

Regulatory Mechanisms in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.,
2024, 15(1), 24–30
doi: 10.15421/022403

Predicting organic carbon in European soils: Only in Southern Ukraine can we expect an increase in humus content

K. Panchenko*, S. Podorozhnyi**, T. Diuzhykova**

*Poltava State Agrarian University, Poltava, Ukraine

**Bogdan Khmelnytsky Melitopol State Pedagogical University, Melitopol, Ukraine

Article info

Received 02.12.2023

Received in revised form 06.01.2024

Accepted 27.01.2024

Poltava State Agrarian University,
Skovorody st., 1/3, Poltava,
36003, Ukraine.
Tel.: +38-066-353-44-89. E-mail:
panchenko.kateryna@pdaa.edu.ua

Bogdan Khmelnytsky Melitopol
State Pedagogical University,
Hemanska st., 20,
Melitopol, 72318, Ukraine.
Tel.: +38-098-543-72-44.
E-mail:
sergey_plantago@meta.ua

Panchenko, K., Podorozhnyi, S., & Diuzhykova, T. (2024). Predicting organic carbon in European soils: Only in southern Ukraine can we expect an increase in humus content. *Regulatory Mechanisms in Biosystems*, 15(1), 24–30. doi:10.15421/022403

Soil organic carbon comprises the majority of the terrestrial soil carbon pool and plays an important role in the global carbon cycle and balance. Even minor changes in soil organic carbon (SOC) can have a significant impact, not only on climate but also on ecosystem stability, due to its key role in soil-atmosphere carbon exchange, plant growth, and food production. In order to assess the feedbacks between the terrestrial carbon cycle and climate change, and to maintain ecosystem functions, it is crucial to understand the spatial and temporal changes in SOC and the drivers of these changes. The role of soil as a source or sink of atmospheric CO₂ is primarily influenced by changes in climate and soil water content. Climate change, particularly global warming, can have a direct or indirect impact on the decomposition of organic matter by regulating soil microbes and fauna, enzyme activity, and soil respiration. A warming climate may increase the loss of soil carbon to the atmosphere because warming has a stronger effect on respiration than on photosynthesis, resulting in a positive soil carbon-climate feedback. Climate warming can significantly affect soil organic matter stocks, with the magnitude of the effect largely dependent on the initial organic matter stock size. Soil carbon content is a crucial aspect of terrestrial ecosystems that affects their functional properties and the climate. Conversely, climate also has an impact on soil organic carbon content. The spatial variability of soil organic carbon content and the predictions made for the west-central European region are also important considerations. The study identified the spatial variation of soil organic carbon throughout Europe and forecast its dynamics in the next 50–70 years, considering global climate change. Digital soil mapping enables a more precise representation of soil properties in space, including the spatial quantification of prediction errors. The accuracy of these predictions increases as more local observations, such as soil profiles, are available to construct the prediction model. Digital soil mapping allows flexible spatial development of soil property maps. Soil properties, such as nutrient concentration and stocks, carbon, heavy metals, pH, cation exchange capacity, and physical properties like particle size and bulk density, can be modelled at different depths and spatial resolutions depending on the project's objectives and available input data. The r GSOCmap project used a 1 km grid to model soil organic matter content. In Europe, the range of soil organic carbon content is from 0 to 750 t/ha, with a mean of 78.1 t/ha and a standard deviation of 50.1 t/ha. Climatic factors were found to account for 29% of the variation in soil organic carbon based on regression analysis. The study revealed that an increase in air temperature leads to a decrease in soil organic carbon content, while an increase in precipitation results in an increase in this indicator. Additionally, the content of soil organic matter is negatively impacted by an increase in the seasonality of precipitation. According to the forecast, global climate change will cause an increase of 1.0–1.1 t/ha in the organic carbon content of 3.6% of the continent's area over the next 70 years. On 7.6% of the area, the changes will be insignificant. The soil organic carbon content is expected to decrease on 88.9% of the area. Of this, 35.1% will experience a slight decrease in carbon content by 0–1 t/ha, 28.4% will experience a moderate decrease in soil organic carbon content by 1.0–1.1 t/ha, and 25.3% will experience a significant decrease by 1.1–1.3 t/ha. The Baltic countries, Belarus, and the Black Earth zone of Russia are at the highest risk. The risk of Russia becoming highly dependent on food imports is increased by this fact. The prospects for Ukraine are quite optimistic. Even in the northern Azov region, we can expect an intensification of humus accumulation processes in the near future, mainly due to increased precipitation. Precipitation in southern Ukraine is a limiting factor that significantly affects agricultural productivity. Increased precipitation and organic matter growth in the soil present positive prospects for agriculture in southern Ukraine, including the northern Azov, Black Sea, and Crimea. It is possible that the occupation of these territories, which are promising for agricultural production, is one of the goals of Russian armed aggression against Ukraine.

Keywords: climate change; global warming; spatial ecology; geomorphological factors; hemeroby; plant community.

Introduction

Agriculture is a major contributor to anthropogenic global warming. Reducing agricultural emissions, mainly methane and nitrous oxide, can play a crucial role in mitigating climate change (Lynch et al., 2021). Climate change is caused by both natural factors and human activity, and it has significant impacts on biodiversity, agricultural production, and food security (Lovynska et al., 2023). Endemic species that are narrowly adap-

ted are particularly at risk of extinction (Kunakh et al., 2023). The concern about species extinction is justified as biodiversity provides food for all forms of life and primary health care for more than 60–80% of people worldwide (Muluneh, 2021). Global climate change has affected agroecological conditions, which in turn has impacted the growth of an important agricultural indicator (Kunakh et al., 2023), the average temperature of the growing season (Amell & Freeman, 2021). The impact of climate change on agriculture has been significant, with hotter summers, changes in preci-

precipitation, and increasingly frequent extreme weather events leading to losses (Diffenbaugh et al., 2021). Furthermore, as the climate continues to warm in the coming decades, the risks to agriculture will only increase (Fick & Hijmans, 2017). Therefore, it is crucial to model the state of agriculture under future climate conditions (Fitzgibbon et al., 2022).

