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Post-Harvest Siderates and Soil Hardness

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ABSTRACT
The results of researches of the perspective direction of solving the problem of growth of hardness of typical chernozem, which consisted in enrichment of the soil with fresh organic matter of postharvest greens, are presented. During the years of our research it was found that growing of post-harvest siderates contributed to a significant reduction in hardness of 0–30 cm soil layer. Among the studied siderates the lowest hardness of 0–30 cm soil layer was under crops of *Raphanus sativum* in all years of research – 10.9–16.8 kg/cm^2. In the variants of potato growing without fertilizers was found close reverse relation between hardness and productive moisture reserves – r = –0.74. These dependences confirm positive effect of siderate *Raphanus sativum* as a factor of biological loosening of soil. After all, it was just the variant where reduction of productive moisture reserves had the smallest share of impact – 22% on the growth of soil hardness. At the same time, this share of influence increased to 27–41% on the background of other siderates and manure, and up to 54% in the control without application of organic fertilizers. The highest yield of potato tubers was obtained on the plots with the lowest soil hardness, where *Raphanus sativum* was used as a post-harvest siderate, followed by the variants with manure, *Phacelia tanacetifolia* and *Fagopyrum esculentum*.

Keywords: typical chernozem, siderates, potato, *Raphanus sativum*, *Phacelia tanacetifolia, Fagopyrum esculentum,* litter manure.

INTRODUCTION

The hardness is rather objective indicator for determining necessary depth of tillage, selection of machinery and equipment for its implementation and assessment of soil loosening quality [Gorokhov, 1990; Slobodiuk, 1997; Semykin, 2002; Bussoher et al. 2000; Zahradnijek et al., 2001; Karbivska et al., 2020]. Kaczynski [1937] was the first to propose the use of this indicator in assessing soil as an object for cultivation. Reviakin [1956] recommended to use hardness for assessing quality of soil tillage and determining its actual depth.

The use of hardometer for assessing tillage quality, allows to record in detail field areas with different level of deformation, which is impossible to detect by other methods [Medvedev 2009]. This allows to prepare field for sowing in full accordance with real physical condition, taking into consideration requirements of plants to agrophysical parameters of soil environment. That is, using hardness as a criterion for assessing agrophysical condition and tillage quality, one can choose the best variant for soil loosening.

Soil hardness is the most reliable indicator for solving problems of destruction surface crust and the plow sole. In particular, there are successful examples of diagnosing soil crust strength with the help of hardness indicators [Carisson & Huss-Daneli, 2003; Lychuk, 2006; Demydas et al., 2021], for solving issues related to selection of equipment for its destruction.

Determination of hardness allows to more accurately establish the parameters the plow sole, the damage from which appears with hardness increasing above 35–40 kg/cm^2. Under such conditions, there is a restriction of root growth into the depth of soil profile. Hardness above 30 kg/cm^2 strongly inhibits and even stops root system growing of most crops. Plants even with the most active-penetrating root system (perennial grasses) are able to overcome resistance up to 45–50 kg/cm^2.

Soil hardness is an integral indicator of physical condition, which is functionally dependent on granulometric composition, structure, density and moisture of soil [Grunwald et al., 2001; Karbivska et al., 2022a]. Increase of soil hardness is a deterioration sign of physico-chemical and agrophysical properties. As a rule, soil compaction increases its hardness, and moistening and improvement of structural and aggregate composition – reduces.

Soil hardness is also directly related to composition of absorbed bases. The hardness is 10–15 times less in black soils saturated with calcium (with the same moistening interval). High-humus soils, saturated with divalent bases, are characterized by lower hardness than low-humus ones. High soil hardness in any layer has a number of negative consequences. First of all, it limits moisture movement and root spreading in the soil, and therefore generally limits root system growth of the crops and complicates their survival in dry years [Laboski et al., 1998; Shein, 2005; Karbivska et al., 2022b]. Also, it is difficult for seeds to germinate on soil with high hardness of its top layer, and the seedlings appear unfriendly with low density, which generally has negative impact on productivity of the sowing.

