ISSN 0304-5250

INDIAN JOURNAL OF ECOLOGY

Volume 48 Issue-3 June 2021

THE INDIAN ECOLOGICAL SOCIETY

The Indian Journal of Ecology is an official organ of the Indian Ecological Society and is published bimonthly in February, April, June, August, October and December. Research papers in all fields of ecology are accepted for publication from the members. The annual and life membership fee is Rs (INR) 800 and Rs 8000, respectively within India and US $ 100 and 350 for overseas. The annual subscription for institutions is Rs 6000 and US $ 300 within India and overseas, respectively. All payments should be in favour of the Indian Ecological Society payable at Ludhiana. See details at web site. The manuscript registration is Rs 500.

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Indian Journal of Ecology (2021) 48(3): 789-795

Manuscript Number: 3290
NAAS Rating: 5.79

Agromeliorative Efficiency of Phosphogypsum Application on Irrigation Saline Soils in the Northern Steppe of Ukraine

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Abstract: The present research represents the influence of chemical reclamation on the saline regime of the soil. Irrigation with limited water suitable for irrigation increased exchangeable sodium in the soil exchange complex to 5% and in the aqueous soil extract by 30%. Phosphogypsum was used as a chemical ameliorant in stock for three years under irrigation conditions and without it. It was applied at rates of 1.4, 3 (in spring) and 6 (in autumn) t/ha. The application of ameliorant in the spring a t the rates of 1.4 and 3 t ha^{-1} under irrigation caused to reducing the ratio of Na/Ca on average from 3 years to 2.53 and 1.51. It was sulfate type of salinity for all period of the time. Sodium exchange was decreased by application rates of phosphogypsum to 2.3% total amount of the exchangeable cations without irrigation (application of ameliorant in autumn) as compared to the control variant. Sodium exchange was decreased to 3.7% with a total amount of the exchangeable cations with irrigation (application of ameliorant in spring). In the first year after the second application of phosphogypsum there were the lowest rates of the density had the variants without irrigation. The density in this period was 1.17-1.2 g cm^{-3}, that was less on 0.04-0.96 g cm^{-3} as compared with the results the first year after first application.

Keywords: Saline composition of soil, Chemical reclamation, Irrigation, Phosphogypsum

It is necessary to use irrigation, for higher yields of crops in the Dnipropetrovsk region, Ukraine. The development and management of modern irrigated agriculture should increasingly be based on environmental orientation. The ecological direction is first of all preservation of soil, increasing fertility and maintain optimum physical and physicochemical properties (Dudiak et al 2019, 2020). The fertile soils of Ukraine are suffering from the different quality of water (Malovanyi 2020).The 23.3% area of irrigated lands of Ukraine (2170.5 thousand hectares) which is irrigated. More than 60% of the area of irrigated land is located in the Steppe zone, excluding the temporarily occupied territories, (1324.1 thousand hectares), of which 461.2 thousand hectares (34.8%) are irrigated (Pichura et al 2018). In particular, in the Dnipropetrovsk region the area of irrigated lands is 198.7 thousand hectares-(14.8%). With the beginning of the application of irrigation reclamation there were changes in the conditions of functioning of all components of the natural environment, in particular, the direction and speed of soil processes changed (Pichura et al 2017, Zelenskaya et al 2018). The results of these changes can have both a positive effect (improved moisture supply, increased productivity, etc.) and negative effect (flooding, salinization, waterlogging, etc.) (Dudiak et al 2019, Pichura et al 2019). Although deficit irrigation (DI) may have the potential to optimize crop yields in water limited environments, the success of such strategies may depend on the ability to manage variability in profile stored soil water during periods of drought. Understanding variability in stored soil water and crop rooting depth is an important component of successfully managing a deficit irrigation strategy. Traditionally, DI is applied at a fraction of the full irrigation (FI) requirement, but managed deficit irrigation (MDI) may optimize yield and irrigation by coordinating irrigation timing with the crop's reproductive stages through the management of soil water depletion and water stress (Bell et al 2020).

