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Spatial Modelling of Agro-Ecological Condition of Soils in Steppe Zone of Ukraine

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Abstract: Soil degradation is the main problem of the decrease of their fertility. This problem in Ukraine occurs due to a number of problems. Active use of lands has led to the fact that about 93% of the territory of Ukraine is used by various economic activities. Plowing is the main problem between others which occupies over then 53% of the territory of the country, which is much higher than allowed in agricultural countries of the European Union, where the maximum use of land for growing crops is only 34%. Another important factor is the afforestation of Ukraine, the area under the forests and shelterbelts is currently only 17%, which means that there is an environmental imbalance, for example, this indicator in the European Union averages between 31-37%. The Southern steppe zone is considered to be the most plowed part of the country. Here the area of plowing is almost 90% of the territory. The problem of plowing is strengthened by non-professional use of land, which is expressed in excessive depletion due to improper crop rotations and lack of black fallow of the fields which leads to a decrease of the humus layer. The difference between the humus content in virgin chernozems and those which are under agricultural use is very significant. The virgin soils have in the fertile layer about 10% of humus, but in steppe soils this indicator is about 4%. Excessive land use, according to some scientists, also contributes to an increase in CO_2 in the air, as soils are a natural storehouse of carbon. As a consequence of this the expansion of the steppe zone in Ukraine is occurs. Therefore, modern situation in agricultural land use requires constant monitoring of the agro-ecological condition of soils to identify changes in their fertile qualities, which will allow timely decision making to take the necessary measures to ensure proper soil condition. And spatial modelling of agro-ecological properties is an instrument of GIS-technologies which helps to present all collected data in the form of maps, which simplifies the perception of information.

Keywords: Agro-ecological condition, Spatial modelling, Heterogeneity, GIS-technologies

Under the conditions of modern intensive agriculture, Ukraine, whose chernozem soils are considered to be the most fertile in the world, suffers from significant problems of soil condition, which is expressed in a decrease of their fertility due to reducing the humus content and nutrient imbalance (Boiko et al 2018). The task of the ecological monitoring is to control, assess, forecast and manage the state of the main indicators of soil fertility in order to obtain high and stable crop yields of good quality as well as to prevent pollution of the natural environment. In modern conditions, the agrochemical maintenance of arable lands provides a periodic receipt of monitoring data on the content of humus, nutrients and a limited range of trace elements. Spatial modelling will provide better understanding of the current state of agricultural lands (Zelenskaya et al 2018). One of the aims of soil monitoring is to develop the economy capable to solve the food security problems of countries to ensure the effective functioning of the domestic markets, fair competition among agricultural producers, confidence of consumer, rational land use and use of natural resources, creating conditions for preservation of soils and increasing of their fertility (Breus et al 2018). Spatial modelling is an integral part and the main stage of comprehensive monitoring of soils. Spatial modelling methods are based on stochastic and deterministic models, the use of which began in the 30s of 20th century by E.N. Gapon. The scientist proposed a thermodynamic model to describe cations exchange in soils, and also created a model to describe the heterogeneity of the distribution of soil properties (Domaratskiy et al 2018). Spatial modelling is a process of determining the spatio-temporal patterns of heterogeneity of changes in soil fertility to determine their suitability by agrochemical and ecological-toxicological properties for growing crops (Pichura et al 2021).