Soil is a significant carbon storage and contains about 1505 Pg C in the topsoil, which is about twice as much as in the atmosphere or three times as much as in terrestrial vegetation (Dlamini et al., 2016). Soil organic carbon (SOC) constitutes the majority of the terrestrial soil carbon pool (accounting for almost 62% of soil carbon) and plays an important role in the global carbon cycle and balance (Piao et al., 2020). Even small changes in SOC can have a significant impact not only on climate but also on ecosystem stability due to its key importance in soil-atmosphere carbon exchange and plant growth and food production (Crowther et al., 2016). The assessment of feedbacks between the terrestrial carbon cycle and climate change, as well as the maintenance of ecosystem functions, requires a critical understanding of spatial and temporal changes in SOC and their associated drivers (Zhao et al., 2020). The function of soil as a source or accumulator of atmospheric CO₂ is largely controlled by the changes in climate and soil water content (Reyna-Bowen et al., 2020). Climate change, especially climate warming, can directly or indirectly affect the decomposition of organic matter by controlling soil microbes and fauna (Yakovenko et al., 2023), enzyme activity and soil respiration (Conant et al., 2011). The warming climate may stimulate the loss of soil carbon to the atmosphere due to the stronger effect of warming on respiration than on photosynthesis, leading to a positive soil carbon-climate feedback (Arora et al., 2013). Climate warming can significantly reduce soil organic matter stocks, and the effect of warming depends largely on the size of the initial organic matter stocks (Ziegler et al., 2017).

Soil water content is another important factor determining soil organic carbon dynamics (Tutova et al., 2023). Moisture plays a crucial role in the growth of vegetation and the supply of carbon substrate for microorganisms under different climatic conditions (Schindlbacher et al., 2012). A high moisture content can stimulate carbon sequestration by stimulating ecosystem productivity or release through soil respiration, but excessive soil moisture can inhibit them in relatively humid climates (Davidson & Janssens, 2006). Humidity levels can have varying effects on the carbon cycle and ecosystem productivity in forests (Shupranova et al., 2022). In cool forests, high humidity may cause delays in the carbon cycle, while in warm forests, increased humidity can accelerate the decomposition of soil organic matter (Kunakh et al., 2022). It is important to note that the direction and nature of these impacts depend on the temperature of the forest (Taylor et al., 2017). High humidity in arid steppes can accelerate the rate of soil respiration, which leads to significant carbon losses from the soil (Jia et al., 2007). The soil water content also plays a crucial role in controlling the carbon cycle response to climate warming (Wan et al., 2007). The effect of warming on soil carbon content changes from positive to negative as soil goes from wet to dry, demonstrating the key role of soil moisture in increasing or decreasing warming-induced carbon (Reich et al., 2018). Warming may stimulate net carbon sequestration in wet conditions but suppress it in very dry conditions (Quan et al., 2019). The carbon cycle is closely linked to soil moisture and this relationship may be more complex in a warming climate. Furthermore, in the context of climate change, changes in groundwater caused by precipitation will continuously have an uncertain impact on future carbon dynamics (Zhao et al., 2021).

Thus, soil carbon content is a key feature of terrestrial ecosystems that affects their functional properties and climate. Climate, in turn, also affects soil organic carbon content, the spatial variability of soil organic carbon content and the prediction made for the area of west-central Europe (Yigini & Panagos, 2016). Therefore, the aim of our work was to determine the features of spatial variation of soil organic carbon throughout Europe and to make a forecast of the dynamics of this indicator in the next 50–70 years, taking into account global climate change.

Material and methods

Organic carbon content in the soil. Digital soil mapping allows more accurate representation of soil properties in space, including spatial quantification of prediction error (Wadoux et al., 2020). The quality of such

predictions improves with an increase in the number of local observations, e.g. soil profiles, available to build the prediction model. Whenever possible, it is recommended to use a digital elevation model (Potapenko et al., 2019). The development of soil property maps using digital soil mapping is spatially flexible. Different soil properties (e.g. soil nutrient concentration and stocks, carbon, heavy metals, pH, cation exchange capacity, physical soil properties such as particle size and bulk density, etc.) can be modelled at different depth classes and spatial resolutions depending on the project and mapping objectives and available input data. To model soil organic matter content, the r GSOCmap project used a 1 km grid. The same methodology and input data can also be used to create higher resolution soil grids. The Global Soil Organic C Stocks (GSOC) mapping is the first implementation of a series of other soil property grids to be developed for GLOIS, based on a country-specific GSP template. The GSOCmap will demonstrate the capacity of countries around the world to collect and manage national soil information systems, and to use and evaluate these data according to agreed international specifications. Information on spatial variation of organic carbon content in the soil layer was obtained from the service GSOC Map (<http://54.229.242.119/GSOCmap>) (Brus et al., 2017).

Bioclimatic variables. Nineteen bioclimatic variables with a spatial resolution of 2.5 minutes from the global climate database WorldClim (www.worldclim.org) were used for bioclimatic modeling. These variables are derived from monthly temperature and precipitation values to obtain more biologically relevant information. They are commonly used in species distribution and related ecological modeling techniques. Bioclimatic variables represent annual trends such as mean annual temperature and annual precipitation, as well as seasonality such as the annual range of temperature and precipitation, and environmental extremes or limiting factors such as the temperature of the coldest and warmest month, and precipitation in wet and dry quarters. A quarter refers to a period of three months or 1/4 of a year. The variables are coded as follows:

BIO1 represents the average annual temperature in degrees Celsius, which approximates the total energy input to the ecosystem.

BIO2 is the average of monthly temperature ranges in degrees Celsius, calculated as the mean monthly tempmax minus tempmin. This index can provide information on the significance of temperature fluctuations for different species.

BIO3 quantifies isothermality in %, which measures how large the day-night temperature variations are relative to the summer-winter (annual) variations (BIO2/BIO7) ($\times 100$). Isothermality is generally useful for tropical, island, and marine environments (Nix, 1986). Isothermicity is a measure of the difference between day-night temperature fluctuations and summer-winter (annual) fluctuations. A value of 100 indicates that the diurnal temperature range is equivalent to the annual temperature range, while a value less than 100 indicates lower temperature variability during an average month compared to a year. Temperature variability within a month compared to a year may influence the distribution of a species. This predictor can provide valuable information.

BIO4 indicates the variability of temperature throughout the year, calculated as the seasonality of temperature (standard deviation of monthly mean temperature $\times 100$).

BIO5 is useful for studying whether species distributions are affected by warm temperature anomalies during the year, as it represents the maximum temperature of the warmest month in degrees Celsius.

BIO6 and BIO7 are useful variables for studying the effects of temperature on species distributions. BIO6 represents the minimum temperature of the coldest month in degrees Celsius, while BIO7 represents the annual temperature range in degrees Celsius (BIO5-BIO6).

