Changes in soil fertility and productivity of agricultural crops under the aftereffect of urban sewage sludge and zeolite

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Abstract. The current research deals with the influence of the aftereffect of zeolite-containing agro-ore, sewage sludge from the city of Penza and their combinations on the total carbon content, agronomically valuable water-resistant aggregates in the arable layer, the efficiency of moisture use by plants and the productivity of agricultural crops. It was determined that the highest effect on meadow-chernozemic low-humus medium-thick leached soil in this case was provided by the aftereffect of increased rates of precipitation of urban wastewater (160-180 t/ha) in combination with zeolite-containing agro-ore. The content of total carbon in the arable layer in these variants of the experiment in the agrocenosis of winter wheat (2020) was 3.109-3.121%, significantly exceeding the initial values by 0.157-0.169%. The number of agronomically valuable water-resistant aggregates in the arable layer under observed conditions was equal to 59.6-60.5% at the end of the research, exceeding the initial values by 21.0-22.0%. The water consumption coefficient in the oat agrocenosis was 544.7-547.2 m$^3$/t, in the pea agrocenosis 683.8-686.9 m$^3$/t, in the winter wheat agrocenosis 558.1-560.8 m$^3$/t, exceeded the control in 2018 by 162.2-164.7 m$^3$/t, in 2019 by 260.7-263.8 m$^3$/t, in 2020 by 141.7-144.4 m$^3$/t. The total productivity of Konkur oats, Jackpot peas, Moskovskaya 56 winter wheat variety under the aftereffect of urban wastewater precipitation at rates of 160 and 180 t/ha was 12.83-12.91 t/ha per unit, exceeding the control by 3.64-3.72 t/ha per unit, or 39.6-40.5%.

1. Introduction
The introduction into agriculture of technological methods for preventing anthropogenic degradation in agricultural landscapes is an urgent problem. Prevention of progressive degradation against under conditions with a low level of application of mineral and organic fertilizers is possible when using urban wastewater sediments as an alternative source of organic matter and plant nutrients. In terms of agrochemical value, sewage sludge is not inferior to manure. In this regard, municipal wastewater sludge could be used as an organo-mineral fertilizer for agricultural crops. At the same time, the problem of their disposal is being solved. A limiting factor in the use of sewage sludge as fertilizer is the content of heavy metals. In this regard, it is promising to use sewage sludge in combination with chemical ameliorants with a high sorption capacity.

2. Materials and methods
A field experiment to study the aftereffect of sewage sludge from the city of Penza and their combinations with zeolite-containing agro-ore on the fertility of meadow-chernozem soil and the productivity of agricultural crops in the forest-steppe Volga region was carried out according to the
following scheme: 1. Without Urban Sewage Sludge (USS) and zeolite-containing agro-ore (control); 2. Zeolite-containing agro-ore; 3. USS 100 t/ha; 4. USS 120 t/ha; 5. USS 140 t/ha; 6. USS 160 t/ha; 7. USS 180 t/ha; 8. USS 100 t/ha + zeolite-containing agricultural ore; 9. USS 120 t/ha + zeolite-containing agricultural ore; 10. USS 140 t/ha + zeolite-containing agricultural ore; 11. USS 160 t/ha + zeolite-containing agricultural ore; 12. USS 180 t/ha + zeolite-containing agricultural ore. The experiment was organized three times, the variants in the experiment were placed by the method of randomized repetitions. The experiment used sewage sludge from the city of Penza with the following composition: nitrogen - 291, phosphorus - 116 and potassium - 120 mg/100 g of precipitation; organic matter carbon - 21.2%. As a chemical ameliorant in the experiment, we used a zeolite-containing agro-ore from the Luninskoye field with a clinoptilolite content of 41%. In the experiments Konkur oats, Jackpot peas, and Moskovskaya 56 winter wheat variety were grown.

