Improving the efficiency of the soil uncompaction by the cultivator-subsoiler through the use of digital systems for working depth control

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Abstract. The article presents the results of scientific studies of the soil state formed under the influence of machine-tractor units in intensive technologies of potato production. It has been established that the main anthropogenic impact that reduces the yield of this crop is over compaction of the soil in the root spreading zone which prevents the spread of the potato root system. The studies used a rheological model of the soil state, statistical methods for assessing processes during the operation of tools for deep tillage and digital maps of fields. To loosen the soil, it is proposed to use a subsoiler cultivator equipped with a digital depth control system which ensures the implementation of differentiated processing that minimizes the energy consumption during tillage.

1. Introduction.

Lot of issues have found that one of the significant factors that reduce the yield of agricultural crops is soil over compaction, which occurs as a result of anthropogenic impact on it of tractors and farm machineries, which carry out multiple passes through the field during growing season. Traditional tillage methods with the using of ploughs perform the technological process of the plowing usually on a depth not exceeding the thickness of the arable layer. This leads to soil over compaction below depth of plowing [1-2] and to a violation of the soil condition required for the normal development of roots plants as well as worsens the water regime of the soil and, accordingly, the entire production process of the crop growing. Over compaction of the soil also leads to the occurrence of water and wind erosion [3-4]. A number of authors have established [1-5] that the critical value of soil density in the root spreading zone is 1.6 g/cm³. In [6] mentioned that to assess the soil state, it is proposed to use the indicator of its cone index, which has a high degree of mutual correlation with soil density. The limiting value of soil cone index for most crops is 4.5 MPa. The excess of the noted indicators of the soil state beyond the critical values makes it impossible for the normal development of the root system of many crops inside the soil. Studies carried out on potato have shown that if there is a sufficient volume of pores in the root layer and an optimal degree of soil compaction, the root system of these plants can reach to a depth of 120 cm [7-8].

Elimination of the consequences of the mentioned negative anthropogenic impacts on the soil is carried out with various tools for deep loosening, which require significant energy consumption during operation. For reducing these costs it is important to control the depth of the subsoilers with goal to sure loosening the over compacted soil horizon. It is possible due to adjust the depth of the cultivator-subsoiler based on the determination the actual position of the over compacted soil horizons in the root
spreading zone with high accuracy. This task is greatly simplified with using digital measuring systems. Promptly conducted monitoring of the soil state using such systems creates prerequisites for the differentiated tillage based on the using of automated adjustment and control devices based on the concept of smart agriculture [9].

2. Materials and methods.
Current study is based on a rheological model of the soil state formed by tillage machines and implements during the cultivation of potatoes using intensive technology [10] as well as statistical methods for assessing the conditions of functioning and quality indicators of the machines and tools used [11].

As noted earlier, chisel tools for deep tillage are widely used to eliminate soil compaction. In our research we used a subsoiler equipped with a hydraulic control system for the position of the implement relative to the field surface. This made it possible to carry out in the process of functioning of the cultivator-subsoiler differentiated tillage by the depth of the stroke of the chisel tines depending on the actual position of the over compacted horizon in the root spreading zone [12]. Such differentiated tillage allows minimizing the energy consumption spent on the formation of the soil condition required for the normal development of plants. For the high-quality implementation of the technological process of soil loosening taking into account the minimization of energy consumption it is necessary to control the height of the position of the over compacted horizons in the root spreading zone during the operation of the cultivator-subsoiler. Energy consumption was estimated using a digital flow meter built into the tractor fuel system.

The concept of smart agriculture implies the use of digital field maps showing various parameters of the soil state. The use of the soil cone index as an information parameter in monitoring the soil state can significantly increase the efficiency of obtaining the information necessary for building a digital map of the field according to the level of its compaction. The actual position of the over compacted horizon is determined in the offline mode by preliminary building a digital map of the field using penetroligers equipped with GPS signal receivers to fix the coordinates of the measurement points. When equipping the machine with a digital soil state measuring system the actual position of the compacted horizon in the soil is determined on the online mode.

3. Results.
On the figures 1 shows a digital map of the studied field in a potato crop rotation with an indication of the locations and heights of the over compacted soil horizons in the root spreading zone. This map was built on the basis of data obtained during field experimental studies on the experimental field of the university using the Top Soil Mapper digital measuring complex.

In our studies [13] for assessing the parameters of the soil state formed during potato growing season the degree of soil compaction is conventionally divided into four zones. Cone index values in the range of 0 – 1.0 MPa will correspond to the normal compaction zone, with values of 1.1 – 2.5 MPa - the medium compaction zone, in the 2.6 – 4.5 MPa range - the high compaction zone, and over 4.5 MPa – extra compacted zone.

The data shown in figure 1 show that the areas of over compacted zones with a value exceeding 4.5 MPa are in the range of heights from 28 to 32 cm. Along the field this process can be represented as a graph of changes in the height of the position of over compacted areas measured with a step of 1 meter shown in figure 2. These data were used in the device for adjusting and controlling the working depth of the cultivator-subsoiler.

