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SOIL DENSITY IN TRADITIONAL MOULDBOARD TILLAGE

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Until recently, mouldboard ploughing was used as the main tillage in almost the entire territory of Ukraine and Russia. However, mouldboard technologies contribute to the formation of a "plough pan", which contributes to additional soil compaction. The intensity of agricultural production exacerbated the problem of soil compaction by machine and tractor units. The over-consolidation of soil results in stunted plant root growth, lack of oxygen, and water and nutrient restrictions. Soil compaction can be reduced by deep local chiselling. The aim of the study was to determine the density of the soil at different depths during continuous traditional cultivation (reverse ploughing). The density of the soil was evaluated by resistance to penetration into the soil in a vegetable-forage crop rotation on an experimental field with continuous traditional tillage. The measurement of penetration resistance was carried out using an automatic electronic hardness tester "DATAFIELD". The boundaries of the experimental field were determined, a computer map of the experimental field was compiled with automatic "grid" of plot sizes, two-dimensional mapping was carried out, and the sequence and place of measurements were developed. As a result, the level of soil compaction at different penetration depths and resistance to root growth was determined. It has been established that with constant traditional reverse tillage, the soil at a depth of more than 10 cm is sufficiently compacted. At a depth of 15 cm, a strong compaction of the soil is observed, which indicates its physical and hydrological degradation.

Keywords: penetration resistance; penetration depth; electronic hardness tester; mouldboard ploughing

Until recently, mouldboard ploughing was used as the main tillage in almost the entire territory of Ukraine and Russia. Mouldboard ploughing ensures the turnover of the layer, crumbling of the soil, and incorporation of crop residues, organic and mineral fertilizers. It is one of the most effective and environmentally friendly ways to control weeds, pests, and pathogens (Tarasenko et al., 2022; Svechnikov and Troyanovskaya, 2019). However, mouldboard ploughing has several serious drawbacks. These include (Rouabhi et al., 2018): high energy intensity of the process; horizontal displacement and mixing of soil layers; high ridge and cloddiness of the field surface, especially in arid farming conditions, and the formation of a "plough pan", expressed in additional soil compaction.

Soil compaction is a common worldwide problem affecting many crop growing areas (Shaheb et al., 2021; Ledermüller et al., 2021). Soil compaction negatively affects plant growth and development. Soil compaction slows down root growth and severely restricts access to water and nutrients (Correa et al., 2019; Priori et al., 2021; Yan et al., 2021). In compacted soil, there is a lack of oxygen, which enhances the activity of pathogens of root diseases (Pierce and Lal, 2017; Pulido-Moncada et al., 2020; Huang et al., 2022). Insufficient aeration of compacted soil increases the likelihood of plant chlorosis due to the production of exogenous soil ethylene (Villeneuve and Geoffriau, 2020).

Multiple passes of agricultural machinery across the field lead to the destruction of the upper soil layer and compaction of the lower soil layer (Villa-Henriksen et al., 2021). The main cause of soil compaction is associated with the constant increase in the size and weight of agricultural equipment used (Yue et al., 2021). An increase in the mass of agricultural machinery compacts not only the arable, but also the subsurface horizon to a depth of 1–1.5 m (Kokieva

et al., 2021). Soil compaction adversely affects its fertility and crop yields (Cerdà et al., 2021). The drop in yield due to over-consolidation of the soil can reach 20–40%. Recovery time for compacted soil, depending on soil type, the degree of compaction and climate, is estimated at 5 to 18 years (Froehlich et al., 1985). With heavy compaction, it can take about 100 years for the soil to recover (Troyanovskaya et al., 2019; Webb, 2002). Soil compaction can be reduced mechanically, by deep local chiselling (Syromyatnikov et al., 2021; Blednykh et al., 2015).

The aim of the study was to determine the density of the soil at different depths during continuous traditional cultivation (mouldboard ploughing). The novelty of this study lies in the method of obtaining spatially distributed information on the state of soil cover in the on-line mode without taking soil samples.

Material and methods

Place of research: Ukraine, Kharkiv region, Selektsionnaya settlement. Natural and climatic zone is forest-steppe; agro-soil province is high left-bank forest-steppe. Geographic coordinates: latitude is 49º 47, longitude is 35º 51 (Fig. 1).

