

Acta Technologica Agriculturae 2
Nitra, Slovaca Universitas Agriculturae Nitriae, 2024, pp. 116–124

IMPACT OF MACHINERY PASSAGES ON SOIL COMPACTION IN FIELD CONDITIONS

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The present study compares the consequences of soil compaction due to machinery in a selected 13.7 ha plot at Hronské Kosihy (Slovak Republic). The crop was winter wheat, while the changes of selected soil properties (penetration resistance and gravimetric soil water content) were monitored. The experimental plot was divided into 11 zones with different initial status of compaction: one of them was the reference zone without compaction (P1), five zones were out of the track line, four were directly in the track lines, and one was a collection route. The number of passages in each zone was from 0 up to more than 15. The impact of the number of machinery passages on gravimetric soil water content was found significant both in and out of the track lines with an average value of 17.37%. The monitoring of the passage number showed to be important also in the monitoring of soil penetration resistance ($P < 0.05$). The average value of penetration resistance in the P1 zone was 2.33 MPa. The dependence of soil compaction on passages ($P < 0.05$) was identified by the assessment and comparison of individual impacts of passages in the track zones (P3, P4, P6, and P7). A similar scenario was found also in case of the dependence of soil compaction on the passages monitored off the track lines (P2, P5). Also, the change of tire pressure was statistically significant, its decrease from 0.19 to 0.15 MPa showed to be beneficial. The highest compaction was monitored in the passages in P11 with an average value of 5.36 MPa, representing 2.3 times higher values than the reference one. The creation of a collection line enables reducing the compaction of the entire plot. The collection line should cover only a very small part of the plot.

Keywords: penetration resistance; agricultural machinery; soil properties

Climate change and population growth exert great pressure on the environment and natural resources (Lombardi et al., 2022). The UN's 2030 agenda for sustainable development has highlighted the importance of adopting sustainable agricultural practices to mitigate the threat posed by climate change to food systems worldwide in order to ensure proper water management and to restore degraded land (United Nations Department of Economic and Social Affairs, Population Division, 2022).

The soil is the top layer of the Earth's crust. Soil texture means the content of three main size categories of the "fine earth" in the soil based on their mass shares, which are sand, silt and clay, with the following sizes of elements for the sand (0.05–2 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) (Ditzler, 2017; USDA, 2017). Land degradation due to soil compaction is a widespread phenomenon. Delineating maps of topsoil compaction is a challenging task due to its dynamic nature, which is highly variable in time and space (Alaoui and Diserens, 2018). The yield of any crop depends on soil moisture and soil structure (Bulgakov et al., 2022). Under the influence of microbial activity, the soil elements are bound to generally stable units called aggregates. They can be destroyed by heavy machinery in combination with a land cultivating equipment. It results in consequent disruption of soil structure that eventually affects its compaction, thus changing density and reducing porosity (Totsche et al., 2018). Soil compaction is one of the most important factors responsible for the physical degradation

of the soil (Pagliai et al., 2003). Various methods were proposed not only for the estimation of soil compaction intensity but also of water content in the soil, density and penetration resistance (Elaoud and Chehaibi, 2011). Penetrometric resistance measurements are performed with a penetrometer. The application of cone penetrometers proved to be useful for identifying compaction (Motavalli et al., 2003). A soil hardness tester makes it possible to obtain soil penetration resistance depending on the depth of the piston (Chamen et al., 2015; Guimarães et al., 2017). Subsoil compaction can be considered a long-term degradation as a result of its persistence, although compaction impacts also surface layers. The soil properties (gravimetric soil water content, penetration resistance, compaction) represent complex aspects that should be paid proper attention (Jobbágy et al., 2014). Based on practical experience, it is clear that this is a phenomenon that must not be neglected. Also, the results of experiments in the world showed that soil pressing and compaction increased the demands for energy consumption, and thus the total costs for processing (Reichenberger, 2002). Based on experience, heavy machinery should not enter the soil and cause excessive compaction at increased soil moisture content. However, this is not always achievable. Agrotechnical dates are fixed and a failure to maintain them can have significant economic consequences. This means that the compromise between economy and compaction should be solved. It is not simple to achieve the minimisation of soil compaction, but it is

achievable when several principles are observed (e.g., to enter the field at suitable soil moisture content, proper chassis, axle load minimisation) (Inflation Solutions, 2018).