BIO8 provides the average temperature during the wettest three months of the year in degrees Celsius. This can be useful in examining how environmental factors may influence the seasonal distribution of species.

BIO9 provides the average temperature during the driest three months of the year in degrees Celsius. This information is useful for studying how environmental factors may influence the seasonal distribution of species.

BIO10 provides the average temperature during the warmest three months of the year in degrees Celsius. This information can be useful for studying how environmental factors may influence the seasonal distribution of species.

BIO11 provides the average temperature during the coldest three months of the year in degrees Celsius. This information is useful for studying how environmental factors may influence the seasonal distribution of species.

BIO12 approximates the total water supply by providing the annual precipitation in millimeters of water column. This information is useful in determining the importance of water availability for species distribution.

BIO13 and BIO14 provide information on extreme precipitation conditions during the year and their potential impact on the species' range. BIO13 represents the precipitation of the wettest month in millimeters of water column, while BIO14 represents the precipitation of the driest month in millimeters of water column.

BIO15, on the other hand, indicates the unevenness of precipitation throughout the year by providing the seasonality of precipitation as a coefficient of variation.

BIO16 represents the precipitation for the wettest quarter in millimeters of water column. This information can be useful for studying how environmental factors affect the seasonal distribution of species. Similarly, BIO17 represents the precipitation for the driest quarter in millimeters of water column, which may be useful for studying how environmental factors influence the seasonal distribution of species.

BIO18 represents the precipitation of the warmest quarter in millimeters of water column. This characteristic can be useful for studying how environmental factors affect the seasonal distribution of species. Similarly, BIO19 represents the precipitation of the coldest quarter in millimeters of

water column, which can be useful for studying how environmental factors affect the seasonal distribution of species.

Information on bioclimatic variables was downloaded using the get-Data function of the raster package (Hijmans, R. J. (2022). raster: Geographic data analysis and modeling. <https://cran.r-project.org>).

Results

Soil organic carbon content in Europe ranges from 0 to 750 t/ha, with a mean of 78.1 t/ha and a standard deviation of 50.1 t/ha (Fig. 1). According to regression analysis, climatic factors explain 29% of the variation in soil organic carbon content (Table 1). An increase in air temperature is associated with a decrease in soil organic carbon content, while an increase in precipitation contributes to an increase in this indicator. Moreover, the content of soil organic matter is negatively affected by increasing seasonality of precipitation (Fig. 2).

The forecast indicates that as a result of global climate change in the next 70 years, on 3.6% of the continent's area the content of organic carbon in the soil will increase by 1.0–1.1 t/ha, and on 7.6% of the area the changes will be insignificant (Fig. 3). In turn, on 88.9% of the area there will be a decrease in soil organic carbon content, among which on 35.1% there will be a slight decrease in carbon content by 0–1 t/ha, on 28.4% of the area there will be a moderate decrease in soil organic carbon content by 1.0–1.1 t/ha, on 25.3% of the area the decrease will be significant by 1.1–1.3 t/ha.

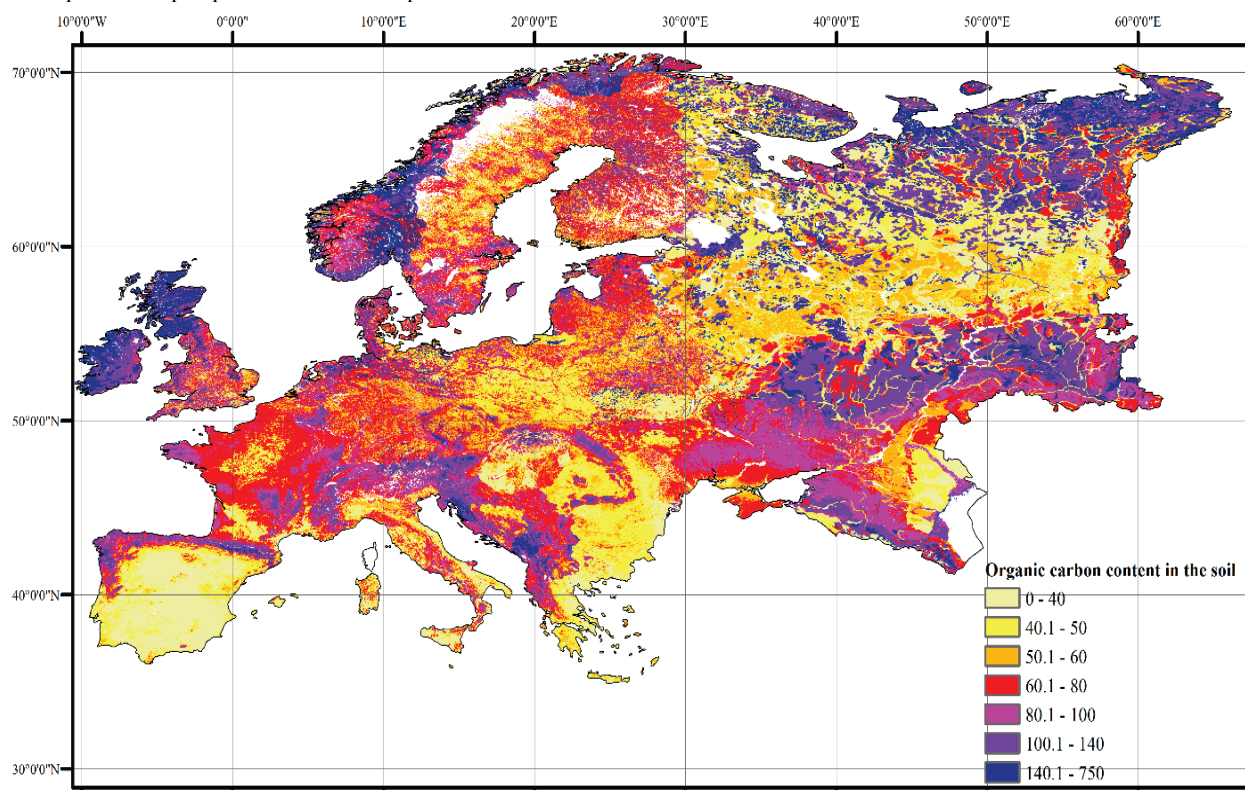


Fig. 1. Spatial variation (t/ha) of soil organic carbon content within Europe at present

Discussion

The content of organic matter in the soil is the result of opposite processes: humification and mineralization (Guggenberger, 2005). As a result of humification, the organic substances that make up living organisms (proteins, fats, hydrocarbons, nucleic acids) are transformed into stable organic compounds of various chemical natures, which are collectively called "humus substances" or soil organic matter. In general, this process takes place in anaerobic conditions (Liu et al., 2021). In the presence of oxygen in the soil air, mineralization of soil organic matter and its transformation into mineral components, water and carbon monoxide becomes possible (Neira et al., 2015).