The study was carried out as part of a long-term (since 1968) field stationary experiment on the topic "Scientific substantiation of the mechanisms for maintaining and reproducing soil fertility in irrigated vegetable agrocenoses of the Forest-Steppe of Ukraine". Within the irrigated vegetable-forage crop rotation, successive crop rotation was used: barley with alfalfa over sowing – alfalfa of the first year of use – alfalfa of the second year of use – cucumber – winter wheat – onion – tomato – white-headed cabbage – table beet. Since 1968, continuous traditional tillage with layer turnover has been carried out.

As the soil in the experimental plot, a typical low-humus heavy loamy chernozem on forest-like loam was used. The depth of the humus layer was 76 cm. Soil penetration resistance was used to evaluate soil density (Medvedev, 2009; Oritsejafor et al., 2022). The advantage of using soil penetration



Fig. 1 Experimental plot with traditional mouldboard tillage

resistance as a characteristic of soil density is a high accuracy of measured values. Soil penetration resistance was measured using a "DATAFIELD" automated electronic hardness tester (Fig. 2). The electronic hardness tester "DATAFIELD" provides a constant speed of translational movement of the cone tip, regardless of soil resistance. Penetration resistance is measured at a constant tip friction coefficient, regardless of the structure and density of soil layers, which significantly increases the reliability of measurements.

The plunger insertion depth is 400 mm and is achieved using an incremental encoder. Surface resistance was transmitted through the plunger and rod to a force-measuring strain gauge. An asynchronous electric motor creates force up to 100 kg. Linear plunger immersion speed is about 1 $cm \cdot s^{-1}$, regardless of surface resistance. The initial and final positions during penetration into the soil were recorded by photoelectronic sensors.

Electrical signals from tensometric, optoelectric, and incremental sensors entered the electronic unit, where they were processed by the microcontroller and stored in the memory.

The structure of the electromechanical soil hardness tester includes a multi-channel receiver of the global positioning system and a memory module for saving field maps. The electronic unit (Fig. 2) is designed to control the operation

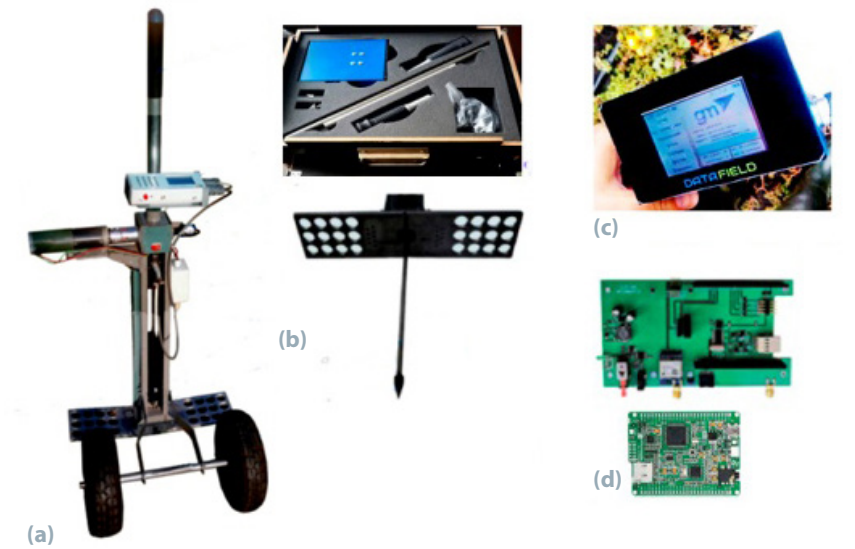


Fig. 2 Electronic soil hardness tester "DATAFIELD": general view (a); plunger (b); electronic unit display (with); microcircuits of the electronic unit (d)