Understanding the impacts of desalination treatments on salt migration in saline soil during the farmland abandonment-reclamation process has significance for saline soil development and utilization. The research have shown that in arid climates there is a significant increase in the salt levels in the soil (Choudhary et al 2018, Shi et al 2021). The researches have shown that long-term irrigation with fresh and mineralized waters has a negative effect on the physical and chemical properties of soils (Morozov et al 2008, Baliuk 2012, Vargas et al 2018, Onopriienko et al 2019). It also caused to changes in the soil-forming process. The causes of secondary irrigation salinization vary with different quality of irrigation water (Baliuk 2012). The ameliorants influence physical and physicochemical properties of soils (Onopriienko et al 2019, Lozovitskyi 2010). The main objectives of research were impact of irrigation on the state of saline composition of soil and the effectiveness of chemical reclamation. It was determined the optimal calculated rates of phosphogypsum application during chemical reclamation.

MATERIAL AND METHODS

The study on agromeliorative efficiency of phosphogypsum application on irrigated saline soils was conducted in the Northern Steppe of Ukraine during five years (2014-2018 at Dnipropetrovsk Research Station of the Institute of Vegetable and Melon NAAS of Ukraine" (Oleksandrivka, Dnipropetrovsk region, Ukraine 48°31,656'N35°13,431'E - 48°31,665'N35°13,428'E, Fig. 1.)

The experiments were in randomized block design with four replications. The oil samples were taken in accordance with the "Instructions for soil and salt surveying on irrigated lands of Ukraine"; sampling to determine water quality was performed according to DSTU ISO 5667-6: 2015. The experiments included two factors: A-humidification conditions (irrigation was with hose-drum sprinklers Irtec; irrigated ration was from 1150 to 1700 m^3 ha^{-1}), and B-application of phosphogypsum. B1 - without the application of phosphogypsum without irrigation (control); B2 - without the application of phosphogypsum with irrigation (control); B3 - application of phosphogypsum under spring cultivation at the rate of 1.4 t/ha without irrigation; B4 - application of phosphogypsum under cultivation in the spring at the rate of 3 t ha^{-1} without irrigation; B5 - application of phosphogypsum in autumn under the main tillage rate of 6 t ha^{-1} without irrigation; B6 - application of phosphogypsum under spring cultivation at the rate of 1.4 t ha^{-1} with irrigation; B7 - application of phosphogypsum under cultivation in the spring at the rate of 3 t ha^{-1} with irrigation; B8 - application of phosphogypsum in autumn under the main tillage rate of 6 t ha^{-1} with irrigation). All application rates of phosphogypsum were for three years with one application in the first year). Application of phosphogypsum was done with and without irrigation. One of the established rate coincided with the recommended agronomic norm (6 t ha^{-1}) and 10.3 t ha^{-1} the ecologically safe rate of phosphogypsum. All of the established rate must be less than ecologically safe rate. The rates of 1.4 and 3 t ha^{-1} were applied for cultivation in spring, and 6 t ha^{-1} was applied in autumn for basic tillage.