Carbon in the form of oxide leaves the soil layer as a result of mineralization of organic matter (Hossain et al., 2017). The rate of chemical reac-

tions in the soil depends on the temperature, so the climatic conditions significantly affect the progress of soil processes (Gelybó et al., 2018). Also, the air regime of the soil largely determines the direction and intensity of the transformation of organic matter (Gavrilescu, 2021). The ratio of aerobic and anaerobic soil conditions depends on the ratio of air and liquid soil phase in the pore space of the soil layer (Kunakh et al., 2021). The quantity and mode of precipitation, as well as the intensity of evaporation from the soil surface determine the content of moisture in the soil, which affects the air regime of the soil (Seneviratne et al., 2010). Also, the ratio of aerobic and anaerobic processes depends on the aggregate state of the soil (Ebrahimi & Or, 2016), which is a function of the mechanical composition of the soil, the presence of calcium or sodium in the soil absorption complex and the content of organic matter (Tsvetkova & Saranenko, 2007, 2010; Saranenko, 2011; Tsvetkova et al., 2015; Tutova et al., 2022).

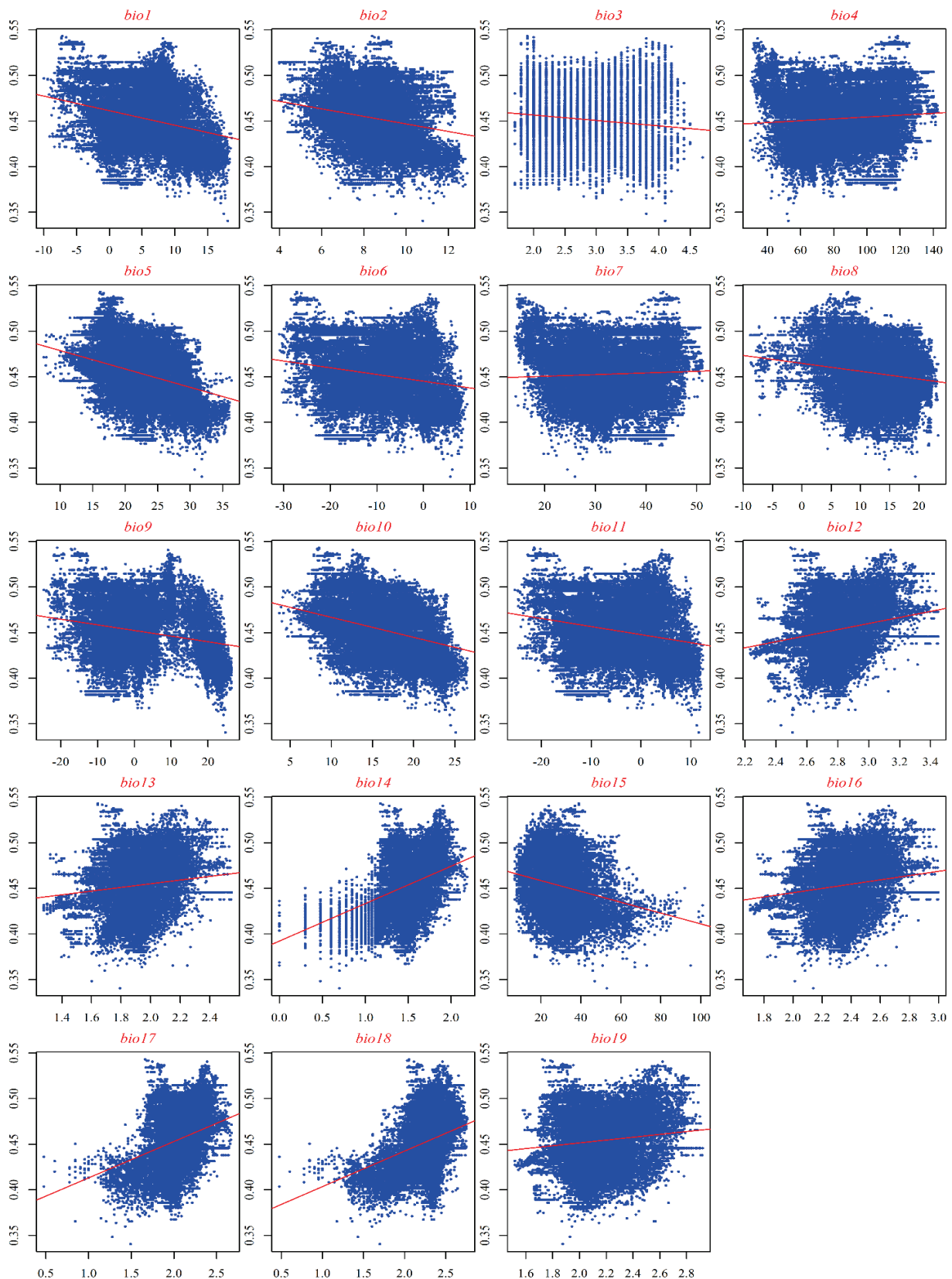


Fig. 2. Dependence of organic carbon content in soils on bioclimatic variables: the abscissa is the value of the corresponding bioclimatic variable (variables 12–14 and 16–19 are presented on a logarithmic scale), the ordinate is the soil organic carbon content (t/ha, on a logarithmic scale); the red line indicates a linear approximation of the relationship; bioclimatic variables: bio1 is the mean annual temperature, bio2 is the mean of monthly temperature ranges, bio3 is the isothermality, bio4 is the seasonality of temperature, bio5 is the maximum temperature of the warmest month, bio6 is the minimum temperature of the coldest month, bio7 is the annual temperature range, bio8 is the mean temperature of the wettest quarter, bio9 is the mean temperature of the driest quarter, bio10 is the average temperature of the warmest quarter, bio11 is the average temperature of the coldest quarter, bio12 is the annual precipitation, bio13 is the precipitation of the wettest month, bio14 is the precipitation of the driest month, bio15 is the seasonality of precipitation, bio16 is the precipitation of the wettest quarter, bio17 is the precipitation of the driest quarter, bio18 is the precipitation of the warmest quarter, bio19 is the precipitation of the coldest quarter