Fried proposed a classification of description models of the soils state by types. The first type of models is based on elements of fertility and is divided into information and management models. Information models is a set of knowledge about fertility and the ability to order them. Management models allows to make a decisions in economic activities based on the components of soil fertility to achieve the desired result (Dudiak et al 2020). Models of fertility management with minor soil disturbances has no significant changes in structural and functional characteristics, and if there are strong changes in soils - management is aimed at creating new models with better characteristics and their subsequent bringing to the established level of functioning. The main requirements for models are their ability to implement, as well as economic efficiency. The second type of models is dynamic, which are divided into long-term, describing long-term phenomena; medium-term - describe the agricultural season, year; short-term - associated with the characteristics of the stage of plant development in shorter periods. For this type of model, time is used as a variable indicator. The third type is related to the territorial boundaries of fertility models, this type is close to the traditional practice of soil science in the field of mapping and zoning. Among the models of this type there are global models, which are built for the entire land area or large countries, regional models, which include limited areas with similar characteristics of climate and relief. The fourth type of models is characterized by differences in the presentation of the model, namely, tabular form, mathematical formulas, graphical or computer software (Borisochkina et al 2019). In the 21st century, the information about the environment has increased significantly, which led to the introduction and development of geoinformation technologies for agri-environmental monitoring purposes. Geoinformation technologies, in our understanding, are a set of tools and methods of information processes for the rapid collection, processing and dissemination of geospatial information on the structure, area volume, condition and productivity of agricultural land, which will predict amount of agricultural production and market prices for agricultural products (Dudiak et al 2019). The use of soils for agricultural purposes leads to disruption of the natural course of humus formation, which affects the intensity and direction of humification processes. Lisetskii (2017) observed that steppe soils, including territory of the steppe part of Ukraine, were formed with an annual productivity of 11000 kg ha^{-1} of plant residues, due to which the annual formation of humus was about 2400 kg ha^{-1} and as the anthropogenic impact on steppe ecosystems increased, the role of this source of humus decreased by 25 per cent (Lisetskii et al 2017). The objective of study is to determine agro-ecological condition of soils in steppe zone of Ukraine, using cartographic and statistical models of spatial heterogeneity of nutrient distribution.

MATERIAL AND METHODS

One of the main prerequisites for rational land use is the spatio-temporal assessment of changes in soil fertility and determination of their quality by agrochemical and ecological-toxicological properties. These properties in the steppe zone soils were studied according to the generally accepted methods in the certified laboratories of the Kherson branch of the State Institution "Institute of Soil Protection of Ukraine" according to 296 stationary monitoring posts of agro-ecological studies of soil conditions in the layer 0-20 cm of the XI-th round of agrochemical certification of lands (Breus et al 2019). The main types of soils of the steppe zone of Ukraine (Fig. 1) are southern chernozem, which occupy 43.7% of the total area of agricultural land, and dark-brown soils (30.7%).

The study of spatial heterogeneity of soil fertility and the dynamics of its change was carried out by visualizing cartographic information and research results, which were carried out using software packages ArcGIS 10.1. This provided a qualitative interpretation of spatial and graphical information and modelling results. The spatial heterogeneity of the distribution of soil properties is marked by the non-stationary (atypical) nature of their distribution on agricultural lands, which is determined by the culture of agriculture and soil diversity.

RESULTS AND DISCUSSION

The soil cover is characterized by low-humus soils with humus content in the range of 0.30-3.85% (Fig. 2). The highest humus content (3.50-3.85%) was in soils of northern part of the Kherson region of Ukraine (Vysokopilsky and Novovorontsovsky districts). The lowest humus content (0.30-1.00%) in the soils of south-western part of the Kherson region of Ukraine (Oleshkivsky and Holoprystansky districts). The highest average weighted humus content of 3.04% was recorded in ordinary chernozems, which are located in the northern part of the region (Fig. 2a). The autocorrelation method was used to establish the maximum distance of distribution and preservation of the spatial energy of typicality of agroecological properties of soils. The minimum (r = 0.39) and maximum (r = 0.14) radius of typicality of humus ranged from 2.5 km (lag 1) to 12.5 km (lag 5). The insignificant relationship between spatial lags indicates significant variability in the distribution of humus within different types (subtypes) of soils. The functions of spatial distribution (Fig. 2b) and the provision of soils with humus (Fig. 2c) make it possible to determine its content in different spatially distributed climatic and economic conditions of the Kherson region.

Humus: The humus content on 72.5 % of the area corresponds to the medium (2.10-3.09 %) and increased 3.10-4.09 % qualitative gradations (Table 1).

