil in wheel tracks and in the lateral ridge zone of the examined plots in [m^3·m^{-3}]

Marking location	Plot	CPC	FWC	IPGR	EWR
A	L	0.316^a	0.229^a	0.191^a	0.038^a
	S	0.309^a	0.254^b	0.218^b	0.037^a
	T	0.309^a	0.257^b	0.217^b	0.4^a
B	L	0.307^a	0.207^a	0.170^a	0.037^a
	S	0.319^b	0.216^a	0.175^a	0.04^a
	T	0.321^b	0.234^b	0.194^b	0.041^a

Marking with the same letter – no statistically significant differences at significance level p = 0.05).
CPC – capillary water content, FWC – fresh water content, IPGR – initial plant growth retardation, EWR – effective water retention.

Effective retention value (EWR) under the impact of soil compaction changed little both in the tractor wheel tracks and in the lateral ridge zone; these differences were statistically insignificant. Analyzing changes in the water content, it can be stated that compacting effect of the tractor wheels led to much greater changes in the content of hardly accessible and non-accessible water than easily and very easily accessible water. In literature, results vary significantly. Research conducted by Suwara [2010] led to conclusion that as soil compaction increased, the quantity of hardly accessible water decreased; Domżał [1979] is of opinion that compaction of light soil leads to a small increase in the quantity of water bound by suction pressure above 98.1 kPa (pF 3.0).

Potato harvesting

Changes in the soil characteristics in individual plots in the vegetation period were reflected by potato harvesting. Average yields from the plots examined have been presented in Figure 5.

Analyzing the values presented in the diagram, one can notice that throughout the entire research period, the plot with run paths was obtaining the highest yield. Compared with the control plot without passages (L), the average potato harvest from the plot with paths was higher by 3.9–13.3% (7% on the average), and in relation to the plot with traditional runs, it was higher by 18.9–34.2% (the average was 25.3%). Higher yield in the plot with paths (S) can be explained by border effect.

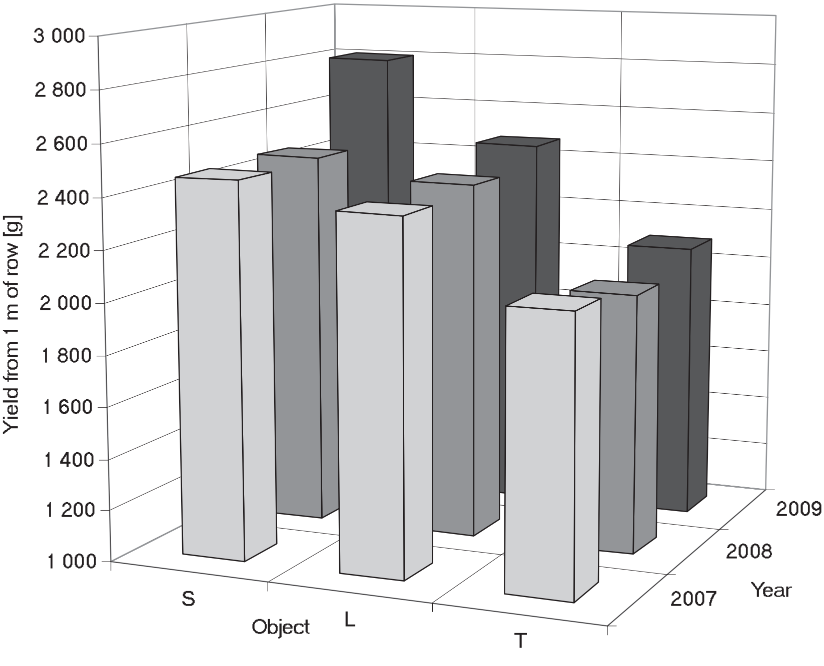

FIGURE 5. Average yield from 1m row in individual plots

Run paths established by omitting one row provided the plants in the neighboring rows with much better conditions of development in terms of access to sunlight, water, nutrients and less competition from other plants. The border effect for potato has been confirmed by the results of German research [Wolf 2000], as well as the previous research projects of the authors of this document [Buliński et al. 2011]. At the same time, the results indicate that in plots with traditional runs (T), that is, adjacent to ridges, average yield from rows was lower in comparison with the plot without passages (L) by 14.5–19.2% (on the average, by 17.4%), and in comparison with the plot with paths – by 19–34% (on the average, by 25.3%). This may be due to the fact that excessive compaction of the soil in the root development area limits both the total root mass and maximum rooting depth, which may lead to weaker plant growth and lower yield [Grzebisz 1989, Stalham 2002]. In order to determine whether the mode of performance of runs in the field had significant effect on potato yields, all measurement results were analyzed statistically.