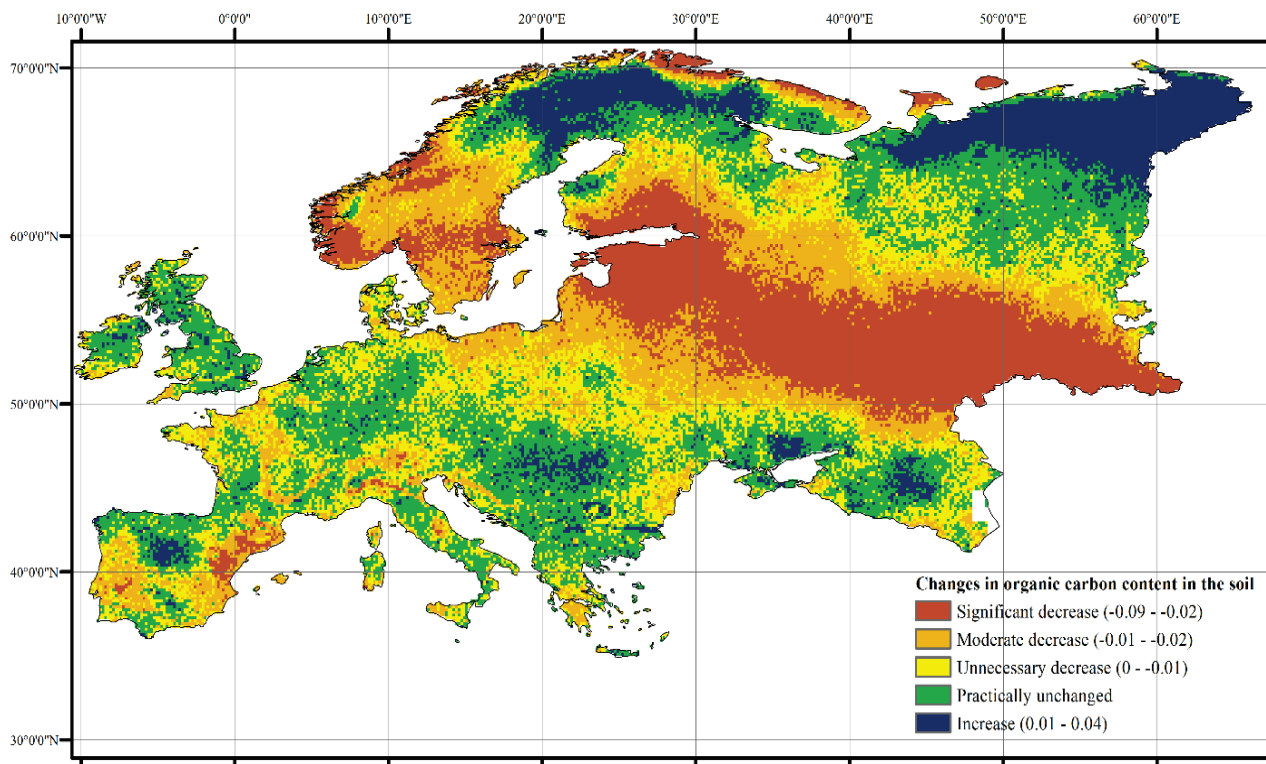


Fig. 3. Forecast of climate-induced changes in soil organic carbon content in the next 70 years (changes compared to the current state, t/ha in logarithmic scale)

Table 1

Regression analysis of soil organic carbon content dependence on bioclimatic variables ($R_{adj}^2 = 0.29$, $F = 1110$, $P < 0.001$)

Predictor*	Coefficient ± st. error	t	P
Constant	0.2539 ± 0.0085	29.9	<0.001
bio1	-0.0097 ± 0.0006	-15.2	<0.001
bio2	-0.0090 ± 0.0004	-22.9	<0.001
bio3	0.0313 ± 0.0010	31.9	<0.001
bio4	0.0100 ± 0.0002	64.1	<0.001
bio5	0.0020 ± 0.0003	6.2	<0.001
bio6	-0.0050 ± 0.0004	-14.1	<0.001
bio8	0.0001 ± 0.00004	2.7	0.008
bio9	-0.0006 ± 0.00004	-16.6	<0.001
bio10	-0.0341 ± 0.0009	-37.6	<0.001
bio11	0.0455 ± 0.0009	50.8	<0.001
bio12	-0.0274 ± 0.0101	-2.7	0.006
bio13	-0.1053 ± 0.0066	-15.9	<0.001
bio14	0.0759 ± 0.0033	23.3	<0.001
bio15	-0.0002 ± 0.0001	-2.1	0.040
bio16	0.1348 ± 0.0115	11.7	<0.001
bio17	-0.0547 ± 0.0060	-9.1	<0.001
bio18	-0.0038 ± 0.0037	-1.1	0.293
bio19	0.0352 ± 0.0035	10.0	<0.001

Note: *bioclimatic variables: bio1 is the mean annual temperature, bio2 is the mean of monthly temperature ranges, bio3 is the isothermality, bio4 is the seasonality of temperature, bio5 is the maximum temperature of the warmest month, bio6 is the minimum temperature of the coldest month, bio7 is the annual temperature range, bio8 is the mean temperature of the wettest quarter, bio9 is the mean temperature of the driest quarter, bio10 is the average temperature of the warmest quarter, bio11 is the average temperature of the coldest quarter, bio12 is the annual precipitation, bio13 is the precipitation of the wettest month, bio14 is the precipitation of the driest month, bio15 is the seasonality of precipitation, bio16 is the precipitation of the wettest quarter, bio17 is the precipitation of the driest quarter, bio18 is the precipitation of the warmest quarter, bio19 is the precipitation of the coldest quarter.

The high aggregation of the soil contributes to the appearance of two opposite regimes in the soil: aerobic and anaerobic (Kunakh et al., 2022). This feature is the reason of high fertility of aggregated soils. Moisture accumulates in the pores of the aggregates and anaerobic conditions are formed there. The presence of moisture is a condition for root nutrition of

plants, as the absorption of nutrients by the roots occurs only in the aquatic environment. In the interaggregate space of the soil there is usually air, which ensures the formation of aerobic conditions (Kunakh et al., 2022). Aerobic conditions ensure the mineralization processes, as a result of which nutrients are released from organic compounds and they become able to be absorbed by plants in the next stage of the cycle of substances. Thus, climatic conditions that affect the thermal, water and air regimes of the soil largely determine the dynamics of organic carbon content in the soil (Pakhomov et al., 2019). But climatic factors act against the background of the important role of soil properties, which depend on its mineralogical and granulometric composition, as well as on the chemical characteristics of plants and the composition and dynamics of soil microorganisms and animals (Zhukova et al., 2020). The variety of acting factors explains that only 29% of soil organic carbon content can be explained by climatic factors.