Nitrogen*:* Graphical and statistical characteristics of the spatial heterogeneity of nitrogen distribution are presented on Figure 3. The autocorrelation analyzes of the spatial heterogeneity of nitrogen formation, were minimum (r = 0.095) and maximum (r = 0.044) radius of typicality of nitrogen formation conditions, which is from 2.5 km to 5.0 km.

The highest nitrogen content (38.2-41.3 mg ha^{-1}) detected in soils of Bilozersky and Henichesky districts and lowest content (3.4-10.0 mg kg^{-1}) in the soils of Oleshkivsky district. The nitrogen content in soils, which corresponds to qualitative gradations from medium to increased content (>21.0 mg kg^{-1}), characterizes 47.4% of the researched area of agricultural lands (Table 2). The largest share of agricultural lands with medium-increased nitrogen content with nitrification capacity was observed in the central and eastern parts of the region.

Phosphorus*:* The autocorrelation analyzes of the spatial heterogeneity of mobile phosphorus formation, were the minimum (r = 0.340) and maximum (r = 0.180) with radius 2.5 to 12.5 km. The highest phosphorus (>60 mg kg^{-1}) detected in soils of Velykooleksandrivsky and Belozersky districts and lowest (<16.0 mg kg^{-1}) in soils of Verkhnorogachytsky and Novotroitsky districts (Fig. 4). The phosphorus content in soils corresponds to qualitative gradations from high to very high (>31.0 mg kg^{-1}) characterizes 87.3% of the studied area (Table 3). The predominant part of the region (56.2%) with high and very high content of phosphorus located near the buffer zones of irrigated lands.

Table 1. Distribution of humus content in soils of agricultural lands of the region

Humus content (%)		Total	
		Thous. ha	%
Very low	<1.10	112.0	6.3
Low	1.10 - 2.09	376.9	21.2
Medium	2.10 - 3.09	1066.6	60.0
Increased	3.10 - 4.09	222.2	12.5
Total		1777.6	100

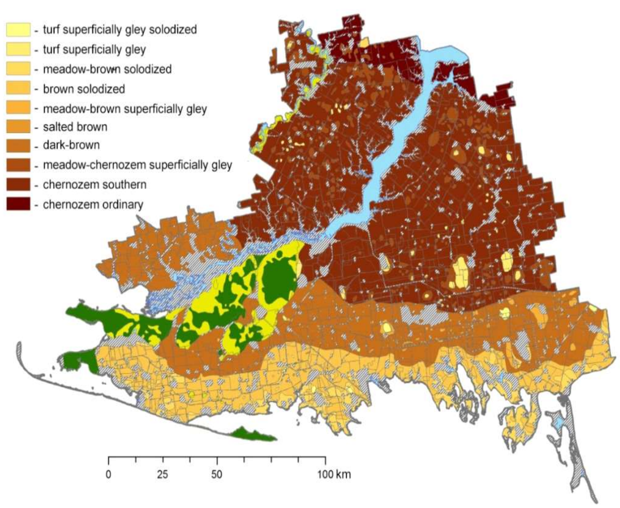
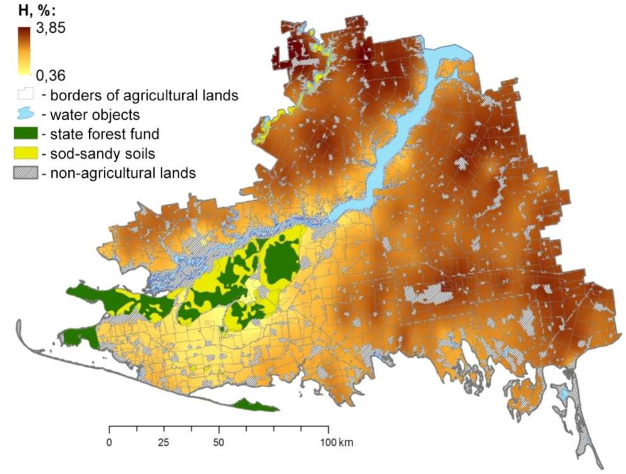


