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Integration of CLUE-S and ANN Models for Geospatial Prediction of Soil Fertility Dynamics (on the Example of Cherkasy region)

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SUMMARY

The subject of this research is the changes in soil fertility within the Cherkasy region caused by natural, anthropogenic, and socio-economic factors. The objective of the study was to develop a scientifically grounded model for forecasting soil fertility, considering the spatial dynamics of land use, agrochemical parameters, and economic factors. The study developed an integrated model combining the spatially explicit dynamic model CLUE-S (Conversion of Land Use and its Effects at Small regional extent) for analyzing land-use changes and an ANN (Artificial Neural Network) for predicting the agrochemical characteristics of soils. The findings indicate that humus content and soil pH are the key indicators of long-term soil productivity. Modeling results showed that, under a business-as-usual scenario preserving current land-use trends, humus content may decrease by 8–12 % by 2050, soil pH may decline to 5.7, and overall soil fertility may decrease by 15–20 %. In contrast, the sustainable management scenario predicts the maintenance of humus content at approximately 4 % and the stabilization of soil pH within the range of 6.3–6.5 through the optimization of crop rotations and the preservation of soil organic matter. A distinctive feature of the proposed model is its incorporation of socio-economic factors, particularly government support for the agricultural sector and prevailing market conditions. The obtained results can be applied to agro-landscape planning, the development of sustainable land-use strategies, and the effective management of land resources.

Keywords: Land resource; Land use; Geospatial modeling; Soil fertility; CLUE-S model; Artificial neural networks (ANN); Spatiotemporal forecasting; Cherkasy region.

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Introduction

Soil fertility is one of the key indicators of land-use efficiency and the sustainable development of agro-landscapes. Its changes are driven both by transformations in land-use structure and by complex agrochemical processes occurring under the influence of natural and socio-economic factors. To predict the spatio-temporal dynamics of land use, the CLUE-S model (Verburg Peter, 2024) is widely applied, whereas artificial neural networks (ANN) provide effective modelling of multifactorial changes in soil agrochemical properties (Liao et al., 2022; Chu et al., 2013).

Despite the significant potential of these methods, their integrated use for assessing the impact of land-use changes on soil fertility remains insufficiently studied. The integration of CLUE-S and ANN models creates opportunities for more accurate prediction of soil resource conditions, identification of degradation risks, and substantiation of management decisions in the field of land management and rational land use (Anputhas et al., 2016).

Method and Theory

The object of the study comprises the main soil types of the Cherkasy region and their agrochemical characteristics (pH, humus content, nitrogen, phosphorus, and potassium levels), which determine the level of land fertility (Ecological Passport of Cherkasy Region, 2023; Trokhymenko et al., 2023). The research is based on the hypothesis of a significant impact of land-use changes – particularly the intensification of agricultural production, urbanization, and transformations in crop structure – on the condition of soil resources. The modelling assumes the possibility of a mathematical description of the effects of natural and anthropogenic factors, the sufficient representativeness of the available data, and the decisive influence of land use on the dynamics of soil fertility.

For forecasting changes in soil fertility, an integrated model was applied, combining CLUE-S for spatial modelling of land-use changes and an artificial neural network (ANN) for predicting the agrochemical indicators of soils (Pindozzi, 2017). The CLUE-S model accounts for natural and socio-economic factors shaping land use, while the ANN uses the outputs of this modelling to estimate future changes in humus content, pH, and macroelements. The model was implemented using CLUE-S software and the MatLab environment with machine learning libraries (Verburg Peter, 2009).

Results

To assess the influence of key factors on soil fertility in the Cherkasy region, variance and correlation analyses of agrochemical indicators were conducted. The analysis included humus content, pH, nitrogen, phosphorus, potassium, soil type, moisture level, and temperature regime. The results (Parakhnenko et al., 2021) showed that the greatest impact on soil fertility is exerted by humus content and pH level ($p < 0.01$). A strong correlation was found between humus content and fertility ($R = 0.85$), as well as a significant influence of pH ($R = 0.78$) and nitrogen ($R = 0.72$). Optimal conditions for maintaining high productivity are formed at a humus content of 4.0–5.0 % and pH 6.2–6.8. A decrease in humus below 3 % or soil acidification ($pH < 5.5$) leads to a 15–30 % loss of fertility due to reduced nutrient availability and degradation of soil structure.

For the quantitative assessment of factor influence, a regression model was constructed, confirming the decisive role of humus content and soil acidity. The highest effect coefficients were obtained for pH ($\beta = 2.1$) and humus ($\beta = 1.8$), while nitrogen, phosphorus, and potassium made a smaller but statistically significant contribution. The analysis of the developed heat and contour maps (Figure 1) showed that maximum predicted soil fertility is characteristic of soils with a neutral or slightly acidic reaction and sufficient organic matter content. Deviations of these parameters from optimal values lead to a 10–25 % decline in productivity (Sopova et al., 2025).