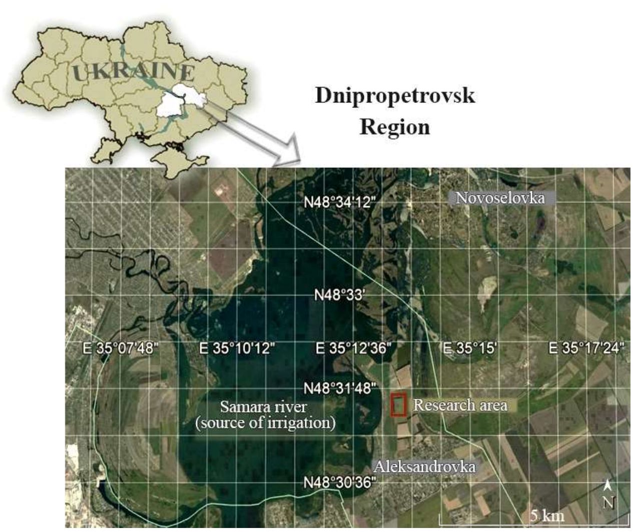


Fig. 1. The place of research

RESULTS AND DISCUSSION

According of soil grading of the experimental plot the soil layer 0-45 cm contains 71.02-74.0% of physical sand and 28.98-26.0% of physical clay, which corresponds to light loamy soil (Makarova et al 2020). The groundwater level is 4-5 m with mineralization up to 15 g l^{-1}. The amount of exchangeable Na is 3.64%; the absorption capacity of the soil exchange complex is 20.1-26.47 meq by 100 g of soil; the content of toxic salts varies up to 0.48%. In the wet state, the soil is viscous, sticky, strongly swollen, easily peptized. According to physicochemical characteristics, salinization processes are observed. There is 2.01–2.50% of humus in the arable layer (0–30 cm). The humus gradually decreases with the depth and it is equal to 0.3% at the depth of 90–105 cm. According to morphological features, the soil belongs to the chernozem of ordinary low-humus leached on the loam. Climatic conditions were characterized by large amplitude of daily and annual temperatures: the predominant amount of precipitation, which was rainy in nature, was recorded in the warm period, which significantly reduced their efficiency in growing crops. The hydrothermal coefficient varied from 0.95 (second year) to 3.52 (fourth year).

Irrigation was done with water from a reservoir on the Samara River with Irtec hose-drum sprinklers. During the research the crop rotation followed were: spring barley, winter wheat, winter wheat, corn for grain, winter wheat. Laboratory tests were conducted on the basis of the Dnipo State Agrarian and Economic University, Dnipropetrovsk branch of the state Institution of Soil Protection of Ukraine, LLC "Center for Radioecological Monitoring". The irrigation water quality belongs to the II class of quality Limitedly suitable (DSTU 2730-2015) according to the danger of its toxic effect on plants and the danger of soil salinization confirmed that water for all years of research. According to agronomic criteria, it was determined the chemical type of water as chloride-sulphate for all years of observation, magnesium-sodium (first, third years) and sodium-magnesium (second, fourth, fifth years). Prolonged irrigation with water of the second class quality Limitedly suitable led to the leaching of calcium carbonates from the arable layer of the soil, which negatively affected the properties of chernozem, namely: the formation of organic matter and its accumulation, maintaining soil stability, formation of favorable water, air, nutrient, thermal regimes and prevention of salinization processes (Figs. 2, 3).

It have been substantiated the conditions of chemical reclamation to improve the poor physical and chemical condition of irrigated saline chernozems. The sulfate type of salinity was observed according to the chemical composition of aqueous soil extract during the observation period, the experimental plots in all variants with phosphogypsum with irrigation and without irrigation, as well as on control during irrigation by anionic components (ratio, meq Cl/SO_4 and HCO_3/SO_4 less than 0.25). It was registered the soda-sulphate type of salinization in the control without ameliorant application and without irrigation in the first year and it was registered chloride-sulphate in the fifth year in the control with irrigation. In other years of research the sulphate type of salinization was noted. According to the cationic composition, the chemistry of soil salinization was determined taking into account the two cations present in larger quantities. In all samples was fixed sodium type of salinity, with the introduction of phosphogypsum. In the control without irrigation from the fourth year there was a change to the calcium-sodium type, there were processes of stop the salinization.