Fig. 1. Cartogram of soil types of steppe zone of Ukraine

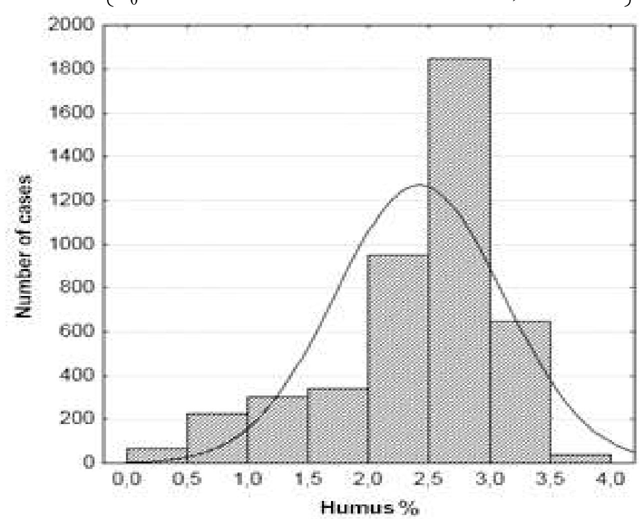


a

F(h) = 25.14.x – 11.98.y+0.07.x^2 – 0.63.x.y+0.36.y^2-168.97; R=0.58
where, x – longitude, decimal degrees*, y* – latitude, decimal degrees

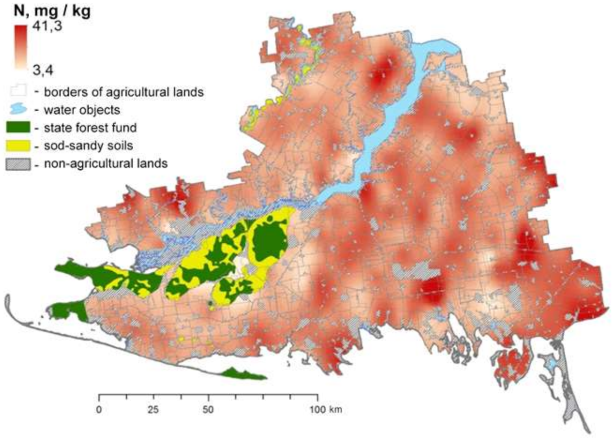
b

$$f(h) = \left\{ \begin{array}{c} \int_0^{60} -0.2447\ .Ln(x) + 3.61 \\ \int_0^{60} -0.0013\ .x^2 + 0.1581\ .x - 2.39\,; r = 0.98 \end{array} \right\}$$



The total number of cases	296
Average value	2.40
Confidence average interval	0.02
Median	2.60
Mode	2.92
Min	0.29
Max	3.83
Percentile 10,0	1.25
Percentile 90,0	3.10
Level of variation, %	26.65
Dispersion	25.54
Standard deviation	0.48
Standard error of the mean	0.69
Asymmetry	0.01
Kurtosis	–1.08

Fig. 2. Statistical-cartographic characteristics of humus distribution in the layer of 0...20 cm in soils of the region: *a* - cartogram of distribution; *b* - the function of spatial distribution; *c* - the function of providing soils with humus; *d* - statistical characteristics



a

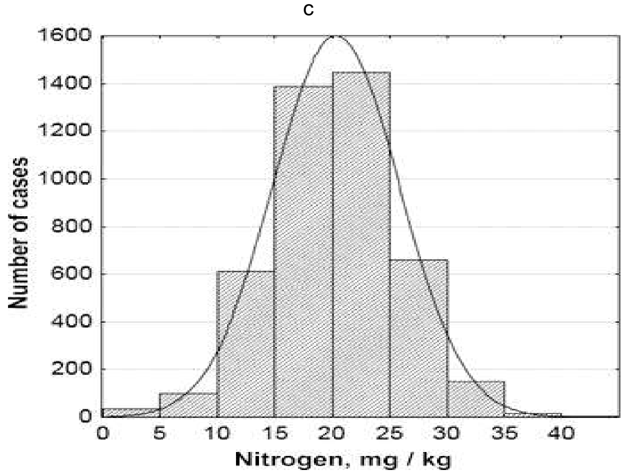
$f(NO_3) = 155.52.x – 149.83.y+1.07.x^2 – 4.83.x.y+0.13.y^2-612.06; R=0.58$