A disorganised movement of equipment causes excessive soil compaction on large parts of croplands. Due to the global problem of soil compaction caused by heavy machinery and the chaotic passage of equipment, we decided to implement a new concept of deployment of equipment passages in the given company, without the need to purchase new equipment. Taking the machinery typically used for agricultural land in Central Europe, we aimed to plan and elaborate a new concept of machinery passage organisation in the field based on results obtained from measuring relevant soil properties, namely a) soil compaction in the selected zones of the investigated plot; and b) gravimetric soil water content.

Material and methods

Characteristics of the investigated site

The measured field with the area of 13.7 ha (bounded part 1 ha) is located in Hronské Kosihy (E 48° 15' 33.3" N, 18° 35' 12.0" E, altitude from 169 to 172 m a.s.l.). Average total precipitation for years 1989–2018 represents 566.4 mm, and average temperature reaches 9.2 °C, ranging from -14 °C in winter to 37 °C in summer (SHMU, 2018). The field has been monitored for a longer period of time (more than 15 years cultivated by a private farmer) while various crops (corn, winter wheat, spring wheat, oilseed rape, etc.) were grown there. The soil of the investigated field is ranked into two different types (Fluvents, typical medium heavy 0006002; muck soils 0019002). The field is bordered by brooks from two sides. Based on long-term experience, it is evident that the field has more soil moisture content than other localities in the surroundings. Horsetails are often present here.

Tillage operations and machinery

The conventional tillage system with medium ploughing (every second year) was used on the investigated field until the beginning of research.

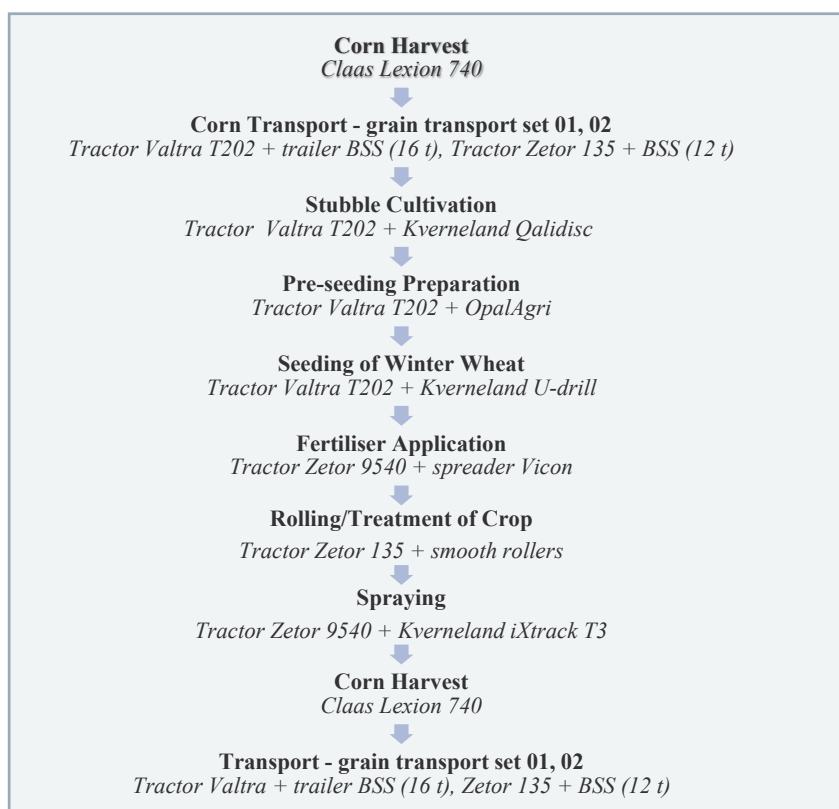


Fig. 1 Flow chart of tillage operations

Measurements took place between 2017 and 2019, while the experiment was established after the cultivation of corn and subsequently during the cultivation of winter wheat. Thus, ploughing was not used during the research. The flow chart of the work operations is shown in Fig. 1. The dates of agrotechnical operations, fertilisation, and crop treatment (including the doses applied) were determined by the agronomist of the company farming on that field.