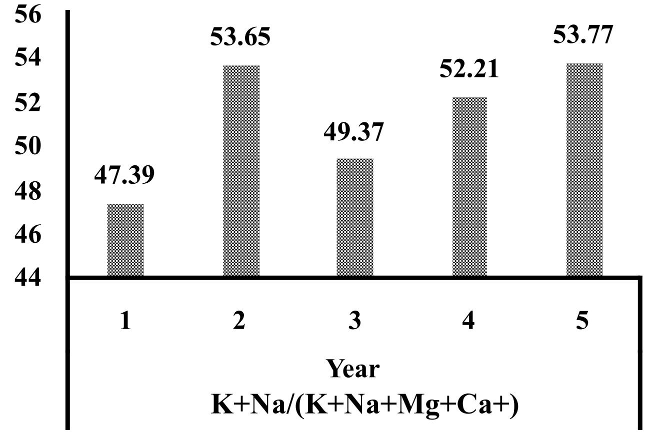


Fig. 3. The changes in irrigation water quality over the years of research

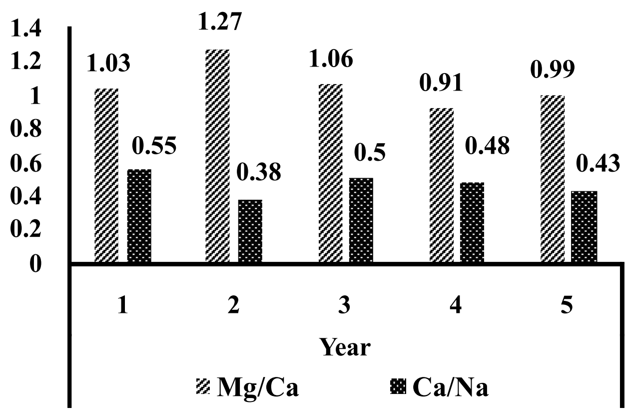
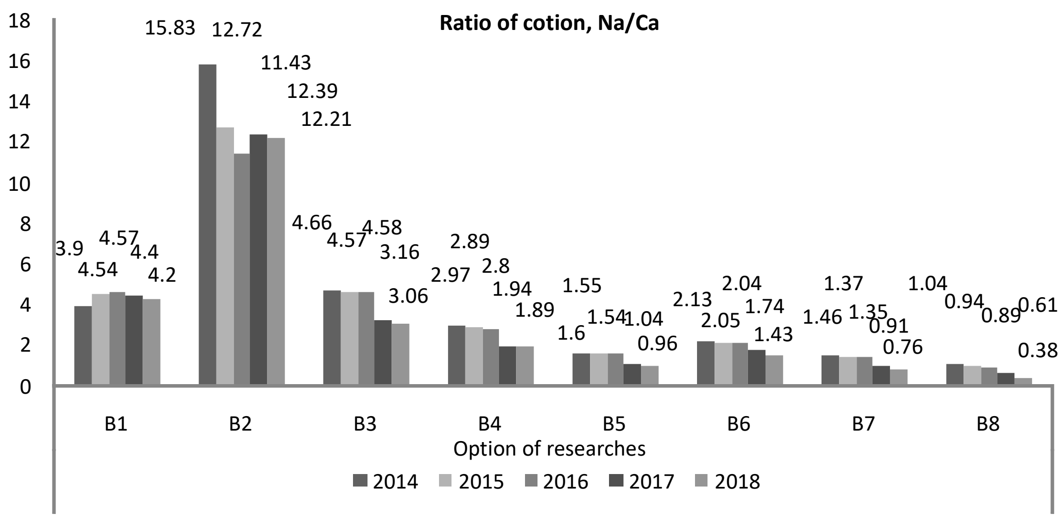


Fig. 2. The changes in the ratio of magnesium, calcium and sodium cations in irrigation water over the years of research

Earlier workers have shown that cationic composition is dominated by calcium and sodium ions. Their ratio was determined and it was established the chemistry of salinity (Fig. 4). The highest Na/Ca ratios were observed in the



B1 - without the application of phosphogypsum without irrigation (control); B2 - without the application of phosphogypsum with irrigation (control); B3 - application of phosphogypsum under spring cultivation at the rate of 1.4 t/ha without irrigation; B4 - application of phosphogypsum under cultivation in the spring at the rate of 3 t/ha without irrigation; B5 - application of phosphogypsum in autumn under the main tillage rate of 6 t/ha without irrigation; B6 - application of phosphogypsum under spring cultivation at the rate of 1.4 t/ha with irrigation; B7 - application of phosphogypsum under cultivation in the spring at the rate of 3 t/ha with irrigation; B8 - application of phosphogypsum in autumn under the main tillage rate of 6 t/ha with irrigation

Fig. 4. The ratio of Na/Ca by years of research in the options

control irrigated variant (15.83-11.43 meq/100 g of soil), which is explained by the influx of sodium ions together with irrigation water. There was a decrease in the ratio in the variants with the introduction of phosphogypsum for all years of observations, which indicates a decrease in the intensity of the salinization process. The best options in this case were 6, 7 and 8, here the average was by 2 times lower than the irrigated option. The application of ameliorant in the spring at the rates of 1.4 and 3 t ha^{-1} under irrigation reduced the ratio by an average of 3 years by 2.53 and 1.51, respectively. The application of 6 t ha^{-1} in autumn under irrigation was reduced by only 0.6 units compared to the non-irrigated option. That was, the amount of precipitation during the autumn-winter period dissolved and removed the resulting sodium sulfate during land reclamation with phosphogypsum less than the amount washed by irrigation for application in the spring.