The temperature factor can be considered as the predominant driver of the mineralization regime, or soil respiration. Therefore, the general spatial trend of this factor is an increase in the intensity of soil respiration from north to south and, accordingly, a decrease in the content of organic matter in this direction. This is in line with the results indicating that mean annual precipitation is the most important predictor variable for explaining spatial variation in soil organic matter content, followed by land use, lithology, soil type and soil pH (Calvo de Anta et al., 2020). Also, the amount of heat that reaches the soil surface affects the rate of evaporation of moisture from the soil surface, which also affects the water and air regime of the soil. Globally, the average depth of recent carbon incorporation into mineral soils is 10 centimeters. Changes in the relative distribution of carbon in the deeper soil layers are better explained by the aridity index than by the average annual temperature. Land use for crops reduces carbon sequestration in the surface soil layer, but not in deeper layers. SOC dynamics and its response to climate control or land use strongly depend on soil depth (Balesdent et al., 2018). The precipitation factor significantly affects the air regime of the soil. In the north, combined with the heat deficit, conditions are formed for a significant predominance of the humification regime, resulting in a large amount of organic matter accumulating in the form of peat reserves. Rising temperatures will stimulate net losses of soil carbon to the atmosphere, leading to a positive feedback between soil carbon and climate, which may accelerate climate change

(Crowther et al., 2016). The forecast is based on the fact that the dependence spaces in a certain period of time can be extended to the dynamics of processes in time (Koshelev et al., 2020). Such an assumption can be considered valid if the model is based on the current equilibrium state of the system, and the system will also reach the equilibrium state by the projected time (Kunakh & Kovalenko 2019). Of course, the projected climate change in the next 50–70 years is very significant, and the establishment of dynamic equilibrium during this time is unlikely. There will be changes in the range of animal and plant species, which will affect the development of a cascade of transformations at the level of communities and ecosystems. The unpredictability of the situation increases with the anthropogenic intensification of the spread of alien species that significantly change the properties and regimes of natural communities. But the forecast is true in terms of determining the trends of changes in soil organic carbon content. But the general conclusion is very disappointing: in a large part of the continent the organic carbon content in the soil will decrease. This prediction is consistent with the results that soil organic carbon will decrease due to climate warming (Zhao et al., 2020).

The Baltic countries, Belarus and the Black Earth zone of Russia are at the highest risk. The latter fact increases the risk of Russia turning from a global food exporter into a country that may become highly dependent on food imports. Ukraine's prospects are quite optimistic. Even the northern Azov region forms a zone where we can expect in the near future the intensification of humus accumulation processes, which are mainly associated with increased precipitation. Precipitation in the south of Ukraine is a limiting factor that significantly affects the productivity of agricultural production. The increase in precipitation and organic matter growth in the soil present positive prospects for agriculture in southern Ukraine, including the northern Azov, Black Sea, and Crimea. It is possible that the occupation of these territories, which are promising for agricultural production, is one of the goals of Russian armed aggression against Ukraine.

The Don River drainage basin, whose waters flow into the Sea of Azov, falls into the ecological disaster zone (Solonenko et al., 2020). This is a very dangerous trend that will negatively affect the ecological state of the Azov Sea (Kunakh & Fedyay 2020). This trend may cause significant salinization of the Sea of Azov waters and an even greater increase in its eutrophication (Fedonenko et al., 2022; Zhukov et al., 2022). Alternative sources of fresh water supply to the Sea of Azov may be the Kuban and small and medium-sized rivers of the northern Azov region. The Kuban may soon take the first place in terms of the amount of fresh water that enters the sea. But now it is necessary to consider the need to create measures to increase the water content of the rivers of the northern Azov region.

Conclusion

Climatic conditions within Europe can explain 29% of the variation in soil organic carbon content. Increasing temperature generally has a negative effect on this indicator, while increasing precipitation, on the contrary, contributes to its increase. Based on the prospects of climate change in the next 50–70 years, changes in soil organic carbon content can be predicted. During this period, a decrease in soil organic carbon content will be observed on 88.9% of the area. The Baltic countries, Belarus and the Black Earth zone of Russia are in the zone of the greatest negative changes. Negative prospects concern the north of Ukraine. In the south of Ukraine, the tendency to increase in the content of organic matter in the soil is not excluded.

References

Amell, N. W., & Freeman, A. (2021). The effect of climate change on agro-climatic indicators in the UK. *Climatic Change*, 165(1–2), 40.

Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., Bonan, G., Bopp, L., Brovkin, V., Cadule, P., Hajima, T., Ilyina, T., Lindsay, K., Tjiputra, J. F., & Wu, T. (2013). Carbon-concentration and carbon-climate feedbacks in CMIP5 earth system models. *Journal of Climate*, 26(15), 5289–5314.

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Comu, S., Derrien, D., Fekiacova, Z., & Hatté, C. (2018). Atmosphere-soil carbon transfer as a function of soil depth. *Nature*, 559(7715), 599–602.

Brus, D., Hengl, T., Heuvelink, G., Kempen, B., Mulder, T. V. L., Olmedo, G. F., Poggio, L., Ribeiro, E., & Omuto, C. T. (2017). Soil organic carbon mapping –

GSOC map cookbook manual. Global Soil Partnership, Food and Agriculture Organization of the United Nations.

Calvo de Anta, R., Luis, E., Febrero-Bande, M., Galiñanes, J., Macías, F., Ortíz, R., & Casás, F. (2020). Soil organic carbon in peninsular Spain: Influence of environmental factors and spatial distribution. *Geoderma*, 370, 114365.

Conant, R. T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyyönönen, R., Kirschbaum, M. U. F., Lavellee, J. M., Leifeld, J., Parton, W. J., Megan Steinweg, J., Wallenstein, M. D., Martin Wetterstedt, J. Å., & Bradford, M. A. (2011). Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. *Global Change Biology*, 17(11), 3392–3404.

Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., Snoek, B. L., Fang, S., Zhou, G., Allison, S. D., Blair, J. M., Bridgham, S. D., Burton, A. J., Carrillo, Y., Reich, P. B., Clark, J. S., Classen, A. T., Dijkstra, F. A., Elberling, B., ... Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, 540(7631), 104–108.