where, x – longitude, decimal degrees*, y* – latitude, decimal degrees

B

$f(NO_3) = 298.6.sin*0.0219x+1.8888+306.2.sin (0.0319x+4.588)+74.66.sin (0.04581x+7.087; r=0.988)$

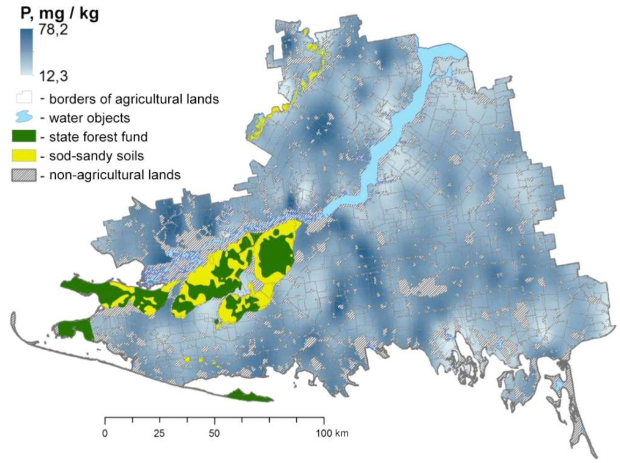
c



d

The total number of cases	296
Average value	20.25
Confience average interval	0.16
Median	20.2
Mode	-
Min	3.53
Max	41.1
Percentile 10,0	13.61
Percentile 90,0	26.94
Level of variation, %	27.01
Dispersion	29.96
Standard deviation	5.47
Standard error of the mean	0.08
Asymmetry	0.03
Kurtosis	0.44

Fig. 3. Statistical-cartographic characteristics of nitrogen distribution in the layer of 0...20 cm in soils of the region: *a*-cartogram of distribution; *b*-the function of spatial distribution; *c* - the function of providing soils with humus; *d* - statistical characteristics



a

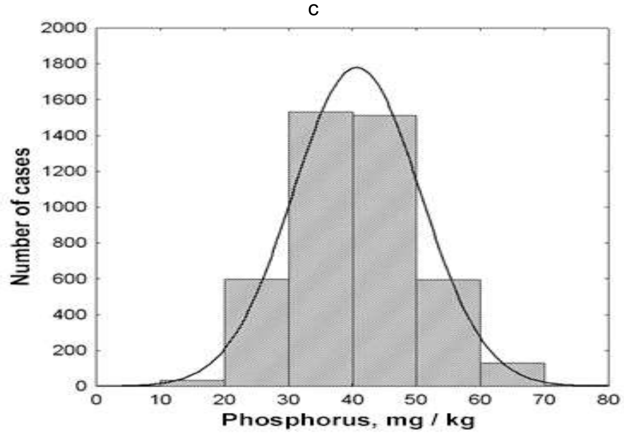
$f(P_2O_5) = 281.4.x + 1103.71.y – 1.92.x^2 – 5.43.x.y – 9.90.y^2 - 31949.82; R=0.38$

where, x – longitude, decimal degrees*, y* – latitude, decimal degrees

B

$f(P_2O_5) = 281.4.sin (0.006052x+2.682) + 60.87.sin (0.03122x+4.653)+7.576. sing (0.06488x+6.113); r = 0.996$

c



d

The total number of cases	296
Average value	40.55
Confidence average interval	0.57
Median	40.21
Mode	-
Min	13.25
Max	77.82
Percentile 10,0	27.71
Percentile 90,0	52.93
Level of variation %	24.02
Dispersion	94.79
Standard deviation	9.74
Standard error of the mean	0.15
Asymmetry	0.25
Kurtosis	0.07