3. Results and discussions
In the control variant, the total carbon content in the arable layer of the meadow-chernozem soil was 2.970% before the experiment (2014), in the oat agrocenosis (2018) - 2.958%, in the pea (2019) and winter wheat agrocenoses (2020) - 2.952%. The decrease in relation to the initial value was 0.012 and 0.018%, respectively (Table 1).

| Variant | Pure steam, 2014 | Oats 2018 | Deviation from control | Oats 2019 | Deviation from control | Oats 2020 | Deviation from control | Peas 2018 | Deviation from control | Peas 2019 | Deviation from control | Peas 2020 | Deviation from control | Winter wheat 2018 | Deviation from control | Winter wheat 2019 | Deviation from control | Winter wheat 2020 | Deviation from control |
|---------|-----------------|----------|------------------------|----------|------------------------|----------|------------------------|----------|------------------------|----------|------------------------|----------|------------------------|---------------------|------------------------|---------------------|------------------------|---------------------|------------------------|
| 1. Without USS and zeolite-containing agro-ore (control) | 2.970 | 2.958 | -0.012 | 2.952 | -0.018 | 2.952 | -0.018 | 2.958 | 0.029 | 2.981 | 0.023 | 2.970 | 0.012 | 2.958 | 0.111 | 3.039 | 0.087 | 3.005 | 0.053 |
| 2. Zeolite-containing agro-ore | 2.958 | 2.987 | 0.029 | 2.981 | 0.023 | 2.970 | 0.012 | 2.952 | 3.063 | 0.111 | 3.039 | 0.087 | 3.005 | 0.053 | 2.958 | 3.103 | 0.145 | 3.086 | 0.128 | 3.051 | 0.093 |
| 3. USS 100 t/ha | 2.952 | 3.063 | 0.111 | 3.039 | 0.087 | 3.005 | 0.053 | 2.958 | 3.115 | 0.151 | 3.103 | 0.139 | 3.074 | 0.110 | 2.958 | 3.144 | 0.186 | 3.126 | 0.168 | 3.086 | 0.128 |
| 4. USS 120 t/ha | 2.958 | 3.103 | 0.145 | 3.092 | 0.134 | 3.051 | 0.093 | 2.958 | 3.161 | 0.203 | 3.144 | 0.186 | 3.097 | 0.139 | 2.958 | 3.132 | 0.174 | 3.115 | 0.157 | 3.074 | 0.116 |
| 5. USS 140 t/ha | 2.964 | 3.115 | 0.151 | 3.103 | 0.139 | 3.074 | 0.110 | 2.958 | 3.144 | 0.186 | 3.126 | 0.168 | 3.086 | 0.128 | 2.958 | 3.144 | 0.186 | 3.126 | 0.168 | 3.086 | 0.128 |
| 6. USS 160 t/ha | 2.958 | 3.144 | 0.186 | 3.126 | 0.168 | 3.086 | 0.128 | 2.958 | 3.161 | 0.203 | 3.144 | 0.186 | 3.097 | 0.139 | 2.958 | 3.132 | 0.174 | 3.115 | 0.157 | 3.074 | 0.116 |
| 7. USS 80 t/ha | 2.958 | 3.161 | 0.203 | 3.144 | 0.186 | 3.097 | 0.139 | 2.958 | 3.132 | 0.174 | 3.115 | 0.157 | 3.074 | 0.116 | 2.958 | 3.144 | 0.186 | 3.132 | 0.174 | 3.092 | 0.134 |
| 8. USS 100 t/ha + zeolite-containing agro-ore | 2.958 | 3.103 | 0.145 | 3.092 | 0.134 | 3.051 | 0.093 | 2.958 | 3.132 | 0.174 | 3.115 | 0.157 | 3.074 | 0.116 | 2.958 | 3.144 | 0.186 | 3.132 | 0.174 | 3.092 | 0.134 |
| 9. USS 120 t/ha + zeolite-containing agro-ore | 2.958 | 3.132 | 0.174 | 3.115 | 0.157 | 3.074 | 0.116 | 2.958 | 3.144 | 0.186 | 3.132 | 0.174 | 3.092 | 0.134 | 2.958 | 3.144 | 0.186 | 3.132 | 0.174 | 3.092 | 0.134 |
| 10. USS 140 t/ha + zeolite-containing agro-ore | 2.958 | 3.144 | 0.186 | 3.132 | 0.174 | 3.092 | 0.134 | 2.958 | 3.167 | 0.215 | 3.150 | 0.198 | 3.109 | 0.157 | 2.958 | 3.167 | 0.215 | 3.150 | 0.198 | 3.109 | 0.157 |
| 11. USS 160 t/ha + zeolite-containing agro-ore | 2.952 | 3.167 | 0.215 | 3.150 | 0.198 | 3.109 | 0.157 | 2.952 | 3.173 | 0.221 | 3.161 | 0.209 | 3.121 | 0.169 | 2.952 | 3.173 | 0.221 | 3.161 | 0.209 | 3.121 | 0.169 |

With the unilateral aftereffect of the zeolite-containing agro-ore, the total carbon content in 2018 exceeded the initial value by 0.029%, in 2019 by 0.023%, and in 2020 by 0.012%. The total carbon content in this variant was 2.987% during the harvesting of oats, 2.981% during the harvesting of peas, and 2.970% during the harvesting of winter wheat.