Optimal for initial development stages of most crops, researchers propose to consider soil hardness value in the range of 5–8 kg/cm^2 [Smagin, 1981; Kryvobochek & Velmyseva, 2005; Litvinov et al., 2020]. Further, with development of plants and their root systems, soil hardness of 20–25 kg/cm^2 is considered to be quite acceptable. At the same time, such increased soil hardness is unacceptable for root crops and vegetables, and its optimal parameters should not exceed 5–10 kg/cm^2 [Medvedev, 2009; Karpenko et al., 2020a]. The upper limit of soil hardness for potato growing, after which conditions of crop development deteriorate, is considered to be 5–6 kg/cm^2 [Bondareva, 1982; Litvinov et al., 2019; Karpenko et al., 2020b]. Thus, soil hardness is very important for the growth and development of crops and especially for their root systems. High soil hardness creates unfavorable conditions for plants as water, air and biological regimes are violated in soils characterized by significant hardness, and this ultimately has a negative impact on crop formation.

Optimization of soil hardness parameters is facilitated by its biological and mechanical loosening. It should be kept in mind that action of biological loosening is longer and largely depends on the type of organic fertilizer. The influence of biological loosening is not limited to surface 0–10 cm layer, it covers lower horizons. Intermediate crops, especially with taproots, are able to loosen the plow sole and compacted traces from passages of tractors and other machines, which reduces traction resistance of tillage machines and implements [Borchert, 1982; Korschens, 1983; Shaheb et al., 2021].

It is established that green manure crops improve soil quality, namely the accumulation of organic carbon and soil structure, increase microbiological activity, improve nutrient status [Sharifi et al., 2014; Yaroshchuk et al., 2020; Starovoitova et al., 2021; Yan Xu, 2021; Meraj et al., 2022; Sartori et al., 2022]. Sidereal crops in potato fields are used both as post-harvest and between rows. In the summer season, cover crops prevent the manifestation of water and wind erosion, regulate the temperature on the soil surface, retain moisture by 5–10% and increase the yield of tubers [Ustroyev & Murzaev, 2021; Chețan et al., 2021; Hryhoriv et al., 2021b]. It has been proven that greening and mulching with straw, in addition to the already mentioned effects, inhibits the development of weeds [Mishchenko et al., 2019; Nowroz, 2021; Lys et al., 2021]. Scientifically based crop rotation can provide soil moisture retention, reduce soil hardness and density, increase absorption capacity and other soil properties [Larkin et al., 2021; Mishchenko & Zakharchenko, 2019]. Improperly selected precursor can stimulate the reproduction of common pathogens and can affect the relative deficiency of nutrients [Vos & Van Loon, 1989; Kvitko et al., 2021).

In organic farming, sometimes too intensive tillage neutralizes the effect of green manure crops and the use of manure on their impact on the physical characteristics of the soil [Diego Sánchez de Cima et al., 2015; Danilchenko et al., 2018]. The effect of greens on reducing bulk density and increasing porosity has been proven by Lithuanian scientists [Kukresh & Bezsylko, 1990; Bakšienė et al., 2014; Hryhoriv et al., 2021a]. Therefore, we consider soil enrichment with fresh organic matter of post-harvest siderates to be a promising way of solving the problem of increasing the hardness of typical black soil.

MATERIAL AND METHODS

Effect of post-harvest siderates on typical black soil environment and their action effectiveness were studied under conditions of Left-Bank Forest-Steppe on experimental field of Sumy National Agrarian University during 2017–2021. The scheme of the experiment provided for growing potato variety Slovianka on the following backgrounds:

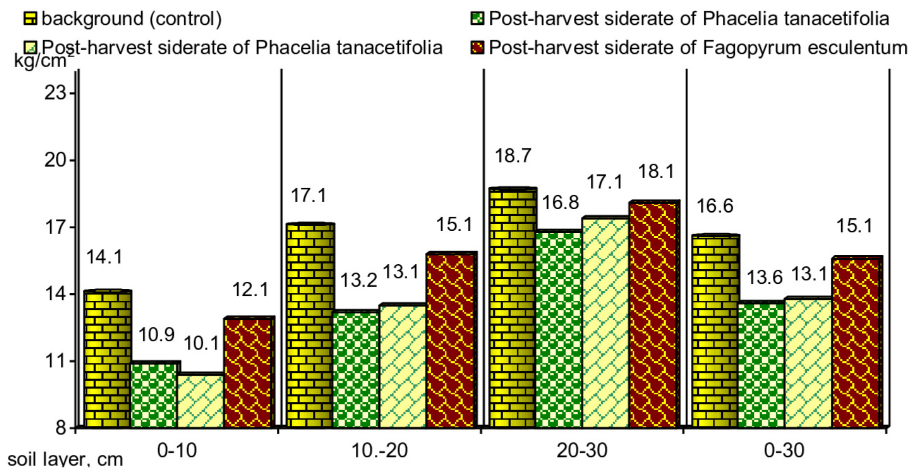
- post-harvest residues of winter wheat 4.6 t ha^{-1} – background (control);
- background + post-harvest siderate of *Raphanus sativum* 29.1 t ha^{-1};
- background + post-harvest siderate of *Phacelia tanacetifolia* 23.3 t ha^{-1};
- background + post-harvest siderate of *Fagopyrum esculentum* 4.6 t ha^{-1};
- background + litter manure 25 t ha^{-1}.

The area of accounting plot is 66 m^2. Placement of plots in the experiment is randomized. Repetition of the experiment – three times. Post-harvest siderates were sown in the first decade of August, and plowing of their mass – at the end of the third decade of October. The technology of potato growing was generally accepted for the Left-Bank Forest-Steppe zone of Ukraine. The study of siderate effect on the hardness of typical low-humus medium-loamy black soil was performed using penetrometer.

RESULTS AND DISCUSSION

During the years of our research it was found that growing of post-harvest siderates contributed to a significant reduction in hardness of 0–30 cm soil layer (Fig. 1). Among the studied siderates the lowest hardness of 0–30 cm soil layer was under crops of *Raphanus sativum* in all years of research – 10.9–16.8 kg/cm^2. Soil hardness under growing of *Phacelia tanacetifolia* (10.4–17.4 kg/cm^2). differed insignificantly compared to the previous variant. Comparing with *Raphanus sativum* variant, there observed a decrease in hardness in 0–10 cm soil layer by 0.5 kg/cm^2 and an increase in lower horizons by 0.3 and 0.6 kg/cm^2. This regularity is stipulated by fibrous type of *Phacelia tanacetifolia* root system with predominantly superficial distribution. Accordingly, in the variant of growing *Phacelia tanacetifolia* siderate was received the highest share of root mass influence on soil hardness change in the upper 0–10 cm layer of soil – 79.6% (Table 1).

In lower soil horizons, the share of root mass influence was higher by 17.5–27.6% when growing *Raphanus sativum*, which had taproot system capable to loosen deeper horizons. In general, the share of root mass influence on soil hardness change in 0–30 cm soil layer in both the variant



LSD05	0.67	1.09	0.29	0.64

Fig. 1. Soil hardness before plowing post-harvest siderates, kg/cm^2

Table 1. Influence share of post-harvest siderate root mass on soil hardness change, %

Soil horizon, cm	Post-harvest siderate		
	Raphanus sativum	*Phacelia tanacetifolia*	*Fagopyrum esculentum*
0–10	71.9	79.6	36.7
10–20	78.3	60.8	22.0
20–30	59.2	31.6	12.1
0–30	78.1	74.6	27.6

with *Raphanus sativum* and *Phacelia tanacetifolia* was quite high – 74.6v78.1%. Growing of *Fagopyrum esculentum* siderate provided 27.6% share of root mass influence on soil hardness. This is explained by the fact that in this variant biological loosening of soil was much weaker due to low root mass of *Fagopyrum esculentum* siderate. Accordingly, the hardness of soil horizons of root-containing 0–30 cm soil layer under crops of *Fagopyrum esculentum* siderate was significantly lower, by 0.7–2.6 kg/cm^2 compared to other variants of the studied siderates. Our correlation analysis showed that there was an inverse relation of middle strength between soil hardness change and root mass amount (Fig. 2).