Grain transport set 02 consisted of the tractor Valtra T202 (front axle – Alliance agri-star 365 540/65 R30, rear axle – Michelin multibib 650/65 R42) in combination with the truck trailer BSS-16t (BSS n.p., Senica na Hané, Czech Republic; tires: Matador 10 R20 radial with a working pressure of 0.7 MPa). The weight of the tractor was 6.4 t without any counterweight, and the weight of the trailer (double wheels) was 16 t. One part of the experimental field was processed by discs (“deeper stubble breaking – 10 to 13 cm with overlay” – P8, P9, P10) to determine differences in soil compaction. The passages by the tractor Valtra T202 were done also in aggregation with the suspended discs Kverneland Qalidisc with a weight

of 3135 kg. Working pressures in the tires were initially 0.19 MPa. Then, pressure decreased to 0.15 MPa in later measurements. The tractor had the counterweights of 1000 kg in the front three-point hitch, and the total weight of the set was 10,535 kg. Some relevant technical parameters of the agricultural machines used during the experiment are listed in Tables 1–2.

Passages created by machinery load

The experimental field was divided into 11 zones with various initial status of compaction due to heaviness or lack of machinery load by tillage operations (Fig. 2). According to the 11 zones, 11 different input conditions were set: one of them was the reference value (P1), while the other routes (P2–P11) were intended to create possible combinations to compare the effect of using all the studied machine sets as in the normal procedure but with strictly organised movements. A track line represents a line for the passage of equipment for protection, nutrition and treatment of the crop, and a non-track area is everywhere outside the track line (Table 3). The number of passages in each zone

Table 1 Machinery used for tillage operations

Tillage operation	Machine set	t_p ($\times 10^5$ Pa)
Pre-seeding preparation, $d = 13 \div 15$ cm, $w_w = 4.7$ m	Valtra T202 + OpallAgri Merkur	tractor: F = 1.9, R = 1.9
Sowing – winter wheat, $w_w = 3$ m	Valtra T 202+ sower Kverneland U-drill	tractor: F = 1.9, R = 1.9 trailer: F = 1.4, R = 1.4
Fertilization 3 \times	Zetor 9540	tractor: F = 3.5, R = 3.5
Offset, rolling 1 \times	Zetor Forterra 135 + full rollers	tractor: F = 1.8, R = 1.8
Chemical protection 3 \times	Zetor 9540	tractor: F = 3.5, R = 3.5 sprayer: R = 2.1
Corn harvesting	Claas Lexion 740	combine harvester F = 3, R = 2.7
Corn harvesting – grain transport set 01	Zetor Forterra 135+BSS-12 t	tractor: F = 1.8, R = 1.8 trailer: F = 5, R = 5
Corn harvesting – grain transport set 02	Valtra T202+BSS-16 t	tractor: F = 1.9, R = 1.9 trailer: F = 7, R = 7
Stubble breaking, $d = 10 \div 13$ cm, $w_w = 4$ m	Valtra T202 + Kverneland Qalidisc	tractor: F = 1.9, R = 1.9

F – front axle, R – rear axle, d – working depth, w_w – working width, t_p – tire pressure

Table 2 Tires of the machinery used

Machine	Front axle	Rear axle	Weight (kg)
Kverneland U-drill	–	BKT Implement AS504 420/55-17	Net 4700 Gross 6100
Claas Lexion 740	Continental 800/70 R32	Continental 600/65 R28	Net 20,557 Gross 24,744
Valtra T202	Alliance agri-star 365 540/65 R30	Michelin multibib 650/65 R42	Net 6400 Gross 7400*
Zetor Forterra 135	Firestone 380/85 R24	Mitas Radialdrive 520/70 R38	6010
Zetor 9540	12.4R24	12.4R46	4000
Kverneland Qalidisc			3135
Trailer BSS-12t	Mitas Implement 12.5/80 R18	Mitas Implement 12.5/80 R18	Net 9000 Gross 11,820
Trailer BSS-16t	Matador 10 R20 radial	Matador 10 R20 radial	16,000
sprayer Kverneland iXtrack T3	–	300/95R52	Empty weight 3750 Full 6950
Rollers (own production)	–	–	Full 3500

* weight of the machine with the counterweight

was from 0 up to more than 15. One of the passages was the reference zone without passage/compaction (P1), five zones were out of the track lines (P2, P5, P8, P9, P10), four were directly in the track lines (P3, P4, P6, P7), and one was a collection route (P11).

To create the experimental passages, it was necessary to ensure that the machine operators are familiarised with the set rules. All the machine sets were not allowed to move in the field out of the required passages.