Under the one-sided aftereffect of urban wastewater sediments, the total carbon content in the arable layer varied in the oat agrocenosis from 3.063 (USS 100 t/ha) to 3.161% (USS 180 t/ha), in the
pea agrocenosis from 3.039 to 3.144%, in the winter agrocenosis wheat from 3.005 to 3.097%, exceeding the initial values in 2018 by 0.111-0.203%, in 2019 by 0.087-0.186%, in 2020 by 0.053-0.139%.

The combined aftereffect of urban wastewater sludge with zeolite-containing agro-ore increased the total carbon content in the arable layer relative to the initial one in 2018 by 0.145 (USS 100 t/ha + zeolite-containing agro-ore) - 0.221% (USS 180 t/ha + zeolite-containing agro-ore), in 2019 by 0.134-0.209%, in 2020 by 0.093-0.169%. The total carbon content against the background of the aftereffect of urban wastewater sediments in combination with zeolite-containing agro-ore varied in the oat agrocenosis from 3.103 to 3.173%, in the pea agrocenosis from 3.092 to 3.161%, and in the winter wheat agrocenosis from 3.051 to 3.121%.

Before setting up the experiment, the content of agronomically valuable water-resistant aggregates in the arable layer of meadow chernozem soil was 38.4-38.9%. The structural condition of the arable layer was characterized as unsatisfactory (Table 2).

**Table 2.** Content of water-resistant aggregates in the arable layer, %.

| Variant | Pure steam, 2014 | Oats 2018 | Deviation from control | Peas 2019 | Deviation from control | Winter wheat 2018 | Deviation from control |
|---------|-----------------|----------|------------------------|-----------|------------------------|-------------------|------------------------|
| 1. Without USS and zeolite-containing agro-ore (control) | 38.9 | 38.0 | -0.9 | 37.7 | -1.2 | 37.0 | -1.9 |
| 2. Zeolite-containing agro-ore | 38.5 | 43.2 | 4.7 | 43.1 | 4.6 | 42.3 | 3.8 |
| 3. USS 100 t/ha | 38.6 | 48.5 | 9.9 | 47.9 | 9.3 | 46.5 | 7.9 |
| 4. USS 120 t/ha | 38.4 | 50.7 | 12.3 | 50.4 | 12.0 | 49.3 | 10.9 |
| 5. USS 140 t/ha | 38.5 | 53.4 | 14.9 | 53.1 | 14.6 | 51.8 | 13.3 |
| 6. USS 160 t/ha | 38.8 | 56.0 | 17.2 | 55.8 | 17.0 | 55.7 | 16.9 |
| 7. USS 80 t/ha | 38.7 | 57.8 | 19.1 | 57.7 | 19.0 | 57.0 | 18.3 |
| 8. USS 100 t/ha + zeolite-containing agro-ore | 38.3 | 53.1 | 14.8 | 52.5 | 14.2 | 50.9 | 12.6 |
| 9. USS 120 t/ha + zeolite-containing agro-ore | 38.6 | 56.0 | 17.4 | 55.6 | 17.0 | 54.1 | 15.5 |
| 10. USS 140 t/ha + zeolite-containing agro-ore | 38.4 | 58.1 | 19.1 | 58.0 | 19.0 | 55.8 | 17.4 |
| 11. USS 160 t/ha + zeolite-containing agro-ore | 38.6 | 60.8 | 22.2 | 60.8 | 22.2 | 59.6 | 21.0 |
| 12. USS 180 t/ha + zeolite-containing agro-ore | 38.5 | 62.0 | 23.5 | 61.6 | 23.1 | 60.5 | 22.0 |
| LSD05 | 2.6 | 2.5 | 2.7 |

On the variant without the use of USS and zeolite-containing agro-ore, the amount of water-resistant aggregates in the arable layer remained unsatisfactory and was lower than the initial values by 0.9-1.9% and was 38.0% in the oat agrocenosis (2018), in the pea agrocenosis (2019) 37.7%, in winter wheat agrocenosis (2020) 37.0%.