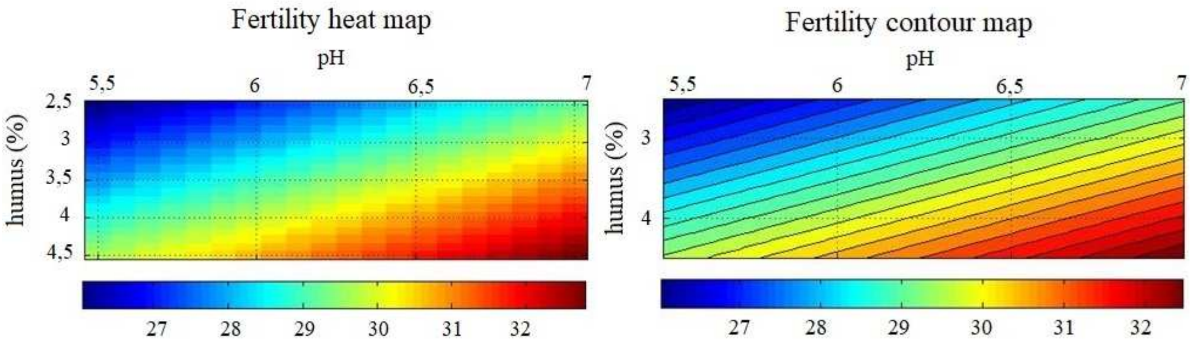

Figure 1. *Geospatial modelling of the influence of humus content and pH level on the predicted soil fertility of the Cherkasy region (heat map and contour map)*

To model nonlinear relationships between agrochemical indicators, an artificial neural network (ANN) implemented as a multilayer perceptron was applied. Training was carried out using the backpropagation algorithm with data split into training, validation, and test sets. The ANN model (Figure 2) demonstrated high predictive accuracy: the mean squared error was 0.0025, and the deviation between observed and predicted values did not exceed 5 %. The results showed that a decrease in humus content from 6 % to 2 % can reduce soil productivity by approximately 25 %, while deviations of pH from its optimal level lead to a 12–18 % decline (Sopova et al., 2025).

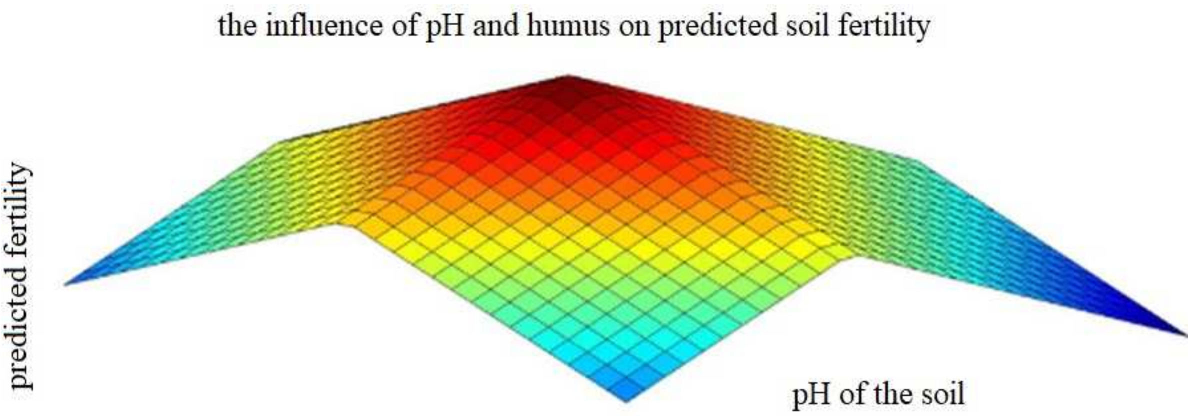

Figure 2. *Geospatial model of the predicted soil fertility of the Cherkasy region*

For forecasting spatio-temporal changes, an integrated CLUE-S+ANN model was used. The CLUE-S model enabled the assessment of future land-use transformations up to 2050, taking into account natural and socio-economic factors, while the ANN determined their impact on soil agrochemical characteristics. According to the modelling results, agricultural land area is projected to increase by approximately 7.5 %, primarily in the central and southern parts of the region, accompanied by a reduction in natural ecosystems and an increase in anthropogenic pressure on the soil cover.

Two development scenarios were considered (Figure 3). Under the BAU (Business as Usual) scenario, the continuation of current land-use trends is expected to lead to an 8–12 % decrease in humus content, a decline in pH to 5.7, and an overall reduction in soil fertility of 15–20 %. A decrease in nitrogen and phosphorus content by 5–10 % is also projected, which will negatively affect agroecosystem productivity.