Determination of actual soil water content

Actual soil water content was determined by the gravimetric method. Soil samples were taken in individual experimental passages (P1–P11). Three samples were taken in each selected passage with a manual drill (Royal Eijkelkamp, EN Giesbeek, Netherlands). All the samples were stored in standardised aluminium bowls; their numbers were recorded and assigned to the respective passages directly

on site. Samples were individually weighed on a certified scales (Kern Microtechnik GmbH, Eschenlohe, Germany) with a sensitivity of 0.01 g. Later, all the samples were put in a soil sample dryer (Venticell 50, MMM Medcenter Einrichtungen GmbH) and were dried at a temperature of 150 °C for 26 h.

Determination of soil penetration resistance

A manual cone penetrometer (Eijlkamp, EN Giesbeek, Netherlands) equipped with a digital Penetrologger (handheld soil cone penetrometer Eijkelkamp 06.15.31. SA, ± 0.01 MPa) was used for the measurements of soil penetration resistance. During the measurements, it was necessary to assure an even pressing of the needle with the coin into the soil (approx $4 \text{ m}\cdot\text{s}^{-1}$). The measuring range of the Penetrologger is from 0 to 10 MPa with working depth down to 0.8 m (depth is measured by an internal ultrasonic sensor). Equipment's resolution sensitivity is 1 N.

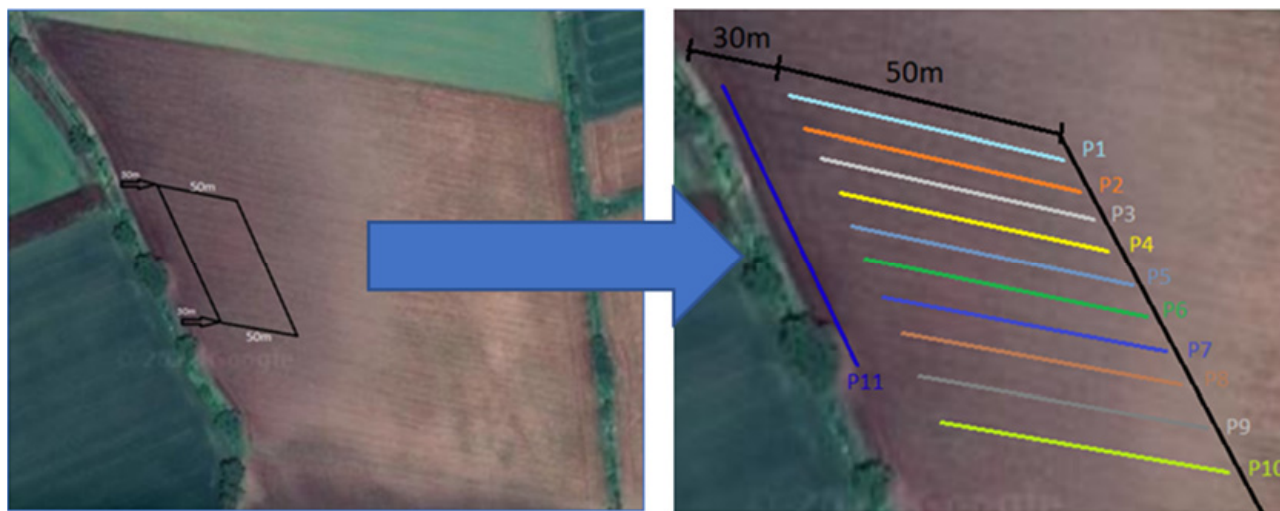


Fig. 2 The investigated field at Hronské Kosihy with the experimental passages

Communication between the Penetrologger and external devices is assured by the communication ports (Eikelkamp, 2020). In the experiments, the measurement points corresponded to the model soil compaction. Penetration resistance values represent the mean values of 10 repeated measurements down to the depth of 0.75 m in the soil profile.

Results and discussion

Gravimetric soil water content

Gravimetric soil water content ($w \cdot w^{-1} \%$) was determined after individual experimental passages. The average gravimetric soil water content of all the measured values

reached $17.36 \pm 1.82\%$ with a variation coefficient of 7.55%. Also, a long-term precipitation deficit was monitored in the given area. However, the measured values of gravimetric soil water content were close to the average or a bit lower than the average. There were evident differences among the individual passages, while the first measurement was performed in the uncompacted reference zone. The measurement depending on the number of passages of various machines had a minimal impact on the differences of gravimetric soil water content, with the maximum difference of 1.82%. Based on the results of the statistical analysis of gravimetric soil water content monitoring, the number of passages in the track is significant ($P < 0.05$).