The content of water-resistant aggregates in the arable layer against the background of the one-sided aftereffect of zeolite-containing agro-ore in 2018 was 43.2%, in 2019 - 43.1%, in 2020 - 42.3%, exceeding the initial values in the agrocenosis of oats by 4.7%, peas - by 4.6%, in winter wheat - by 3.8%. The structural condition of the arable layer was assessed as satisfactory.

Depending on the rate of precipitation of urban wastewater, against the background of their one-sided aftereffect, the number of water-resistant units varied in 2018 in the range from 58.5 to 57.8%, in 2019 - from 47.9 to 57.7%, in 2020 - from 46.5 to 57.0%. Deviations from the initial values in the oat agrocenosis were 9.9-19.1%, in the pea agrocenosis 9.3-19.0%, and in the winter wheat...
agrocenosis 7.9-18.3%. Upon completion of the research, the structural state of the arable layer against the background of the aftereffect of urban wastewater precipitation at rates from 100 to 140 t/ha was satisfactory, and against the background of 160 and 180 t/ha it was good.

| Variant | Oats | Peas | Winter wheat |
|---------|------|------|---------------|
| 1. Without USS and zeolite-containing agro-ore (control) | 709.4 | 947.6 | 702.5 |
| 2. Zeolite-containing agro-ore | 640.6 | 850.9 | 680.8 |
| 3. USS 100 t/ha | 629.3 | 814.5 | 662.0 |
| 4. USS 120 t/ha | 606.0 | 817.0 | 636.2 |
| 5. USS 140 t/ha | 596.1 | 781.9 | 618.6 |
| 6. USS 160 t/ha | 574.7 | 727.0 | 581.2 |
| 7. USS 80 t/ha | 578.9 | 729.6 | 577.4 |
| 8. USS 100 t/ha + zeolite-containing agro-ore | 592.4 | 786.0 | 642.1 |
| 9. USS 120 t/ha + zeolite-containing agro-ore | 572.8 | 746.6 | 618.4 |
| 10. USS 140 t/ha + zeolite-containing agro-ore | 554.1 | 748.1 | 595.9 |
| 11. USS 160 t/ha + zeolite-containing agro-ore | 544.7 | 686.9 | 560.8 |
| 12. USS 180 t/ha + zeolite-containing agro-ore | 547.2 | 683.8 | 558.1 |
| LSD_05 | 42.6 | 49.3 | 39.2 |

Under the combined aftereffect of urban wastewater precipitation with zeolite-containing agro-ore, the content of water-resistant aggregates in the oat agrocenosis varied in the range from 53.1 to 62.0%, in the pea agrocenosis from 52.5 to 61.6%, in the winter wheat agrocenosis from 50.9 to 60.5%, exceeding the initial values in 2018 by 14.8-23.5%, in 2019 by 14.2-23.1%, in 2020 by 12.6-22.0%. During the harvesting of winter wheat (2020), a satisfactory structural condition was noted in the variants with the aftereffect of urban wastewater precipitation at rates of 100 and 120 t/ha in combination with zeolite-containing agro-ore, good in the variants with the aftereffect of urban wastewater precipitation at rates of 140-180 t/ha in combination with zeolite-containing agricultural ore.

The one-sided aftereffect of zeolite-containing agro-ore, urban wastewater sludge and their combined aftereffect ensured a more rational use of moisture from the soil.

To create one ton of oat grain in the conditions of 2018, 709.4 m$^3$ of water was used for the control variant, one ton of pea grain in the conditions of 2019 was 947.6 m$^3$ of water, and one ton of grain of winter wheat in the conditions of 2020 was 702.5 m$^3$ of water.

Against the background of the one-sided aftereffect of the zeolite-containing agro-ore, the water consumption coefficient was 640.6 m$^3$/t in the oat agrocenosis, 850.9 m$^3$/t in the pea agrocenosis, 680.8 m$^3$/t in the winter wheat agrocenosis and was lower than the control in 2018 by 68.8 m$^3$/t, in 2019 by 96.7 m$^3$/t, in 2020 by 21.8 m$^3$/t (Table 3). The one-sided aftereffect of urban wastewater precipitation, depending on their norm, significantly reduced the water consumption coefficient in the oat agrocenosis by 80.1-134.7 m$^3$/t, in the pea agrocenosis by 130.6-220.6 m$^3$/t, in the winter wheat agrocenosis by 40.5-125.1 m$^3$/t.
The highest effect on the use of moisture by plants was recorded against the background of the aftereffect of urban wastewater precipitation in combination with zeolite-containing agro-ore. The water consumption coefficient in the oat agrocenosis in these variants of the experiment varied from 592.4 to 544.7 m$^3$/t, in the pea agrocenosis from 786.0 to 683.8 m$^3$/t, in the winter wheat agrocenosis from 642.1 to 558.1 m$^3$/t. The decrease in relation to the control option was significant and amounted to 117.0-164.7 m$^3$/t in 2018, 161.6-263.8 m$^3$/t in 2019, and 60.4-144.4 m$^3$/t in 2020.