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081), 165–173.

Diffenbaugh, N. S., Davenport, F. V., & Burke, M. (2021). Historical warming has increased U.S. crop insurance losses. *Environmental Research Letters*, 16(8), 084025.

Dlamini, P., Chivenge, P., & Chaplot, V. (2016). Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows. *Agriculture, Ecosystems and Environment*, 221, 258–269.

Ebrahimi, A., & Or, D. (2016). Microbial community dynamics in soil aggregates shape biogeochemical gas fluxes from soil profiles – upscaling an aggregate biophysical model. *Global Change Biology*, 22(9), 3141–3156.

Fedonenko, E. V., Kunakh, O. M., Chubchenko, Y. A., & Zhukov, O. V. (2022). Application of remote sensing data for monitoring eutrophication of floodplain water bodies. *Biosystems Diversity*, 30(2), 179–190.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302–4315.

Fitzgibbon, A., Pisut, D., & Fleisher, D. (2022). Evaluation of maximum entropy (MaxEnt) machine learning model to assess relationships between climate and corn suitability. *Land*, 11(9), 1382.

Gavrilescu, M. (2021). Water, soil, and plants interactions in a threatened environment. *Water*, 13(19), 2746.

Gelybó, G., Tóth, E., Farkas, C., Horel, Á., Kása, I., & Bakacsi, Z. (2018). Potential impacts of climate change on soil properties. *Agrokémia és Talajtan*, 67(1), 121–141.

Guggenberger, G. (2005). Humification and mineralization in soils. In: Vama, A., & Buscot, F. (Eds.). *Microorganisms in soils: Roles in genesis and functions*. Springer-Verlag. Pp. 85–106.

Hossain, M. B., Rahman, M. M., Biswas, J. C., Miah, M. M. U., Akhter, S., Maniruzzaman, M., Choudhury, A. K., Ahmed, F., Shiragi, M. H. K., & Kalra, N. (2017). Carbon mineralization and carbon dioxide emission from organic matter added soil under different temperature regimes. *International Journal of Recycling of Organic Waste in Agriculture*, 6(4), 311–319.

Jia, B., Zhou, G., & Yuan, W. (2007). Modeling and coupling of soil respiration and soil water content in fenced *Leymus chinensis* steppe, Inner Mongolia. *Ecological Modelling*, 201(2), 157–162.

Koshelev, A. I., Pakhomov, O. Y., Kunakh, O. M., Koshelev, V. A., & Fedushko, M. P. (2020). Temporal dynamic of the phylogenetic diversity of the bird community of agricultural lands in Ukrainian steppe drylands. *Biosystems Diversity*, 28(1), 34–40.

Kunakh, O. M., & Fedyay, I. O. (2020). Are Heteroptera communities able to be bioindicators of urban environments? *Biosystems Diversity*, 28(2), 195–202.

Kunakh, O. M., Ivanko, I. A., Holoborodko, K. K., Lisovets, O. I., Volkova, A. M., Nikolaieva, V. V., & Zhukov, O. V. (2022). Modeling the spatial variation of urban park ecological properties using remote sensing data. *Biosystems Diversity*, 30(3), 213–225.

Kunakh, O. M., Ivanko, I. A., Holoborodko, K. K., Volkova, A. M., & Zhukov, O. V. (2023). Age estimation of black locust (*Robinia pseudoacacia*) based on morphometric traits. *Biosystems Diversity*, 31(2), 222–228.

Kunakh, O. M., Volkova, A. M., Tutova, G. F., & Zhukov, O. V. (2023). Diversity of diversity indices: Which diversity measure is better? *Biosystems Diversity*, 31(2), 131–146.

Kunakh, O. M., Yorkina, N. V., Turovtseva, N. M., Bredikhina, J. L., Balyuk, J. O., & Golovnya, A. V. (2021). Effect of urban park reconstruction on physical soil properties. *Ecologia Balkanica*, 13(2), 57–73.

Kunakh, O., & Kovalenko, D. (2019). Fitting competing models of the population abundance distribution: Land snails from Nikopol Manganese Ore Basin Technosols. *Ekologia (Bratislava)*, 38(4), 367–381.

Kunakh, O., Umerova, A., & Degtyarenko, E. (2022). Spatial distribution of micro-mollusks under the impact of recreation. *IOP Conference Series: Earth and Environmental Science*, 1049(1), 012063.