The statistical values (F = 18.99, $p < 0.05$) indicated statistically significant differences between average yields in the plots examined (L–S–T) – Table 3.

In order to determine, which plots differ in terms of yields and how much, the mean plot values were compared using multiple range tests according to Tukey's method (HSD 95% confidence level). The results of this analysis have been presented in Table 4.

TABLE 3. Results of variance analysis for the runs examined in potato cultivation

Source	Sum of squares	Degree of freedom	Mean square	F-ratio	p-value
Between groups	8.53919E6	2	4.26959E6	18.99	0.0000
Within groups	3.97989E7	177	224853.0	–	–
Total	4.83381E7	179	–	–	–

TABLE 4. Comparison of significance of mean values

Value	Mean	Contrast	Difference	+/– Limits
T	2 057.40	L–S	–164.747	204.626
S	2 414.49	S–T	521.832*	
L	2 579.23	L–T	357.085*	

*Denotes a statistically significant difference at the 95% confidence level.

The results of the analysis conducted indicate that the difference between potato yield from the plot with traditional treatment (T) and yields from the remaining plots (L and S) was statistically significant, while path runs led to increased yield, however, in comparison with the control plot without passages (L), the difference was not statistically significant.

CONCLUSIONS

1. Volumetric soil density in wheel tracks increased significantly after the first runs of agricultural machines and was retained at a similar level until the end of the vegetation period.
2. Soil compaction in wheel tracks resulted in significant reduction of overall porosity and changes in differential porosity: decrease of the share of pores above 30 μm to the critical air capacity value and insignificant increase in the quantity of pores below 3 μm, filled with water, which is hardly accessible and non-accessible for the plants.
3. In the lateral ridge zone, significant changes in density and water-air properties of the soil are seen in the plot cultivated in the traditional manner, while in the plot with paths, these changes were insignificant.
4. On the basis of the entire three year period of research, it can be found that the plot with run paths was characterized by higher potato yield from 3.9 to 13.3% (on the average, 7%) in relation to the canopy plot. In the plots with traditional runs, that is, adjacent to ridges, average yield from rows was lower in comparison with the canopy by 14.5–19.2% (17.4% on the average) and by 19–34.2% (23.5% on the average) in comparison with the plot with paths.
5. Traditional runs led to decreased potato yield at a statistically significant level in comparison with yields from the remaining plots examined.

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Streszczenie: *Wpływ ugniatania gleby kołami agregatów rolniczych w uprawie ziemniaka na właściwości fizyczne gleby i plonowanie.* W trzyletnich doświadczeniach polowych badano zmiany gęstości i właściwości wodno-powietrznych gleby w śladach kół i w redlinie stosowanych w uprawie ziemniaka. Porównywano obiekt bez przejazdów z przejazdami po ścieżkach przejazdowych oraz systemem tradycyjnym. Gęstość objętościowa gleby wzrosła istotnie w miejscu przejazdów kół już po pierwszych zabiegach i na takim poziomie utrzymała się do końca okresu wegetacji. W wyniku zmiany zagęszczenia gleby udział porów zajętych przez powietrze obniżył się do poziomu minimum aeracyjnego, wzrósł udział porów zajętych przez wodę trudno dostępną i niedostępną dla roślin. W wyniku oddziaływania bocznego zmiany istotne badanych parametrów stwierdzono w redlinach sąsiadujących z przejazdami w obiekcie z uprawą tradycyjną, co w konsekwencji skutkowało istotną obniżką plonu bulw.

MS received February 2016

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