The smallest value of correlation coefficient was observed in the variant of growing *Fagopyrum esculentum* ($r = -0.41$), and the largest – in the variant with *Raphanus sativum* ($r = -0.61$). Thus, registering hardness of soil horizons at the time of plowing post-harvest siderates showed that the decrease of this indicator is facilitated most of all by growing of *Raphanus sativum*.

Data from scientific sources indicate that the use of traditional organic fertilizers – manure, makes it possible to reduce rather high indices of soil hardness [Tanchyk et al., 2021; Tonkha et al., 2021; Rieznik et al., 2021]. However, influence of siderate crops on decrease of soil hardness is currently little studied. That is why, in further studies, we compared effectiveness of siderates and traditional fertilizers concerning provision of optimal soil hardness values for growing potatoes.

Hardness determination of soil horizons under potato crops showed that application of post-harvest siderates and manure significantly reduced this indicator compared to the control (Table 2). The lowest hardness indices of soil horizons when growing test crops were observed in the variant with of *Raphanus sativum* – 3.0–15.9 kg/cm^2. This variant had a significant advantage over application of *Fagopyrum esculentum* siderate, where, respectively, the highest soil hardness values among the studied variants of organic fertilization were observed – 4.4–17.4 kg/cm^2. Application of *Phacelia tanacetifolia*, compared to siderate of *Fagopyrum esculentum*, led to a slight increase of soil hardness, the absolute value of which was equal to the variant of applying 25 t ha^{-1} of manure – 4.1–15.8 kg/cm^2.

Analyzing average indices of soil hardness, it should be noted that they were the most optimal for potatoes in the variants with organic fertilizers. Thus, at the beginning of growing sugar beets and potatoes on the background of these fertilizers, soil hardness in the upper 0–10 cm layer did not exceed optimal limits and, accordingly, was 3.0–4.4 kg/cm^2 (Table 2). Close to optimal limit level of soil hardness in the layer of 10–20 cm for sugar beets were indices in the variants after *Raphanus sativum* siderate – 7.0 kg/cm^2 and 25 t ha^{-1} of manure – 7.9 kg/cm^2.

In other variants of potato growing, soil hardness values were higher than the optimal ones, but they became closer to optimal values after application of *Raphanus sativum* siderate. In general, analysis of averaged data showed soil hardness