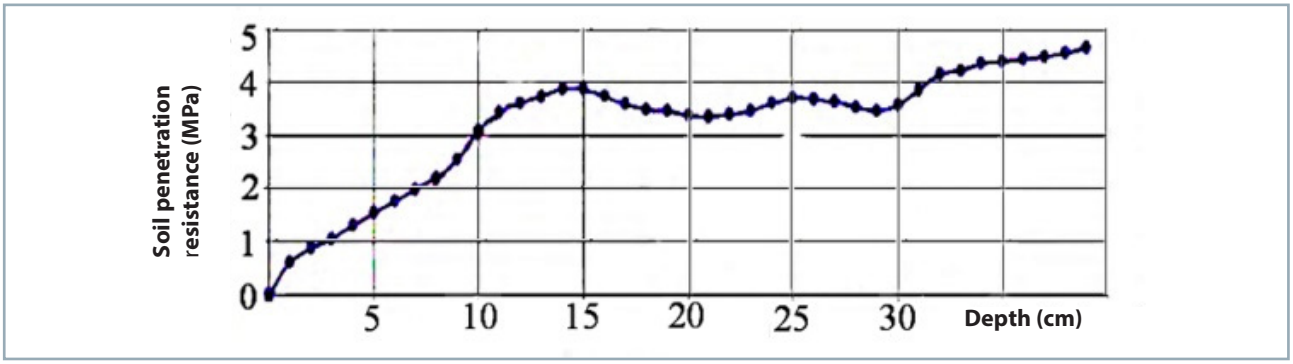


Fig. 3 Experimental data of soil hardness measurement at one point of the field

of the hardness tester and to process the signals of the tensometric sensor of immersion force and the rod position sensors. Soil penetration resistance values were measured through each centimetre of plunger travel (Fig. 3). The measured soil hardness values were stored in the memory together with the positional coordinates of the measurement point.

Kazan Federal University has developed a program for statistical processing of measurement results. With this program, an average value was calculated for every three points and compared with the experimental value at the middle measurement point. For example, a test of soil hardness values at a plunger depth of 10 cm was evaluated by the deviation from the mean measurement value between hardness at 9 cm and hardness at 11 cm. In the case of a large discrepancy, the electronic unit signalled the need to repeat the experiment.

The electronic control unit has a large colour touch display. The microcontroller STM32F407VGT6 is used as a processor, operating at a frequency of 168 MHz.

To accurately determine the coordinates of soil hardness measurements, the control unit has:

– GPS/GLONASS global positioning module;
– wireless communication module for transmitting information about measurement results via the Internet.

The location geographic coordinates update rate is 0.1 s. This allows determining the hardness of the soil at each point in order to compile reliable maps of the hardness of various parts of the field. Maps are transferred to a personal computer using a built-in radio module at a frequency of 433 MHz. The maximum communication range in open areas reaches 1.5 km.

Measurement technique:

– formation of a map of measurements (Fig. 1);
– preparation of the hardness tester for operation (checking the connections of power cables; connection of the encoder connection; strain gauge and electronic unit);
– moving the hardness tester to a given point of the field in accordance with the map of measurements;
– turning on the electronic unit and taking measurements;
– saving measurement results to a memory card.

The readings of the penetrometer make it possible to determine the level of compaction and resistance to root growth and to quantify the density of the soil and the traction resistance of the working bodies of tillage machines and implements (Sudduth et al., 2004).

When measuring the penetration resistance of the soil, soil moisture was taken into account, which was measured using an electronic moisture meter MC-7828 SOIL (Syromyatnikov et al., 2023). The average values of soil moisture at a depth of 30 cm were 23–26%.

Results and discussion

Assigning its own colour designation to each value of soil hardness made it possible to translate the array of experimental data from tables into a graphical representation. The correspondence of soil penetration resistance values and coordinates of measurements (Fig. 4) makes it easy to identify areas where additional deep machining (chiselling) is required.

The green colour of interpolation means that soil compaction is within acceptable values (0.5–2 MPa). Yellow means that the areas of soil are compacted (2.5–3.5 MPa). The red colour indicates sufficiently high compaction (4.0–5.5 MPa). Figure 4 shows that the soil in the experimental field is over-compacted. Even in the upper soil layers up to 15 cm deep, there are areas with soil compaction up to 3.5 MPa. Exceeding soil compaction (2.5–3.5 MPa) was already observed when the plunger was deepened by 15 cm. The small areas of high compaction (4.0–5.5 MPa) were present at a depth of 20 cm. Significant soil compaction (4.0–5.5 MPa) was noted in almost the entire experimental area when the plunger was deepened from 25 cm to 40 cm. This over-consolidation of the soil requires additional deep loosening at this depth.

The approximation of average values made it possible to obtain the dependences of resistance to penetration into the soil in the centre and at the edge of the experimental field on plunger immersion depth (Fig. 5). The measurement was interpolated every 2.5 cm. The coefficient of correlation with experimental data was $R^2 = 0.95$.