- Kunakh, O., Zhukova, Y., Yakovenko, V., & Daniuk, O. (2022). Influence of plants on the spatial variability of soil penetration resistance. *Ekológia (Bratislava)*, 41(2), 113–125.
- Liu, J., Liang, J., Bravo, A. G., Wei, S., Yang, C., Wang, D., & Jiang, T. (2021). Anaerobic and aerobic biodegradation of soil-extracted dissolved organic matter from the water-level-fluctuation zone of the Three Gorges Reservoir region, China. *Science of the Total Environment*, 764, 142857.
- Lovynska, V., Holoborodko, K., Ivanko, I., Sytnyk, S., Zhukov, O., Loza, I., Wiche, O., & Heilmeyer, H. (2023). Heavy metal accumulation by *Acer platanoides* and *Robinia pseudoacacia* in an industrial city (Northern Steppe of Ukraine). *Biosystems Diversity*, 31(2), 246–253.
- Lynch, J., Cain, M., Frame, D., & Pierrehumbert, R. (2021). Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO₂-emitting sectors. *Frontiers in Sustainable Food Systems*, 4, 518039.
- Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: A global perspective—a review article. *Agriculture and Food Security*, 10(1), 36.
- Neira, J., Ortiz, M., Morales, L., & Acevedo, E. (2015). Oxygen diffusion in soils: Understanding the factors and processes needed for modeling. *Chilean Journal of Agricultural Research*, 75, 35–44.
- Nix, H. A. (1986). A biogeographic analysis of Australian elapid snakes. In: Longmore, R. (Ed.). *Atlas of elapid snakes of Australia*. Australian Flora and Fauna Series. Australian Government Publishing Service. Vol. 7. Pp. 4–15.
- Pakhomov, O. Y., Kunakh, O. M., Babchenko, A. V., Fedushko, M. P., Demchuk, N. I., Bezuhla, L. S., & Tkachenko, O. S. (2019). Temperature effect on the temporal dynamic of terrestrial invertebrates in technosols formed after reclamation at a post-mining site in Ukrainian steppe drylands. *Biosystems Diversity*, 27(4), 322–328.
- Piao, S., Wang, X., Wang, K., Li, X., Bastos, A., Canadell, J. G., Ciais, P., Friedlingstein, P., & Sitch, S. (2020). Interannual variation of terrestrial carbon cycle: Issues and perspectives. *Global Change Biology*, 26(1), 300–318.
- Potapenko, O., Kunakh, O. M., & Fedushko, M. P. (2019). The effect of technological oil spill in soil within electrical generation substations, analysed by ecological regime in the context of relief properties. *Biosystems Diversity*, 27(1), 43–50.
- Quan, Q., Tian, D., Luo, Y., Zhang, F., Crowther, T. W., Zhu, K., Chen, H. Y. H., Zhou, Q., & Niu, S. (2019). Water scaling of ecosystem carbon cycle feedback to climate warming. *Science Advances*, 5(8), eaav1131.
- Reich, P. B., Sendall, K. M., Stefanski, A., Rich, R. L., Hobbie, S. E., & Montgomery, R. A. (2018). Effects of climate warming on photosynthesis in boreal tree species depend on soil moisture. *Nature*, 562(7726), 263–267.
- Reyna-Bowen, L., Fernandez-Rebollo, P., Fernández-Habas, J., & Gómez, J. A. (2020). The influence of tree and soil management on soil organic carbon stock and pools in dehesa systems. *Catena*, 190, 104511.
- Saranenko, I. (2011). Application experience of agricultural lands productivity improvement methods. *Polish Journal of Natural Sciences*, 26(4), 285–292.
- Schindlbacher, A., Wunderlich, S., Borken, W., Kitzler, B., Zechmeister-Boltenstern, S., & Jandl, R. (2012). Soil respiration under climate change: Prolonged summer drought offsets soil warming effects. *Global Change Biology*, 18(7), 2270–2279.
- Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3–4), 125–161.
- Shupranova, L., Holoborodko, K., Loza, I., Zhukov, O., & Pakhomov, O. (2022). Assessment of *Parectopa robinella* Clemens (Lepidoptera: Gracillariidae) effect on biochemical parameters of *Robinia pseudoacacia* under conditions of an industrial city in Steppe Ukraine. *Ekológia (Bratislava)*, 41(4), 340–350.
- Solonenko, A. M., Arabadzy-Tipenko, L. I., Kunakh, O. M., & Kovalenko, D. V. (2020). The role of ecological groups in the formation of cyanobacterial communities in the ecosystems of the North Azov Region (Ukraine). *Biosystems Diversity*, 28(3), 216–223.
- Taylor, P. G., Cleveland, C. C., Wieder, W. R., Sullivan, B. W., Doughty, C. E., Dobrowski, S. Z., & Townsend, A. R. (2017). Temperature and rainfall interact to control carbon cycling in tropical forests. *Ecology Letters*, 20(6), 779–788.
- Tsvetkova, N. M., & Saranenko, I. I. (2007). Physicochemical and morphological soils' properties of the technozone of Kremenchuk Town. *Visnyk of Dnipropetrovsk University, Biology, Ecology*, 15(1), 145–149.
- Tsvetkova, N. M., & Saranenko, I. I. (2010). Influence of the fertilizers use on indices of chemozem's quality. *Visnyk of Dnipropetrovsk University, Biology, Ecology*, 18(1), 117–122.
- Tsvetkova, N. M., Saranenko, I. I., & Dubina, A. O. (2015). Application of geographic information systems in evaluating the development of gully erosion in the steppe zone of Ukraine. *Visnyk of Dnipropetrovsk University, Biology, Ecology*, 23(2), 197–202.
- Tutova, G. F., Kunakh, O. M., Yakovenko, V. M., & Zhukov, O. V. (2023). The importance of relief for explaining the diversity of the floodplain and terrace soil cover in the Dnipro River valley: The case of the protected area within the Dnipro-Orylskiy Nature Reserve. *Biosystems Diversity*, 31(2), 177–190.
- Tutova, G. F., Zhukov, O. V., Kunakh, O. M., & Zhukova, Y. O. (2022). Response of earthworms to changes in the aggregate structure of floodplain soils. *IOP Conference Series: Earth and Environmental Science*, 1049(1), 012062.
- Wadoux, A. M. J.-C., Minasny, B., & McBratney, A. B. (2020). Machine learning for digital soil mapping: Applications, challenges and suggested solutions. *Earth-Science Reviews*, 210, 103359.
- Wan, S., Norby, R. J., Ledford, J., & Weltzin, J. F. (2007). Responses of soil respiration to elevated CO₂, air warming, and changing soil water availability in a model old-field grassland. *Global Change Biology*, 13(11), 2411–2424.
- Yakovenko, V., Kunakh, O., Tutova, H., & Zhukov, O. (2023). Diversity of soils in the Dnipro River valley (based on the example of the Dnipro-Orylskiy Nature Reserve). *Folia Oecologica*, 50(2), 119–133.
- Yigini, Y., & Panagos, P. (2016). Assessment of soil organic carbon stocks under future climate and land cover changes in Europe. *Science of the Total Environment*, 557–558, 838–850.
- Zhao, F., Wu, Y., Hui, J., Sivakumar, B., Meng, X., & Liu, S. (2021). Projected soil organic carbon loss in response to climate warming and soil water content in a loess watershed. *Carbon Balance and Management*, 16(1), 24.
- Zhao, F., Wu, Y., Yao, Y., Sun, K., Zhang, X., Winowiecki, L., Vågen, T.-G., Xu, J., Qiu, L., Sun, P., & Sun, Y. (2020). Predicting the climate change impacts on water-carbon coupling cycles for a loess hilly-gully watershed. *Journal of Hydrology*, 581, 124388.
- Zhukov, O., Kunakh, O., Bondarev, D., & Chubchenko, Y. (2022). Extraction of macrophyte community spatial variation allows to adapt the Macrophyte Biological Index for Rivers to the conditions of the middle Dnipro River. *Limnologia*, 126036.
- Zhukova, Y. O., Yorkina, N. V., Budakova, V. S., & Kunakh, O. M. (2020). The small-scale variation of herb-layer community structure in a riparian mixed forest. *Biosystems Diversity*, 28(4), 390–398.
- Ziegler, S. E., Benner, R., Billings, S. A., Edwards, K. A., Philben, M., Zhu, X., & Laganère, J. (2017). Climate warming can accelerate carbon fluxes without changing soil carbon stocks. *Frontiers in Earth Science*, 5, 2.