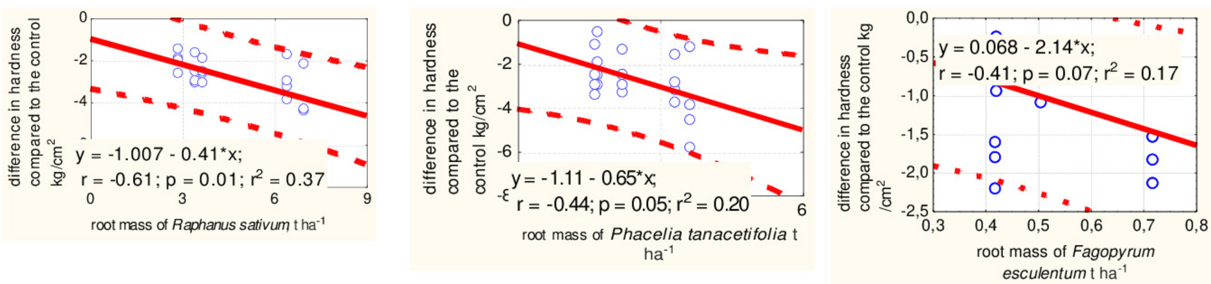


Fig. 2. Dependence of soil hardness changes on the root mass of the siderates

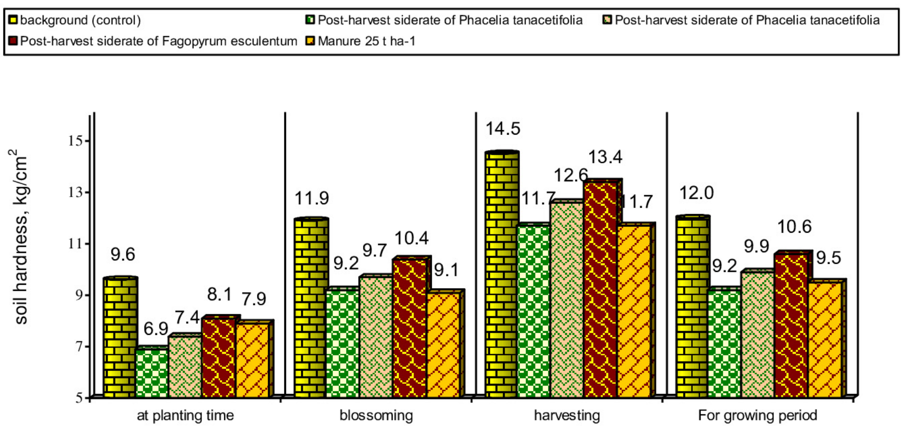
Table 2. Influence of fertilizers on hardness dynamics of soil horizons for potato growing, kg/cm^2

Variant	Soil horizon, cm								
	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
	at planting period			blossoming			harvesting		
Control (without siderate)	5.4	9.8	13.5	6.9	11.3	17.5	10.6	14.2	18.6
Post-harvest siderate of *Raphanus sativum*	3.0	7.0	10.6	4.2	8.6	14.7	7.6	11.5	15.9
Post-harvest siderate of *Phacelia tanacetifolia*	3.6	7.5	11.2	4.7	9.2	15.2	8.1	12.8	16.9
Post-harvest siderate of *Fagopyrum esculentum*	4.4	8.2	11.8	5.4	10.0	15.7	9.2	13.5	17.4
Manure 25 t ha^{-1}	4.1	7.9	11.6	4.4	8.3	14.5	7.7	11.5	15.8
LSD_{05}	0.9	1.1	1.1	0.7	0.7	0.9	1.7	0.8	0.8

increase both with increasing depth of accounting and the time of its implementation (Fig. 3). In particular, the hardness of arable 0–30 cm soil layer was increasing since planting potatoes till the middle of its vegetation by 1.2–2.3 kg/cm^2, and till the time of harvesting – by 2.5–3.0 kg/cm^2. At the same time, when growing potatoes on the background of *Raphanus sativum* siderate, the lowest soil hardness values were determined, only 0–30 cm of the soil layer – 6.9–11.7 kg/cm^2.

When growing potatoes, the hardness of 0–30 cm soil layer was within optimal limits only at the time of planting on the variant with *Raphanus sativum* siderate. Thus, among studied siderate crops, *Raphanus sativum* provided the most favorable parameters of soil hardness for growing potatoes. According to the results of correlation and regression analysis, we determined the influence of phytomass of siderate crops on soil hardness change when growing potato (Fig. 4).

Reverse dependences of strong relation – r = – 0.84–0.86 were found between the hardness of arable layer and siderate mass of *Raphanus sativum* and *Phacelia tanacetifolia*.



LSD_{05}	1.0	0.7	0.9	0.7

Fig. 3. Influence of fertilizers on the dynamics of hardness in 0–30 cm soil layer for potato growing, kg/cm^2