Table 3 Tillage operations and penetration resistance values for the passages

Passages	Description	Number of passages	Track line	Average PR (MPa)	Increase of resistance (MPa)
P1	reference value – no passage from sowing	0	–	2.33	reference value
P2	out of the track line, only passage of the combine harvester	1×	–	2.63	0.30
P3	track line – protection (3×), offset (1×), and nourishment (3×), no passage during the harvest	7×	✓	2.69	0.36
P4	track line – 7× (protection, nourishment, and offset), combine harvester 1×	8×	✓	2.72	0.39
P5	out of the track line, combine harvester 1×, and collection grain transport set 01 – 1×	2×	–	2.84	0.51
P6	track line – P4 and collection grain transport set 02 – 1×	9×	✓	3.57	1.24
P7	track line – P4 and collection grain transport set 01	9×	✓	3.13	0.8
P8	stubble breaking to the depth of 0.10–0.13 m, no passage, Valtra T202 Qalidisc, measurement in the wheel track	0	–	3.18	0.85
P9	P8, crossing 2× (Valtra with front counterweight 1 t, with suspended discs 3535 kg), $p_t = 0.19$ MPa, measurement in the wheel track	2×	–	4.13	1.8
P10	P9, $p_t = 0.15$ MPa, position change – transfer to P10	2×	–	2.96	0.63
P11	collection route and headland at the edge of the field, combine harvester and grain transport sets	more than 15×	–	5.36	3.03

pt – working tire pressure (MPa); PR – penetration resistance (MPa)