Under the SLU (Sustainable Land Use) scenario, which involves optimized crop rotations, the application of organic fertilizers, and soil conservation practices, humus content can be stabilized at 3.8–4.2 %, while pH would be maintained within the range of 6.3–6.5. This approach is expected to increase soil productivity by 10–12 % compared to the current state (Sopova et al., 2025).

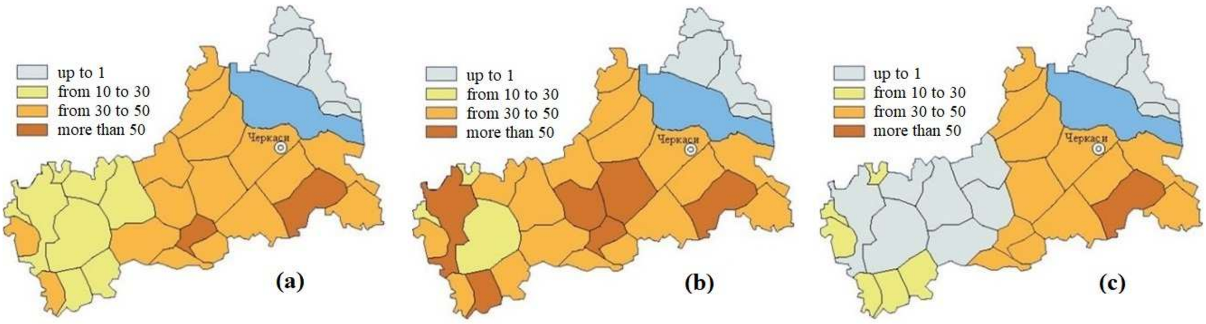

Figure 3. *Cartographic representation of the spatial dynamics of soil fertility in the Cherkasy region: current state (a), forecast under the BAU scenario (b), and forecast under the SLU scenario (c), in relative units*

An important feature of the study was the consideration of socio-economic factors alongside biophysical parameters. The greatest impact on changes in soil fertility is exerted by the level of state support for the agricultural sector, prevailing market conditions, and the pace of urbanization, which collectively shape land-use decisions and intensify or mitigate soil degradation processes (Yu et al., 2023). Incorporating these parameters into the ANN structure significantly improved forecasting accuracy and model stability: the coefficient of determination of the integrated model reached $R^2 = 0.92$, which clearly exceeds the results of the separate application of CLUE-S ($R^2 = 0.78$) and ANN ($R^2 = 0.85$), demonstrating the advantage of combining spatial simulation with machine learning approaches.

The results obtained confirm the effectiveness of the integrated CLUE-S+ANN approach for assessing future changes in soil fertility and the consequences of land-use transformation. The proposed model demonstrates high predictive capability and robustness, making it a reliable tool for scenario-based analysis of spatial and temporal dynamics in soil fertility. It can be effectively used to support decision-making in land management, agricultural land administration, and the development of targeted planning measures aimed at preventing soil degradation (Anputhas et al., 2016). This is particularly important under conditions of increasing anthropogenic pressure, intensifying land-use change, and ongoing climate change, which collectively amplify uncertainty and environmental risks in agricultural systems.

Conclusions

The study established that the key factors for predicting soil fertility are humus content, pH level, and the availability of nitrogen, phosphorus, and potassium. According to the regression analysis results, the strongest influence is exerted by humus and pH (coefficients 1.8 and 2.1, respectively). A decrease in humus below 3 % and deviations of pH from the optimal range of 6.2–6.8 lead to a significant deterioration of agrochemical conditions and a reduction in crop productivity.

The use of the integrated CLUE-S and ANN model for the Cherkasy region improved the accuracy of forecasting land-use changes and soil fertility. Under the BAU scenario, an increase in agricultural land area of 6.5–7.5 % by 2050 is projected, along with an 8–12 % decrease in humus content and a decline in pH to 5.7, which may lead to soil fertility losses of up to 15–20 %. Under the SLU scenario, humus content is expected to stabilize at around 4 %, while pH approaches the optimal value of 6.3, ensuring the preservation of soil productivity.

The comparison of models showed that their integration increases forecasting accuracy by 14 % ($R^2 = 0.92$) due to the combination of spatial modelling and the incorporation of nonlinear relationships among agrochemical indicators, which allows for a more comprehensive representation of complex environmental interactions. The obtained results demonstrate the practical value of the proposed approach and can be effectively used for planning sustainable land resource management, optimizing agricultural practices, and supporting long-term strategies aimed at preserving soil quality and ecosystem stability.

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