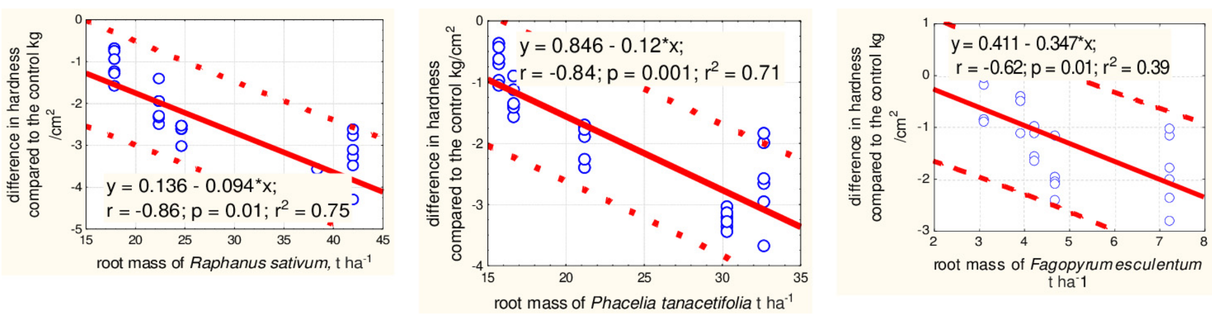


Fig. 4. Dependence of soil hardness on the phytomass of siderate crops

In the variant with *Fagopyrum esculentum,* reverse dependence was also found, but of medium strength (r = – 0.62). The share of phytomass influence on soil hardness change on the variants with siderates of *Fagopyrum esculentum* and *Phacelia tanacetifolia* was 71 and 75%, and when using *Fagopyrum esculentum* – 39%.

Analysis of regression dependence showed that increase by 1 ton of soil phytomass fertilizer in the soil provided a decrease in its hardness by 0.09–0.34 kg/cm^2 depending on the type of siderate. In addition to organic fertilizers, the hardness of soil is also significantly affected by its moisture, which we reflected through reserves of productive moisture. We found a reverse relation between soil hardness and the content of productive moisture of medium strength in the variants with application of siderates and manure, where correlation coefficient (r) ranged from –0.47 to – 0.64 (Fig. 5).

In the variants of potato growing without fertilizers was found close reverse relation between hardness and productive moisture reserves – r = –0.74. These dependences confirm positive effect of siderate *Raphanus sativum* as a factor of biological loosening of soil. After all, it was just the variant where reduction of productive moisture reserves had the smallest share of impact – 22% on the growth of soil hardness. At the same time, this share of influence increased to 27–41% on the background of other siderates and manure, and up to 54% in the control without application of organic fertilizers. The most positive effect of siderate crops *Raphanus sativum* and *Phacelia tanacetifolia* on decrease of typical black soil hardness was reflected in the formation of the highest potato yields (Table 3).

Depending on the selected green manure/cover crop, manure application, soil and climatic conditions, potato growing technology, scientists receive different data on the effect on potato yield. For example, in eastern Canada [Nyiraneza et al., 2021] on sod-podzolic sandy soils with the application of manure there was an increase in potato yield compared to the option without application by 22%, the best effect was given by millet, sorghum, Sudan grass compared to clover, ryegrass and other mixtures. Although some scientists emphasize that the share of weather conditions significantly exceeds the impact of cover crops, compatible crops, crop rotation [Romaneckas et al., 2022]. Moisture regulation has a greater effect on tuber formation than hardness control [Huntenburg, 2021; Yakupoglu et al., 2021]. Sidereal crops loosen the soil, reduce