The degree of salinity in the percentage of toxic salts was established for salinity (Fig. 4). According to the content of toxic salts, all variants (except B1) had a value of 0.3-0.6%, which corresponded to the sulfate (S) type of medium salinity. In B1 for the sulfate type, the values were in the range of 0.15 to 0.3%, which characterizes the slightly saline type (1, 3, 4, 5 years). The "total effect" of toxic ions in chlorine equivalents (mEq) almost always coincided with the degree of salinity, determined by the content of toxic salts (%). In the study, the exception was option B1, where in 4 and 5 years the values fell in the range of 0.3-1.0 it was medium salinity. Research of changes in the salt composition of the soil profile in the third year of the aftermath showed the largest accumulation of salts in the layer 0-15 cm: it was 4.22 meq/100 g of soil in the option with the introduction of phosphogypsum for spring cultivation at 3 t ha^{-1} with irrigation (B7). The option B5 increased the amount of salts by 0.19 meq/100 g of soil relative to the reclamation start data. In the option B7, the amount of salts per 0.022 meq/100 g of soil was higher compared to B5 to the layer 0-30 cm while for B7 layer 75-60cm (3.43 meq/100 g of soil). In the soil layer of 90-105 cm, the amount of salts was equalized to the initial conditions. In all options of the experiments, the concentration of Cl^{-1} and SO_4^{-2} ions decreased in profile, but still exceeded the toxicity limit of 0.3 and 2 meq/100 g of soil. During irrigation, the highest concentration of HCO_3^{-1} ions was observed in the layer of 15-30 cm (0.62 meq/100 g of soil).

The concentration of sodium before the experimenting in the layer 0-15 cm was 3.25 meq/100 g of soil. The application of ameliorant reduced the amount to 2.04 meq/100 g of soil, with irrigation to 2.25 meq/100 g of soil, which is explained by the flux of ions with irrigation water. According to the profile, Na^{+1} ions were pulled up at B7 to a layer of 60-75 cm (2.66 meq/100 g of soil), for B5 to a layer of 45-60 cm (2.03 meq/100 g of soil). In the lower horizons, the concentration gradually leveled off. With the application of phosphogypsum there was a major positive reclamation effect: an increase in Ca^{+2} ions throughout the profile. There were the largest amount in B5 layer 0-15 cm; it was 1.69 meq/100 g of soil. According to the profile during the reclamation for the third year of the aftermath the Ca^{+2} ions were concentrated in the layer 45- 60 cm and was 1.41-1.51 meq/100 g of soil, which overcomes the deficiency of this element in the soil profile. The present study has shown that irrigation with water of class II suitability on ordinary chernozem maintains with the signs of salinity: increased the share of sodium and magnesium exchange (Table 1) and decreased the percentage of calcium exchange. Although the chemical

Table 1. The change of cations exchange under the action of phosphogypsum in the arable layer of the soil

Option of research	First year of the aftereffect, the first application				Third year of the aftermath, the first application				First year of the aftermath, the second application			
	the amount of cations exchange, meq / 100 g of soil	% of the amount of cations exchange			the amount of cations exchange, meq / 100 g of soil	% of the amount of cations exchange			the amount of cations exchange, meq / 100 g of soil	% of the amount of cations exchange		
		Ca^{+2}	Mg^{+2}	Na^{+}		Ca^{+2}	Mg^{+2}	Na^{+}		Ca^{+2}	Mg^{+2}	Na^{+}
B1	28,76	71,28	24,69	4,03	28,34	70,29	25,41	4,24	28,53	70,10	25,38	4,25
B2	28,87	68,90	26,60	4,50	28,27	67,92	26,95	5,13	28,58	68,23	26,59	5,18
B3	29,43	75,77	21,58	2,65	26,79	74,65	22,77	2,58	29,29	77,84	20,48	1,67
B4	30,01	76,31	21,33	2,37	27,28	74,96	22,76	2,27	29,59	77,73	20,75	1,52
B5	30,63	76,40	21,48	2,12	27,88	75,44	22,67	2,08	30,37	78,04	20,71	1,25
B6	27,21	73,87	24,00	2,13	26,76	74,36	23,92	1,72	27,65	75,95	22,82	1,23
B7	28,27	75,70	22,76	1,54	27,88	75,32	23,32	1,36	29,70	77,04	21,91	1,05
B8	29,96	76,28	22,23	1,49	27,57	75,70	23,03	1,27	28,43	77,40	21,70	0,90

characteristics of the soil were not high enough, there were significant signs of salinization visually: the soil was unstructured, sticky, dense, low permeability.