**Table 4. Crop productivity.**

| Variant | Oats, t/ha per unit (2018) | Peas, t/ha per unit (2019) | Winter wheat, t/ha per unit (2020) | Total productivity, t/ha per unit | Deviation from control t/ha per unit | % |
|---------|-----------------|-----------------|-----------------|---------------------|-----------------|------|
| 1. Without USS and zeolite-containing agro-ore (control) | 2.21 | 2.27 | 4.71 | 9.19 | - | - |
| 2. Zeolite-containing agro-ore | 2.52 | 2.64 | 5.04 | 10.20 | 1.01 | 11.0 |
| 3. USS 100 t/ha | 2.50 | 2.66 | 5.05 | 10.21 | 1.02 | 11.1 |
| 4. USS 120 t/ha | 2.64 | 2.68 | 5.31 | 10.63 | 1.44 | 15.7 |
| 5. USS 140 t/ha | 2.70 | 2.82 | 5.49 | 11.01 | 1.82 | 19.8 |
| 6. USS 160 t/ha | 2.81 | 3.05 | 5.90 | 11.76 | 2.57 | 28.0 |
| 7. USS 80 t/ha | 2.81 | 3.06 | 5.97 | 11.84 | 2.65 | 28.8 |
| 8. USS 100 t/ha + zeolite-containing agro-ore | 2.82 | 2.87 | 5.39 | 11.08 | 1.89 | 20.6 |
| 9. USS 120 t/ha + zeolite-containing agro-ore | 2.94 | 3.05 | 5.64 | 11.63 | 2.44 | 26.6 |
| 10. USS 140 t/ha + zeolite-containing agro-ore | 3.06 | 3.07 | 5.87 | 12.00 | 2.81 | 30.6 |
| 11. USS 160 t/ha + zeolite-containing agro-ore | 3.17 | 3.38 | 6.28 | 12.83 | 3.64 | 39.6 |
| 12. USS 180 t/ha + zeolite-containing agro-ore | 3.18 | 3.40 | 6.33 | 12.91 | 3.72 | 40.5 |
| LSD$_{0.05}$ | 0.13 | 0.17 | 0.24 | | | |

The total productivity of oats, peas and winter wheat in the control variant was 9.19 t/ha per unit the one-sided aftereffect of the zeolite-containing agro-ore increased the total productivity of the studied crops by 1.01 t/ha per unit, or 11.0% (Table 4).

Under one-sided aftereffect of urban wastewater precipitation, the total productivity, depending on the sediment rate, varied in the range from 10.21 to 11.84 t/ha per unit, exceeding the control by 1.02-2.65 t/ha per unit, or by 11.1-28.8%. With the combined aftereffect of urban wastewater sediments with zeolite-containing rock, the total productivity varied from 11.08 to 12.91 t/ha per unit and was higher than the control by 1.89-3.72 t/ha per unit, or 20.6-40.5%.

4. Conclusions

The one-sided aftereffect of urban wastewater sediments and their joint aftereffect with zeolite-containing agro-ore had a positive effect on the content of total carbon, agronomically valuable water-resistant aggregates in meadow-chernozem soil, and contributed to a more rational use of moisture by plants. The highest effect was provided by the aftereffect of increased rates of precipitation of urban wastewater (160 and 180 t/ha) in combination with zeolite-containing agro-ore. The total carbon content against their background in the winter wheat agrocenosis (2020) exceeded the initial values by 0.157-0.169%, the number of water-resistant aggregates by 21.0-22.0%.

The water consumption coefficient was lower than the control in the oat agrocenosis by 162.2-164.7 m$^3$/t, in the pea agrocenosis by 260.7-263.8 m$^3$/t, in the winter wheat agrocenosis by 141.7-144.4 m$^3$/t. The total productivity of the studied crops from the aftereffect of increased precipitation rates of urban wastewater in combination with zeolite-containing agro-ore increased by 3.64-3.72 t/h per unit, or by 39.6-40.5%.
Acknowledgments
The current research was financed by RFBR, project number 20-316-90007

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