Fig. 4. Statistical-cartographic characteristics of phosphorus distribution in the layer of 0...20 cm in soils of the region: *a* - cartogram of distribution; *b* - the function of spatial distribution; *c* - the function of providing soils with humus; *d* - statistical characteristics

Potassium: Soils that are characterized by a sufficient level of calcium can by limited in the sorption of potassium that increases its content in the soil solution, high concentrations of other cations, especially Ca^{2+} and Mg^{2+}, prevent the adsorption of potassium by plants, due to competition on the surface of the roots. Thus, grown on carbonate soils, crops have a potassium deficiency even if soils are sufficiently available with potassium. The autocorrelation analyzes of the spatial heterogeneity of the formation of exchangeable potassium, were the minimum (r = 0.413) and maximum (r = 0.170) with radius 2.5 to 12.5 km (Fig. 5). The content of exchangeable potassium in soils (Table 4), which corresponds to qualitative gradations from medium to very high content (>200 mg kg^{-1}), characterizes 85.8% of the area. The highest content of exchangeable potassium (> 600mg kg^{-1}) detected in soils of Vysokopilsky and Henichesky districts and lowest (<200 mg kg^{-1}) is typical for soils of Oleshkivsky and Hornostaivsky.

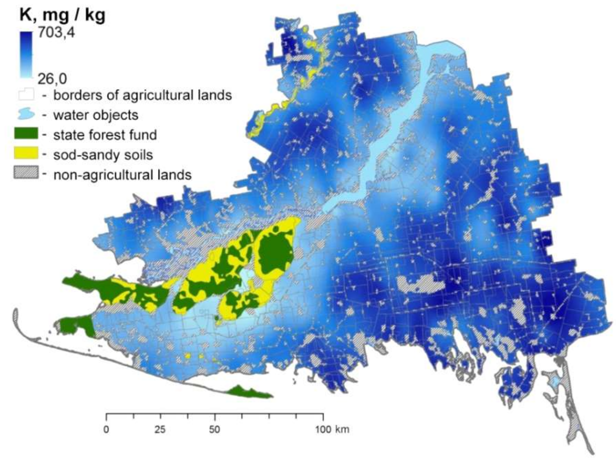
Soil acidity (pH): Assimilation of trace elements strongly depends on soil acidity. Best adsorption of these elements will be on slightly acidic soil or neutral soils (pH 5.5 to 7.0). The indicator of acidity or alkalinity of soils has a significant impact on the development of roots and plant nutrition through the absorption of nutrients. The reaction of the soil (pH) is a sign on which the agrochemical properties of soils and plant growth largely depend. Soil acidity is a property of soils due to the presence of hydrogen (H^+) ions in the soil

Table 2. Distribution of nitrogen content in soils of agricultural lands of the region

Nitrogen content (mg kg^{-1})		Total	
		Thous. ha	%
Very low	<10.0	56.9	3.2
Low	11.0 - 20.0	876.4	49.3
Medium	21.0 - 30.0	794.6	44.7
Increased	31.0 - 45.0	48.0	2.7
Total		1777.6	100

Table 3. Distribution of phosphorus content in soils of agricultural lands of the region

Phosphorus content (mg kg^{-1})		Total	
		Thous. ha	%
Medium	16.0 – 30.0	225.8	12.7
Increased	31.0 – 45.0	959.9	54.0
High	46.0 – 60.0	540.4	30.4
Very high	>60.0	51.6	2.9
Total		1777.6	100.0