The rapid salinization processes were observed in the control samples (the options 1, 2 of Table 1), especially in irrigated. Over 5 years of research, the amount of sodium exchange under irrigation increased from 4.5 to 5.18% of the amount of cations exchange. In the non-irrigated control, the average value of sodium exchange was 4.28% of the amount of cations exchange, which was 15% lower than this indicator under irrigation, but in this case there are processes of secondary salinization of soils. The ratio of calcium to magnesium exchange in the 2nd option was 2.53, and in the 1st it was 2.76, which indicates the displacement of calcium exchange by magnesium from the soil exchange complex. The amount of cations exchange in the control options did not change significantly and amounted to 28.3–28.87 meq/100 g of soil. With the application of phosphogypsum, the rate of exchangeable sodium decreased by 2.3% compared to the control by 2.3% of the amount of able cations exchange in the absence of irrigation (application of ameliorant in autumn) and by 3.7% of the amount of cations exchange (application of ameliorant in spring). This fact indicates a more significant effect of spring application of phosphogypsum during irrigation. There was tendency to a decrease in metabolic sodium of an increase in the rate of phosphogypsum application. In the options without irrigation, the lowest rates of exchangeable sodium were observed for the application of phosphogypsum in autumn under the main tillage rate of 6 t ha^{-1} and 2.12% of the amount of cations exchange in the first year afterglow and it was 2.08% of the sum of cations exchanging the third year aftertaste. After re-introduction of phosphogypsum in stock, the best indicators were again at the rate of 6 t ha^{-1} (1.25%) for the first year of the aftereffect. The value of sodium exchange decreased from 4.25 to 1.25%, but remained within a weak degree of salinization. As in the options without irrigation, watering was observed a tendency to decrease the sodium exchange with increasing rate of application of ameliorant.

In this case, the best option was the application phosphogypsum for spring cultivation at a rate of 3 t ha^{-1}. The value of exchangeable sodium was 1.49% of the sum of exchangeable cations after the first year of the aftereffect. In the third year of the aftereffect decreased to 1.27% of the amount of exchange cations. Re-application at the rate of 3 t ha^{-1} reduced the presence of exchangeable sodium in the soil absorption complex to 0.98% of the amount of exchangeable cations in the first year of the aftereffect. This indicates that salinization processes in the soil have slowed down. There was significant amount of exchangeable magnesium (25.44-21.65% of the sum of exchangeable cations) which provide negative visual characteristics of the soil (Table 1).Chemical reclamation with phosphogypsum also had a positive effect on the physical properties of the arable soil layer (Table 2).

The application of phosphogypsum affected of the soil density in the improvement direction (Table 2). Even with the application of phosphogypsum, there was a tendency to increase the density with irrigation comparatively to non-irrigated counterparts. Over the years, trend of increasing density in dry years was observed. The lowest densities were without irrigation in the first year of the aftereffect with repeated application of phosphogypsum. The f density in this period was 1.17-1.2g cm^{-3}, which is 0.04-0.96 g cm^{3} less compared to the aftereffect of the first year in the first application. With irrigation conditions, the effect of phosphogypsum as a chemical ameliorant on the density of soil formation during spring application was more significant compared to non-irrigated options. In the years of research, the same trend was observed without irrigation. It was the increase in density in dry years and it was the lowest rates in the first year of the aftermath of repeated application of phosphogypsum. The density was 1.18-1.21 g cm^{-3} at the first

Table 2. Change of physical indicators of soil according to soil layer (0-30 cm)

Option h	Density of soil structures (g/cm^3)			Soil porosity (%)			Soil permeability (mm min^{-1})		
	1st year	3rd year	4th year	1st year	3rd year	4th year	1st year	3rd year	4th year
B1	1,37	1,35	1,35	50,20	50,40	50,50	2,14	2,07	2,00
B2	1,36	1,40	1,39	47,28	47,20	47,10	1,10	1,14	1,10
B3	1,24	1,25	1,20	52,00	52,00	52,35	2,48	2,45	2,50
B4	1,22	1,23	1,19	52,41	52,14	52,76	2,50	2,50	2,58
B5	1,21	1,21	1,17	52,83	52,02	53,00	2,51	2,52	2,60
B6	1,27	1,28	1,23	49,45	49,40	49,51	1,70	1,60	1,81
B7	1,25	1,24	1,20	49,98	50,00	49,91	1,73	1,71	1,89
B8	1,22	1,26	1,18	50,00	50,10	50,20	1,79	1,77	1,90

year of the aftereffect with repeated application of ameliorant. The porosity of the soil changed from 50.0 to 50.8% without the application of phosphogypsum and without irrigation over the years of research (Table 2). With irrigation, the average porosity of the arable soil layer in the control was 47.14% and without irrigation 3.24% higher. This was due to the increased of soil density during irrigation. With irrigation, there was the tendency to decrease the porosity and without irrigation the values changed chaotically we didn't observe clear dynamics.