The top layers of the soil have the lowest penetration resistance. On average, at a depth of more than 15 cm, the over-consolidation of the soil is observed, indicating physical and hydrological degradation. Soil compaction is detrimental to plant growth, as root growth is retarded. The associated lack of oxygen can increase the incidence

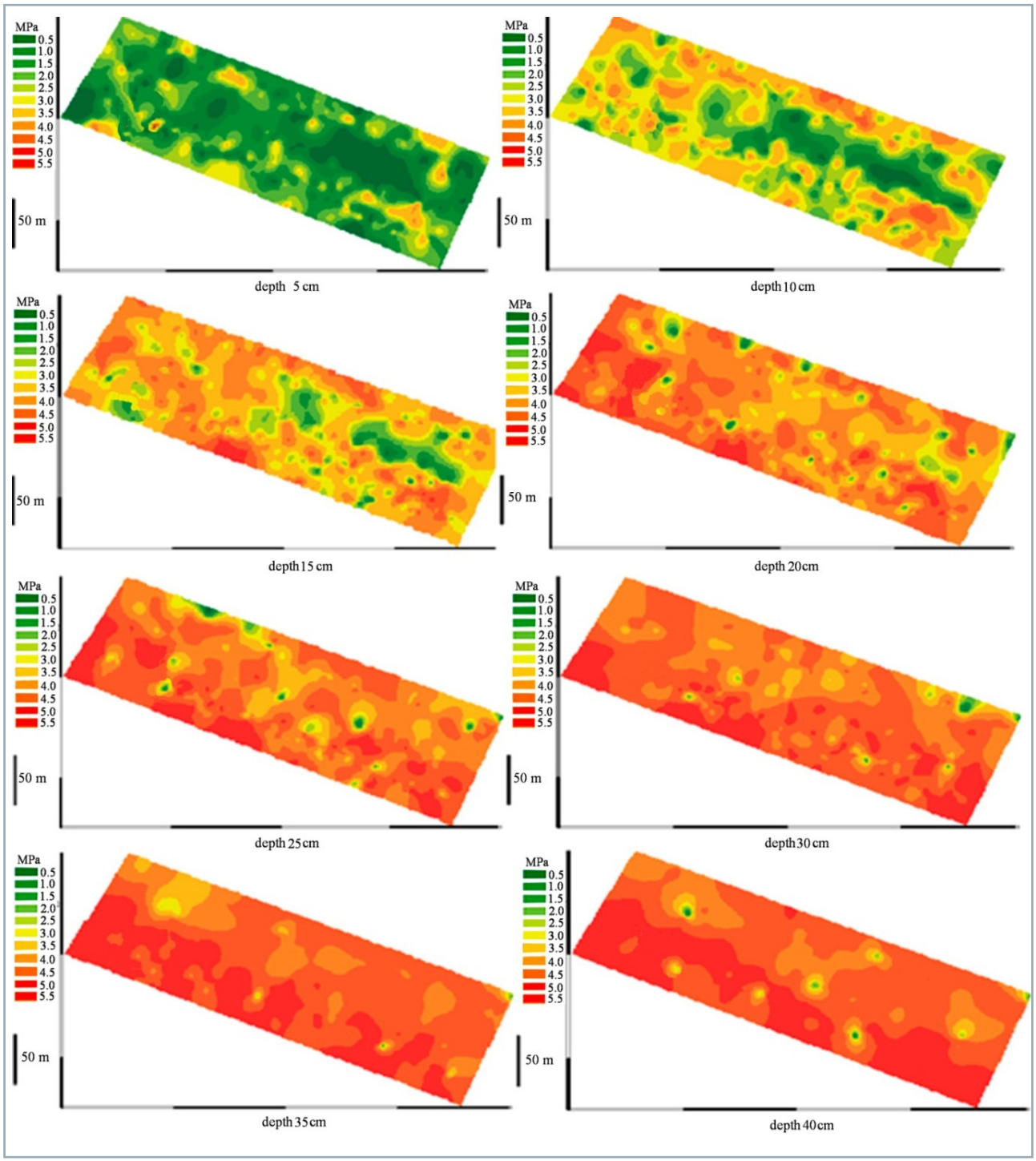


Fig. 4 Resistance to penetration into the soil depending on the depth of penetration of the plunger of the soil hardness tester