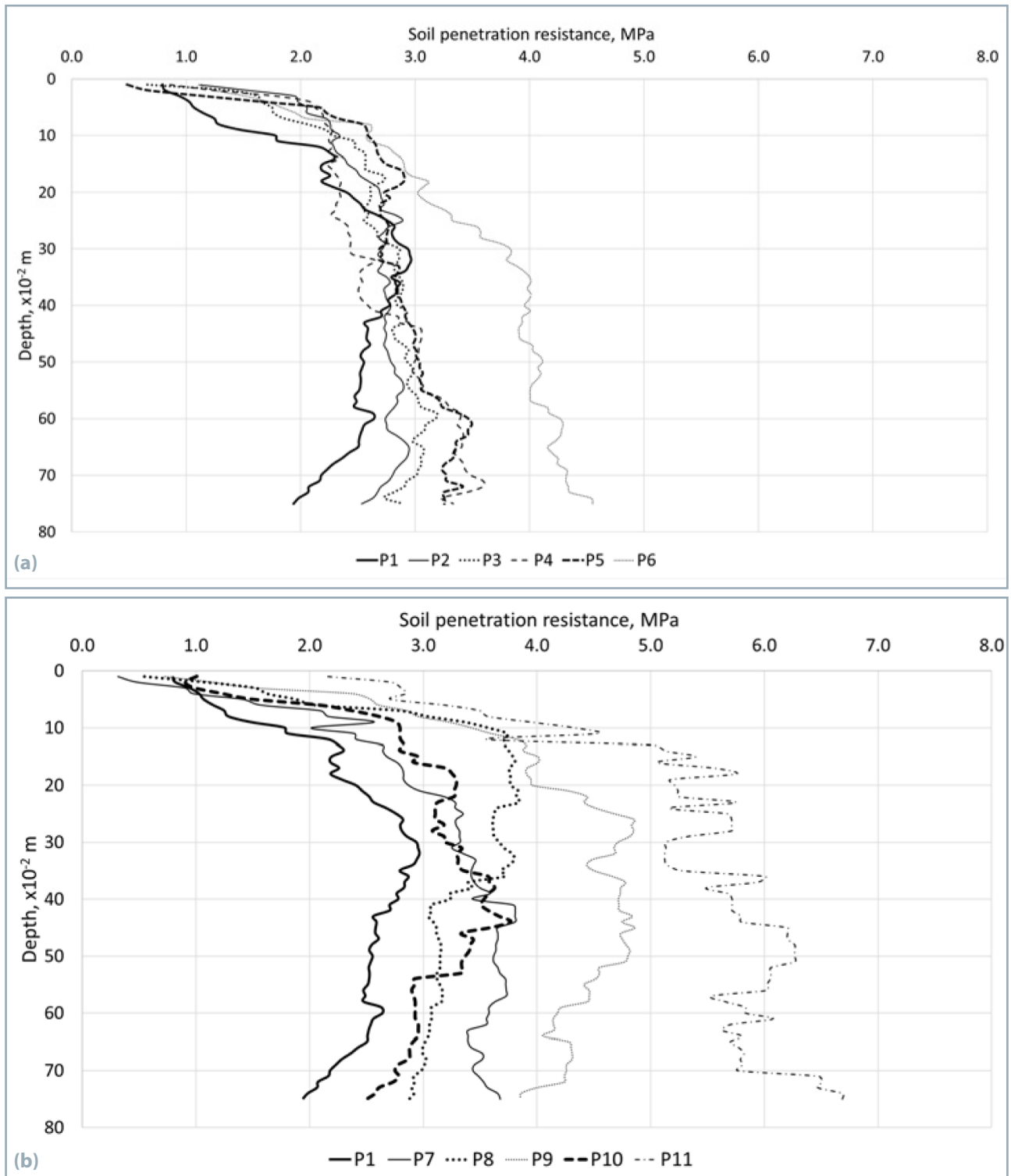


Fig. 3 Dependence of soil penetration resistance on measurement depth, a) P1, P2, P3, P4, P5, P6, b) P1, P7, P8, P9, P10, P11

Soil penetration resistance

The first penetration resistance measurement (in P1) was performed as a reference value for comparing the impact of machinery passages after sowing of winter wheat in autumn. The graphic illustration of the results is shown in Fig. 3. It is evident that the level of 3 MPa was not exceeded. The average value of penetration resistance was 2.33 MPa at the variation coefficient of 23.10%. It is evident that there has been a continuous increase of penetration resistance up to the depth of 0.32 m, while soil compaction was increasing from the zero value. The limit of permanent value of penetration resistance was recorded within the depth range of 0.11–0.16 m. Then, a continuous increase of resistance was recorded up to the maximum value of 2.97 MPa (in the depth of 0.32 m). Further investigation proved the reducing of resistance up to the depth of 0.75 m.

Increasing penetration resistance in the surface layer was clearly evident in the second measurement (P2). Within the research works, the task was to specify soil resistance changes after harvesting passage by the combine harvester Claas Lexion 740. The input parameters of the combine harvester related to tire types and total weight are given in respective tables. The change of penetration resistance depending on depth is given in Fig. 3a on the right side. In the under-plough layer (depth over 0.40 m), the values were again higher, namely by 0.34 MPa in average. The results were then subjected to the statistical evaluation of a single-factor analysis. At the significance level of 95%, the results showed statistically significant impact of combine harvester passage on the increase of soil penetration resistance ($P < 0.05$). That means when monitoring the combine harvester passage and its impact on soil compaction change, there is a statistically significant difference between two values of resistance in various monitored depths down to 0.75 m.

Another measurement of penetration resistance (P3, Fig. 3a) was focused on the assessment of compaction rate after multiple passages of the machinery in the sowing line tracks. That means there was the zero passage at the sowing, and then, there were 7 passages based on the application of protection and offset (protection – 3, offset – 1), or nourishment (3 passages) of the crops. The machinery passage during the harvesting with combine harvester is P3. In experimental passages P1 and P3, an increase in the mean value of resistance by up to 0.42 MPa was recorded in contrast to P2 where there was a difference of 0.12 MPa. The maximum resistance reached the value of 3.19 MPa in the depth of 59 cm. The variation coefficient value was 16.65%. In comparison with passage P2, there is a slight increase of penetration resistance in the total monitored depth of the soil horizon. There was a significant change in the depth of 0.10–0.20 m, namely by as much as 0.17 MPa. Based on the research task, there was an interesting change of resistance in the depth of 0.29–0.36 m, where the average increase reached as much as 0.29 MPa. Based on the statistical analysis, there is a significant demonstration of machinery passages in the field ($P < 0.05$).

Experimental measurement P6 was focused on investigating the impact of cereal combine harvester passage with the grain transport set 02 in the track line, while considering also passages for protection and

nourishment (stated in P3). A truck trailer with the weight of 16 t was used with four wheels on both axles (radial tires 10R20 for roads), which were pressurised to 0.7 MPa. There were 9 passages. The technical parameters of the machines were also monitored. Based on the analysis of results, the average value of penetration resistance increased by 1.24 MPa in case of the excessive number of passages. The maximum values reached 4.55 MPa in the measurement depth of 0.75 m. The increase of resistance in these measurements was evident already from the soil surface, with the resistance value of 1.11 MPa (in the depth of 0.01 m). The variation coefficient was 22.94% at the average value of 3.57 MPa. The graphic illustration of the results is given in Fig. 3a. A significant increase of resistance in comparison with the reference measurement is evident from the beginning of measurements. From the statistical aspect, comparing the passages P3, P4, P6 in the track lines also proved the impact of the number of passages on soil compaction ($P < 0.05$). These further passages proved the fact that significant compaction was found also in lower layers.