Chemical reclamation (application of phosphogypsum) significantly changed the porosity of the soil. They were improved in all option of the research compared to the control. The best option without irrigation (as in the research of density) was the option with the introduction of phosphogypsum in autumn under the main tillage rate of 6 t/ha. The best results of soil porosity were characterized without irrigation with repeated autumn application of phosphogypsum in the first year of the aftereffect. The porosity increased to 0.17-0.35% compared to the aftereffect of the first application of ameliorant. Irrigation didn't lead to a radical change in porosity. The same trend was observed as without irrigation in the years of research. The best value of porosity was recorded in the first year of the aftereffect with repeated spring application of phosphogypsum as a chemical ameliorant(49.51-50.2%).

The soil permeability was higher in the control without the application of phosphogypsum and without irrigation compared to the irrigation options in our data (Table 2). The application of phosphogypsum significantly increased the soil permeability in the all options of the experiment. It was an increase in the average values of research to 2.46-2.54 mm/min with the application of phosphogypsum without irrigation. The increase of the soil permeability was proportional to the increase in the rate of application of ameliorant. This proves the theory of increasing the soils permeability with irrigation by chemical reclamation with calcium-containing ameliorants due to coagulation of soil colloids by calcium cations. The highest indicators of soil water permeability were observed in without irrigation with repeated application of phosphogypsum in autumn in the first year of the aftereffect. The soil permeability increased to 0.02-0.1 mm/min compared to the aftereffect at the first application in the first year of the aftereffect with repeated application. With chemical reclamation and irrigation there was a decrease in the soil permeability compared with options without irrigation. The first year of the aftereffect was better with repeated application. It was 1.81-1.9 mm/min as in the options without irrigation. This fact confirms the formation of water-resistant aggregation and the reduction of mobility of silty particles with the introduction of calcium with phosphogypsum. This increases the water resistance of the soil, increases filtration. This helps to wash the salts out of the soil. Assessment of soil permeability showed that it has from satisfactorily acquired to the status of good due to the action of chemical reclamation (Kovda 1971).

Phosphogypsum increases the crop productivity and leads to an increase the root residues in the soil, due to which there is an increase in humus. This change indicates a slowdown in the dehumidification of common chernozems during irrigation. The best options for restoring the organic part compared to the control were with irrigation. With irrigation, the best options were the application of phosphogypsum for cultivation in the spring at a rate of 3 t ha^{-1} (increase in humus by 0.35%) and in the autumn under the main tillage at a rate of 6 t ha^{-1} (increase in humus by 0.39%). In present research without irrigation, compared with the control, the best option for the restoration of the organic part was where phosphogypsum was applied in the fall under the main tillage at a rate of 6 t ha^{-1} (increase in humus by 0.29%).

CONCLUSION

Analysis of the content of heavy metals in phosphogypsum proved the possibility of its use in compliance with environmentally safe norm. With irrigation the improvement of the ecological condition of saline soils was registered when applying ameliorant in the spring. Application of phosphogypsum at the rate of 3 t ha^{-1} increased the soil permeability by 0.66 mm/min. It reduced the amount of toxic salts to 0.41% in the third year. It reduced the amount of Na exchange to 1% of the amount of exchangeable cations. Without irrigation the application of spring didn't show positive changes. Without irrigation, the option with the application of phosphogypsum in the fall under the main employer of the soil at a rate of 6 t ha^{-1} was the best. It increased the soil permeability by 0.68 mm/min. It reduced the amount of toxic salts to 0.38% in the third year. It reduced of the amount of exchangeable Na for the third year aftereffect to 2.08% of the amount of exchangeable cations. It was increased the humus content by 0.29%.

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Received 15 March, 2021; Accepted 20 May, 2021