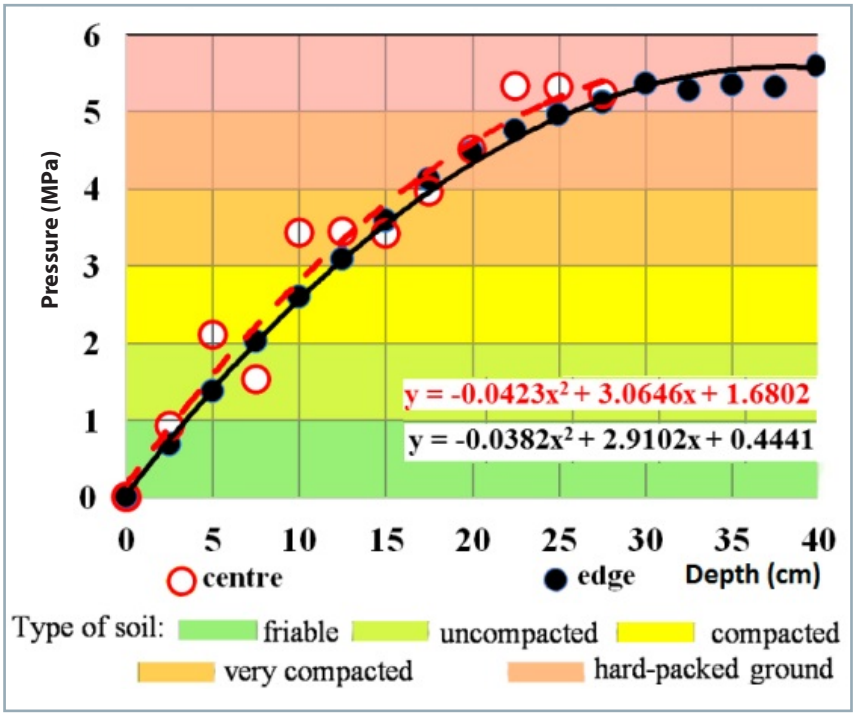


Fig. 5 Approximation of average experimental pressure values depending on plunger penetration depth

of root infections and cause plant chlorosis due to the production of exogenous soil ethylene.

Mirzavand and Moradi-Talebbeigi (2021) obtained data on how much effort should be applied to the roots of plants in order to overcome soil resistance. "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, and for small-seeded crops (carrots and onions for turnips) – no more than 0.5–0.7 MPa" (Mirzavand and Moradi-Talebbeigi, 2021). Dos Santos et al. (2021) noted that soil penetration resistance above 4 MPa causes significant damage to soil fertility due to over-consolidation and this problem cannot be ignored.

Thus, traditional reverse tillage does not provide the necessary looseness of the soil. This result is in good agreement with the results of other scientists on the influence of the tillage method on its density and productivity (Voltr et al., 2021; Hernández et al., 2019; Hu et al., 2021; de Moura et al., 2021).

Soil penetration resistance is a reliable indicator for deciding whether additional treatments are needed to reduce compaction. The determination of soil penetration resistance allows choosing the depth of mechanical processing and eliminating the risk of soil degradation. The best conditions in the pre-sowing period are in the soil with a soil penetration resistance of no more than 1–1.5 MPa, and for small-seed crops – no more than 1 MPa (Medvedev and Plysko, 2016). Furthermore, physical properties deteriorate with soil compaction and more intensive and deep mechanical processing is required to obtain a favourable physical condition and density.

Conclusion

As a result of the study, it was found that with constant traditional mouldboard cultivation, the soil at a depth of more than 10 cm is sufficiently compacted. At a depth of 15 cm, a strong compaction of the soil is observed, which indicates its physical and hydrological degradation. Soil compaction slows down root growth, promotes the lack of oxygen, and can lead to the spread of root disease pathogens.

The soil hardness tester made it possible to obtain the results of soil penetration resistance depending on the depth of the plunger. This is incontrovertible evidence of its superiority over the determination of soil structural properties using a ground-penetrating radar (Lombardi et al., 2022; Alaoui and Diserens, 2018) or visual soil assessment (Chamen et al., 2015; Guimarães et al., 2017).

The soil penetration resistance of the soil hardness tester plunger, depending on the depth of immersion, is an indicator of precision farming. The choice of technology for differentiated cultivation of agricultural crops and precise mechanical tillage is based on spatially distributed information of soil properties (Abbaspour-Gilandeh and Abbaspour-Gilandeh, 2019; Pentoś et al.; 2022). The soil hardness tester "DATAFIELD" makes it possible to obtain information about the state of the field on-line without taking soil samples, transporting them to the laboratory, and in-office analytical work. The study of soil compaction using a penetrometer is important not only for improving soil cultivation, but also for designing tillage machines and implements (Syromyatnikov et al., 2022).

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