Experimental measurements P8–P10 were focused on the changes of compaction by using stubble breaking in the field (Fig. 3b). The average working depth of soil cultivation was 0.115 ± 0.150 m. In these measurements, there were no passages of the above-mentioned application, harvesting, or collection machinery recorded in the given year. Stubble breaking was carried out by the tractor Valtra T202 combined with the agricultural tool Kverneland Qalidisc. The measurements of penetration resistance were done in the tractor line in the processed surface layer. The tractor line was compacted twice (tractor passage in one way, its turning, tractor passage on the way back) by tractor's wheels (with the counterweight in the front part, 1000 kg) with the attached suspended tool Kverneland Qalidisc in the upper position of the suspension (discs with the total weight of 3525 kg). The total weight of the tractor and tool and counterweight set was 10,950 kg. Tire working pressures were set to 0.19 MPa and later to 0. MPa. The average value of penetration resistance was 4.13 MPa at the variation coefficient of 20.29%. The maximum value of penetration resistance reached the value of 4.86 MPa. The graphic illustration of the results is given in Fig. 3b. The resistance value reached 3.4 MPa in the depth of 0.10 m. The maximum resistance value close to 5 MPa was reached in the depth of 0.26 m, while the value in the horizon range of 0.21–0.73 m was equal or greater than 4 MPa. The results show that compaction is present also in deeper soil horizons. In the measurements of vertical penetration resistance in the middle passage area (clay subsoil), it was difficult to insert and pull out the Penetrologger.

Experimental measurement P10 was based on the research works of P9. It was focused on measuring the impact of reduced tire pressure (0.15 MPa) on soil compaction. The average value of the penetration resistance was 2.96 MPa at the variation coefficient of 20.11%. Thus, based on the results, it is evident that the average resistance value is higher by 0.63 MPa in comparison with the reference measurement (P1), but its value decreased in comparison with P9 by 1.17 MPa. The maximum resistance

value (3.77 MPa) was recorded in the depth of 0.44 m. Furthermore, compaction impact can be seen in Fig. 3b, while the resistance value of 3 MPa was reached already in a shallow layer (0.17 m). Based on all the measurements done, compaction in passage P9 proved to have the highest values, namely at the tire pressure of the tractor Valtra T202 with the value of 1.9 MPa. After reduction of tire pressure by 40 kPa, soil compaction was reduced by 28% on average, as can be seen in Fig. 3b. When comparing the passages P1, P9, and P10, the statistical results proved the dependence of the impact of passages on soil compaction (i.e., on the change of penetration resistance values, $P < 0.05$).

Experimental measurements P11 were focused on the evaluation of soil compaction on the collection route (Fig. 3b). The average value of penetration resistance was the highest among all measurement combinations (5.36 MPa). The variation coefficient was 18.93% at the maximum penetration resistance of 6.69 MPa. The increase of the average resistance value in measurement P11 reached 3.03 MPa in comparison with the reference value. The statistical analyses proved the hypothesis of soil compaction dependence on performed passages ($P < 0.05$). Thus, it can be assumed that soil compaction in this area was even greater than shown by the results. The measurements with extreme values were not included in the assessment of results in passages P11. The collection route was used as the headland of the field for turning the machine sets and the place, parking the transport sets, for unloading the grain from the combine harvester.

Soil compaction is the main environmental issue of modern agriculture. Soil compaction can be significantly variable in space, depending on the number and distribution of passages by agricultural machines in the field (Carrara et al., 2007). This fact was also confirmed in our research works. The analysis of soil compaction caused by the passage of equipment pointed to the fact that the increase in penetration resistance compared to the reference value represented the variability from 0.3 to 3.03 MPa. A single pass during harvest increased the average resistance value up to 2.63 MPa (increase by 0.3 MPa); however, the addition of passes to one line caused an increase in the average resistance value up to 5.36 MPa for the collection route. Compaction impacts on yield are the highest when the crop is exposed to stress (e.g., drought or excessively wet vegetation period) (Sidhu and Duiker, 2006). The deployment of various agricultural grain transport sets used in wheat harvesting during our measurements pointed out to its clear influence on soil compaction. The total weight of the loaded trailer (a difference of more than 10 t) affected the average value of penetration resistance by up to 0.44 MPa.