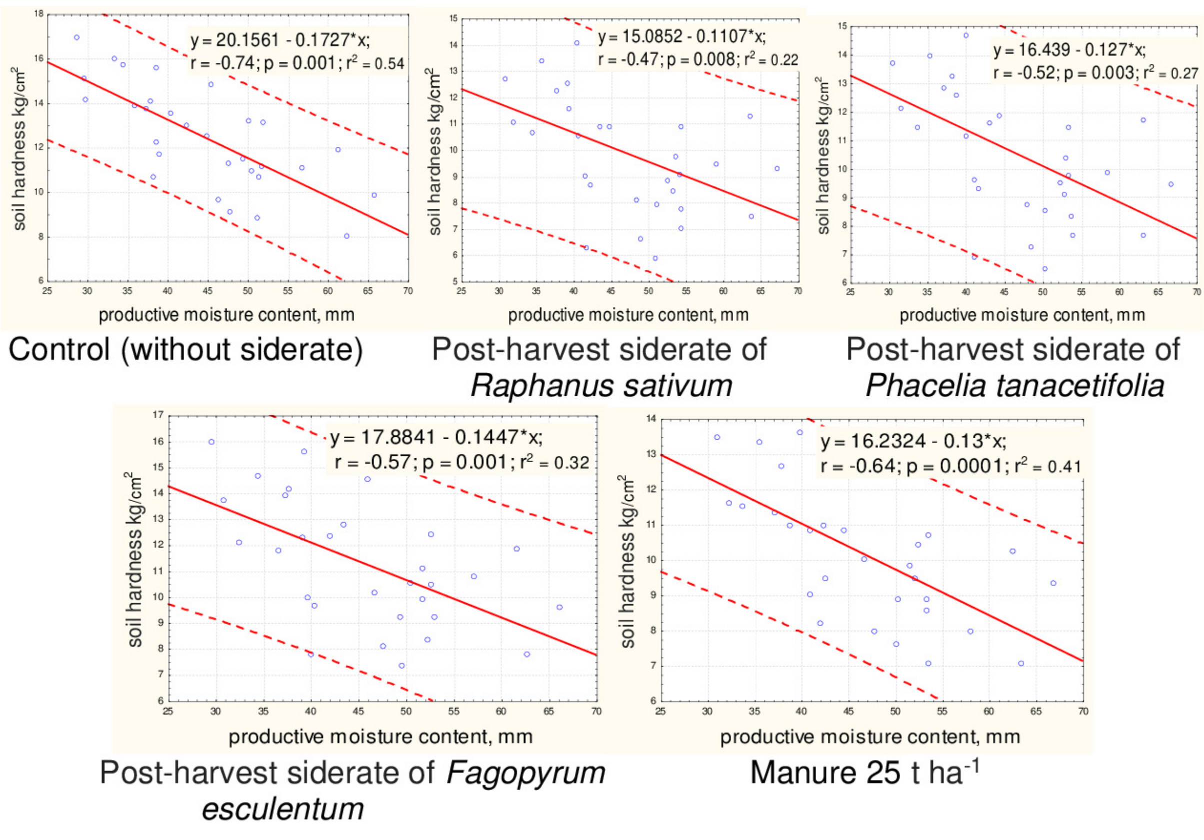


Fig. 5. Dependence of soil hardness on reserves of productive moisture on different fertilizer backgrounds

Table 3. Influence of organic fertilizers on potato yields, average for 2018–2021

Experiment variants	Yielding capacity		Yield increase, t ha^{-1}
	t ha^{-1}	%	
1. Control	24.7	100	-
2. Siderate of *Raphanus sativum*	30.8	125	6.1
3. Siderate of *Phacelia tanacetifolia*	28.7	116	4.0
4. Siderate of *Fagopyrum esculentum*	26.2	106	1.5
5. Manure 25 t ha^{-1}	30.1	122	5.4
LSD_{05}			1.4

its hardness, but tillage also has a significant impact. Root systems of plants, in particular, yellow mustard reduce soil hardness [Mischenko & Masik, 2017; Woźniak, 2019; Ustroev & Murzaev, 2020). Mixtures of green manure crops without mineral fertilizers and with the introduction of increasing the yield of potato tubers, you can use a double, triple mixture (eg, winter rye, vetch, white mustard), as well as make manure. For example, in the control without fertilizers and greens, the yield of potatoes was 16.03 t ha^{-1}, and when applying the binary mixture, the yield increased by 2.86 t ha^{-1} on chernozems leached heavy loam Ossetia [Mamiev et al., 2019].

CONCLUSION

Thus, application of sidereal crops contributed to long-term maintenance of low hardness of cultivated soil layer 0–30 cm, which accordingly improved agrophysical conditions of growing plants and, as a consequence, significantly increased the yield of potatoes.

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