To select the minimum control interval LK during the operation of the device which provides statistical reliability of information about the random process of the height of the location of the over compacted soil horizon h (l), based on the results of experimental studies, a graph of changes in the estimate of the standard deviation σh=f(N) was obtained, where N is the sample size (figure 3). It can be seen from the presented graph that at N = 30 the values of σh stabilize and with a further increase in the number of measurements it changes insignificantly. With the values of the discretization step of
the controlled process $\Delta l = 1 \text{ m}$, the control length calculated by the expression $L_K = N \cdot \Delta l$ will be 30 m. The obtained parameter $L_K$ is used to determine the average value of the height of the over compacted horizon. This value was used to adjust and control the depth $a$ of the cultivator-subsoiler.

![Figure 1. Field map indicating the depth of over compacted soil horizon.](image)

![Figure 2. Graph of changes in the height of the position of over compacted horizon along the length of the field.](image)

![Figure 3. The graph of the change in the estimate of the standard deviation $\sigma_h=f(N)$ to determine the length of the control $L_K$.](image)

The schematic drawing of the device for setting and controlling for the depth control of the cultivator-subsoiler is shown in figures 4. A cultivator-subsoiler 2 with a support roller 3 is mounted on the rear hitch of the tractor 1. Working depth is adjusted by changing position of the support roller. The position of this roller in height is controlled by a hydraulic cylinder 4. On the frame of the cultivator-subsoiler is installed a position sensor 5 of the implement relative to the field surface to obtain information about the actual working depth $a$ of the cultivator-subsoiler. Hydraulic cylinder 4 is controlled by electro-hydraulic valve 6, which is included in the tractor hydraulic system. Position sensors 5 and electrohydraulic valve 6 are connected to a process controller 7 equipped with a monitor and a keyboard for data entry. The same unit receives a signal from the GPS receiver 8 which records the coordinates of the tractor location and its current speed. A digital measuring system Top Soil
Mapper 9 is mounted on the front hitch of tractor 1 for measuring the height $h$ of the position of the over compacted horizon 10 in the root spreading zone in the online mode. The electrical output of the digital measuring complex is connected to the corresponding input of the technological controller 7. In addition, the technological controller 7 has a data exchange port for copying into device the digital maps of the field with information about the depth of over compacted soil horizon to work in offline mode as well as for transmitting information about the quality of performance technological process and volume of work performed.

The signal reflecting the position in height $h$ of the over compacted areas of the field as a control action enters the technological controller 7 of the device for setting and controlling the depth of the working bodies of the implement to promptly adjust the process of functioning of the cultivator-subsoiler in accordance with the actual soil state.

In the setting mode the device within the LK control interval determines an estimate of the average value of the height of the location of the over compacted horizon which is used to set the depth of cultivator-subsoiler. In control mode the device monitors the current height of the over compacted horizon compares it with the current working depth of the implement and in case of mismatch generates a signal that corrects the position of the cultivator-subsoiler in depth.

4. Discussion

When preparing the soil for planting potatoes to ensure favorable conditions for the development of the root system of plants an analysis of the soil condition was carried out using mobile digital measuring devices. Based on the results of these measurements a digital map of the soil state was obtained according to the parameter of soil cone index on which zones of increased compaction were marked with an indication of the height of their position in the root spreading zone. The critical values of the degree of soil compaction were determined as a result of ranking its cone index into four zones in which different penetrating ability of the potato root system in the soil is observed.

Analysis of the obtained digital map of the field showed that the position of the over compacted horizon along the length of the run has a random character and for guaranteed destruction with minimal energy consumption it is necessary to carry out tillage differentiated in depth. To obtain reliable information about the random process of the position along the height of the over compacted horizon the statistical characteristics obtained as a result of mathematical processing of experimental data were evaluated. In addition to ensure accurate adjustment of the cultivator-subsoiler to the depth which guarantees the destruction of the over compacted horizon the parameters of the length of the control interval at a given step were determined which were used during the operation of the automated device for setting and control working depth of the implement.
As a result of the research work a device was proposed for operational adjustment and control of the operation of the cultivator-subsoiler which allows with a given accuracy to provide the setting of the working depth implement and to carry out its operational correction depending on the real soil state. The modes of this device provides adopted for online operation when measuring the soil state with a mobile digital measuring complex such as Top Soil Mapper or offline when using a previously compiled digital map of the field with a designation of the height of the position of the over compacted horizon in the root spreading zone.

The use of this device made it possible to carry out depth-differentiated soil cultivation, which guarantees the destruction of over compaction zones inside the root spreading zone with minimal energy consumption. The assessment of energy consumption was carried out on the basis of comparative experimental studies of a cultivator-subsoiler operating with a setting and control device and without it. The use of the device made it possible to reduce fuel consumption by up to 10%.

5. Conclusion
The obtaining of digital maps of the soil state in terms of soil cone index and their analysis made it possible to get estimates of the statistical characteristics of the process of the position along the height of the over compacted horizon in the root spreading zone which were taken as a control parameter of the proposed device for setting and controlling the depth of the cultivator-subsoiler. To obtain estimates of this process used information obtained in the online mode from a digital measuring complex or from a digital map of the soil state for the operation of this device in the offline mode.

When forming a root spreading zone favorable for the development of the potato root system sensitive to increased compaction it is necessary to apply depth-differentiated tillage with a cultivator-subsoiler equipped with a device for depth setting and control which helps to reduce energy consumption for this technological process by up to 10%.

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