Soil compaction caused by wheeled agricultural machines has a negative impact on arable land structure. At boundary values and significant conditions, it affects plant production in both short and long term (Soane and van Ouwerkerk, 1994). Soil compaction impacts the final yield of crops and the total number of plants. The number of plants can be excessively decreased by 20–30% due to compaction impact (Shaheb et al., 2021). Soil compaction has an impact on the development of the root system of the grown crop (Atwell, 1990). Soil compaction and

follow-up damage to the crop causes a decrease of yields. Annual losses in yields may reach as much as 37% (Duiker, 2005).

An intensive application of agricultural procedures is performed during short periods and often when the soil is wet. This leads to a higher tendency for soil compaction that is permanent and cumulative (Hakansson et al., 1988). The application of irrigation and intensive plant production results in the increase of yields on one hand but also in the change of soil properties (gravimetric soil water content, penetration resistance, etc.) on the other hand. The quality of work is a significant property of application machinery (Jobbágy et al., 2021). Higher compaction values are associated with increasing weights of agricultural machinery (combine harvesters, tractors) (Keller et al., 2019). Ploughing applications also contribute to additional soil compaction (Syromyatnikov et al., 2023).

The monitoring of soil compaction in our experiments took place in the track line and in the non-track area. Track lines were mainly used for the passage of equipment for the protection, nutrition, and treatment of the crop. The increase in the value of penetration resistance was 0.36 MPa in the rail line. The addition of the combine harvester drive caused a further increase in the average resistance value by 0.03 MPa.

The traction and flotation elements of agricultural vehicles and the volume and distribution of their contact pressures on the soil surface directly influence the impact on the topsoil and its substrates (Abou-Zied et al., 2004). As part of our experiments, stubble cultivation was created to the depth of 0.10–0.13 m. With stubble cultivation, there was an increase in the average value of penetration resistance by 0.85 MPa in the tracks of the tractor wheels. The increase in resistance was mainly observed from the depth range of 0.10–0.38 m, which was also confirmed by graphic evaluations. The subsequent double passage of the tractor with the weight and with the disc implement raised to the upper position caused an increase in the average value of penetration resistance by up to 0.95 MPa. This simulates the effect of turning the machines at the headland of the field and therefore the increase of compaction with each turn. This often leads to the degradation of physical properties of soil, especially the increase of its density due to heavy machinery causing excessive soil compaction (Rataj et al., 2022).

Penetration resistance up to 2 MPa is easily overcome by the roots of all cultivated crops. A resistance of 3–4 MPa hinders the growth and development of roots. For successful seed germination and root development, it is desirable that resistance to penetration into the soil does not exceed 1 MPa (Mirzavand and Moradi-Talebbeigi, 2021).

Conclusion

The study focused on evaluating the influence of the passage of selected agricultural machines on the change in soil compaction monitored by penetration resistance variability. During the research work, 11 different input conditions were created, one of which was the reference value (P1). The other passages (P2 to P11) were intended to create possible combinations to compare the effect of using all the machine sets as in the normal procedure but with

strictly organised movement. The following conclusions can be drawn from the achieved results:

1. The impact of agricultural machinery on soil compaction has been shown to be significant.
2. Soil compaction is also influenced by the agricultural equipment used. The measurements were carried out in the track line with two different agricultural grain transport sets used in wheat harvesting.
3. The passage of the combine harvester in the track line or non-track line represents a difference in the value of penetration resistance of 0.09 MPa (increase by 30%).
4. When the stubble cultivation in the 0.1–0.13 m depth is compared with the reference value, the value of penetration resistance increased by 0.85 MPa in the track line of the tractor wheels. The subsequent passage of agricultural equipment also demonstrated the influence of the change in tire pressure on soil compaction. It can be stated that the collection route should cover the smallest possible area of the field.

Based on the results, the company management decided not only for deep aeration of the compacted area but also for this more rational and effective system of movement of grain transport sets during harvesting works in the future. In the future, they will continue with this system of organisation, as it has been shown that it is possible to concentrate excessive soil compaction into one edge line. In this way, soil damage can be minimised on a large part of the field without the need to purchase other machinery. Even though results like with controlled-traffic farming (CTF) will not be achieved, this tested system can be practiced without investing in machines and can still help protect the soil.

Acknowledgement

This paper is a result of the project “Scientific support of climate change adaptation in agriculture and mitigation of soil degradation” (ITMS2014+ 313011W580) supported by the Integrated Infrastructure Operational Programme funded by the ERDF.

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