a

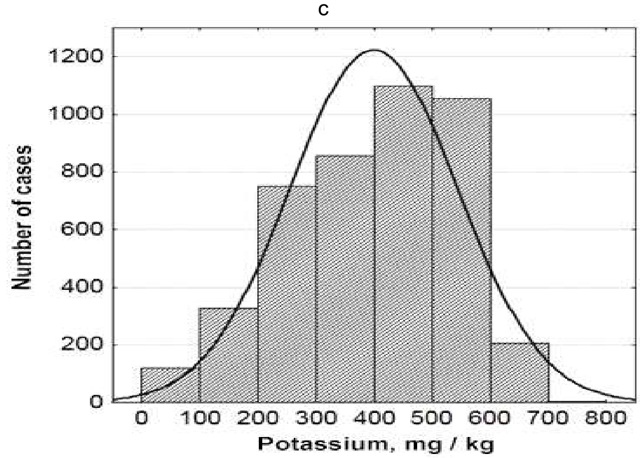
$f(K_2O) = 9628.88.x - 3150.26.y + 11.05.x^2 - 220.27.x.y + 112.49.y^2 - 88216.68;\ R=0.46$

where, x – longitude, decimal degrees, *y* – latitude, decimal degrees

b

$$f(h) = \left\{ \begin{array}{c} \int_0^{30} -42.95 \,.\, Ln(x) + 660.28 \\ \hline \int_{30}^{100} -0.0504 \,.x^2 + 1.0186 \,.x - 495.29;\ r = 0.98 \end{array} \right\}$$

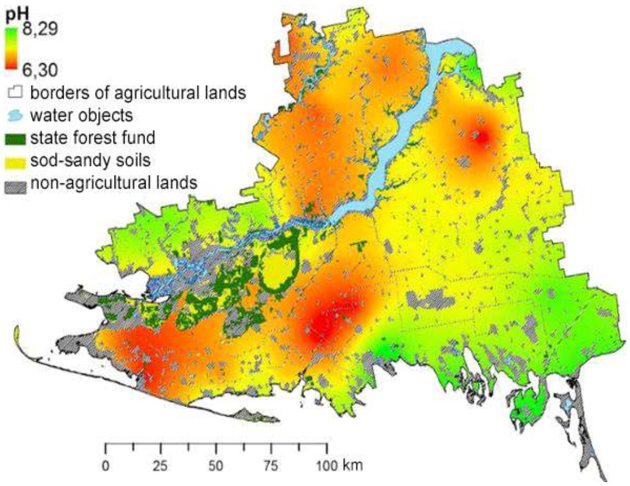
c



d

The total number of cases	296
Average value	396.78
Confidence average interval	4.24
Median	414.94
Mode	–
Min	23
Max	703.1
Percentile 10,0	199.63
Percentile 90,0	572.48
Level of variation, %	36.23
Dispersion	20669,97
Standard deviation	143.77
Standard error of the mean	2.16
Asymmetry	–0.37
Kurtosis	–0.64

Fig. 5. Statistical-cartographic characteristics of potassium distribution in the layer of 0...20 cm in soils of the region: *a* - cartogram of distribution; *b* - the function of spatial distribution; *c* - the function of providing soils with humus; *d* - statistical characteristics



a

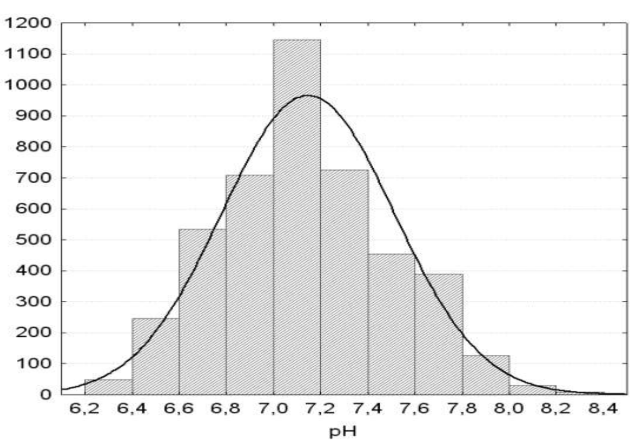
f(pH) = 13.09.x + 2.71.y + 0.19.x2 – 0.55.x.y+0.17.y2 – 274.74; R = 0.66

where, x – longitude, decimal degrees, *y* – latitude, decimal degrees

B

*f(pH) = 44.2 . sin (0.02298.x+0.7929) + 37.11 . sin (0.02589.x+3.815) + 0.3988*sin (0.06104.x+5.379); r = 0.0993*

c



d

The total number of cases	296
Average value	7.14
Confidence average interval	0.01
Median	7.13
Mode	7.69
Min	6.24
Max	8.52
Percentile 10,0	6.65
Percentile 90,0	7.65
Level of variation, %	5.1
Dispersion	0.13
Standard deviation	0.36
Standard error of the mean	0.005
Asymmetry	0.2
Kurtosis	–0.26

Fig. 6. Statistical-cartographic characteristics of soil distribution in the region (layers 0 ... 20 cm) by acidity (pH): *a* - cartogram of distribution; *b* - the function of spatial distribution; *c* - the function of providing soils with humus; *d* - statistical characteristics

Table 4. Distribution of exchangeable potassium content in soils of agricultural lands of the region

Exchangeable potassium content (mg kg^{-1})		Total	
		Thous. ha	%
Very low	< 100	64.0	3.6
Low	101 – 200	190.2	10.7
Medium	201 – 300	414.2	23.3
Increased	301 – 400	517.3	29.1
High	401 – 600	538.6	30.3
Very high	> 600	55.1	3.1
Total		1777.6	100.0

Table 5. Distribution of soil acidity in soils of agricultural lands of the region

Exchangeable potassium content (mg kg^{-1})		Total	
		Thous. ha	%
Neutral	6.1 - 7.0	636.4	35.8
Weakly alkaline	7.1 - 7.5	730.6	41.1
Medium alkaline	7.6 - 8.0	364.4	20.5
Strongly alkaline	8.1 - 8.5	46.2	2.6
Total		1777.6	100.0

solution. Under the influence of high acidity, harmful for plants substances may appear in the soil, for example soluble aluminum or excessive amounts of manganese. They may disrupt the carbohydrate and protein metabolism of plants. Increased soil acidity inhibits the activity of beneficial bacteria involved in the decomposition of manure, peat, compost and other fertilizers (Breus et al 2020). The autocorrelation analyzes of the spatial heterogeneity of the pH parameter, were minimum (r = 0.166) and maximum (r = 0.027) radius of typical conditions for pH, which is from 2.5 km to 7.5 km (Fig. 6). The lands of Henichesky and Chaplynsky districts have the highest soil pH. The lowest rate is in Oleshkivsky and Velykolepetysky districts. Among surveyed area, the share of alkaline soils (pH> 7.0) is 64.2%, among which strongly alkaline (pH > 8.0) - 2.6 %, medium alkaline (pH = 7.6-8) - 20.5%, slightly alkaline (pH 7.1–7.5) - 41.1%, neutral and close to neutral - 35.8% (Table 5).

CONCLUSIONS

The spatial modelling, the current state of spatial heterogeneity of the distribution of agroecological properties of soils in the steppe zone has been established. The soil cover of the region is characterized by low-humus soils with humus content in the range of 0.30-3.85%. The nitrogen content in the soils of agricultural lands of the region varied from 3.4 mg kg^{-1} to 41.3 mg kg^{-1}, phosphorus - 12.3 mg kg^{-1} to

78.2 mg kg^{-1}, potassium - 26.0 mg kg^{-1} to 703.4 mg kg^{-1}, the reaction of the soil solution (pH) varied from neutral 6.30 to strongly alkaline 8.29. Further preservation of soil cover and improvement of agro-ecological condition of soils depends on the development and implementation of methods for protecting soil from pollution and preserving its fertility. The stopping soil erosion processes is possible only if special measures are developed to classify lands according to erosion resistance, introduction of effective crop rotations, restoration of the field protective plantations (shelterbelts) that inhibit water runoff and the negative impact of wind on the humus layer in fields. Reducing of further chemical contamination of soils is possible by limiting the use of chemicals by farmers, and by using of environmental methods of plant protection through organic fertilizers based on the principles of organic farming, formulated by the International Federation of Organic Agriculture Movements (IFOAM).

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