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Landscape and soil cover diversity in Polissia and Forest-Steppe of Ukraine

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Abstract. Recent research has revealed the patterns of spatial and temporal variability of crop yields for the Polissia and the Forest-Steppe regions of Ukraine. In addition, the approaches to differentiating agroeconomic and agroecological components in the variability of the productive potential of the territories were developed. Approaches have been developed to quantify the spatial and temporal variability of soil erosion for individual areas of the region. The issue of assessing the impact of erosion processes on crop yields at the regional level remains unresolved. The diversity of landscapes and soil cover in Polissia and the Forest-Steppe of Ukraine was assessed in this article. The research covered 10 administrative regions of the north and northwest of Ukraine, which are located mainly within mixed forests (Polissia) and the eastern European forest steppe (Forest-Steppe). Part of the territory is tangential to the Carpathian mountain forests and the Pontic steppe. Within the study area, 30 WRB soils were identified. The largest area is occupied by Phaeozems Albic (21.7% of the total area of the region). These soils are located mainly in the southern and central parts of the region. In the north of the region, Phaeozems Albic form an almost continuous cover, and to the north, the areas of these soils become island-like. Phaeozems Luvic cover 12.1% of the region's territory. The Phaeozems group also includes Phaeozems Gleyic (0.93%), Phaeozems Haplic (0.13%), and Phaeozems Sodic (1.78%). Albeluvisols Umbric (17.1%) occupy a significant part of the region's territory. These soils occupy the north of the region and extend south along the Dnipro River floodplain. Spatially close to these soils are Albeluvisols Gleyic (12.8%). In the western part of the region, in Prykarpattia, there are Albeluvisols Stagnic (0.82%). The organic carbon content in the soils of the administrative districts of the region in the 0-5 cm layer was 5.2±3.3% and ranged 0.5% to 23.9%. In the layers of 5–15 and 15–30 cm, this figure decreased to 1.9 ± 1.1% and 1.9 ± 1.0%, respectively. In the 30–60 cm layer, the organic carbon content was 1.4 ± 0.8% and ranged 0.1% to 6.1%. The lowest organic carbon content was observed in the north central part of the region, and the highest content was observed in the north-east and north-west of the region. In the south of the region, there was found a strip of soils with moderate organic carbon content. The lowest content of organic carbon is characteristic of Albeluvisols and Podzols, which are located in the north of the region. In turn, the highest content of organic carbon is characteristic of organogenic Histosols, which, together with Albeluvisols and Podzols, form the basis of the soil cover structure of the territories in the northeast and northwest of the region. It should be noted that the agronomic role of these soils is insignificant, and their organic carbon content cannot be considered as a traditional indicator of fertility. Nevertheless, organic carbon is a reliable indicator of the anti-erosion properties of both natural and agricultural soils. The organic carbon content of Chernozems is quite high, which is a factor in the high fertility of these soils and their importance in agricultural production. The organic carbon content of Fluvisols and Gleysols is naturally high. The importance of these hydromorphic soils is due to their high productive potential, which ensures their use in agriculture. It is also worth noting their high seed protection potential. Phaeozems cover a large area of the region and contain a high level of organic carbon. These soils form the basis of agricultural production and forestry in the region. The silt content in the region's soils measured 45.6 ± 8.5%, ranging 19.1% to 57.6%. The north of the region is represented by soils with the lowest silt content (19–41%). In the center, in the west of the region, there is a zone with the highest silt content (53–58%). In other parts of the region, there are transitional levels of silt content in the soil. The clay content in the soils was 30.7 ± 13.8% and ranged 7.4% to 36.0%. The zone with the lowest clay content in soils has been formed in the north. The highest clay content in soils is typical for the southern part in the center of the region. The sand content in soils is highest in the northern part of the region, and the lowest in the southwestern and southern parts of the region.

Keywords: organic matter; granulometric composition; soil erosion; cluster analysis; zonation.

Introduction

The global human population is forecasted to increase by 35% by 2050, which will demand a 70–100% growth in food production, taking into account the expected trends in diets, consumption, and incomes. The study of the causes of agricultural yield stagnation and the possibilities of increasing it in the countries of the world, and in Ukraine in particular, is therefore an urgent issue of today (Zymaroieva, 2019). Soil erosion is among the most significant environmental challenges in the world, resulting in the significant loss of cultivated and potentially fertile soils and crop yields (Jankauskas et al., 2008). Strongly eroded soils tend to be less productive, have deteriorated structure and lower organic matter levels, and are unfavorable for root growth (Frye et al., 1982). Soil degradation processes are a significant challenge in agricultural areas, with water erosion representing a particularly pressing issue. This process has already led to the removal of approximately 430 million hectares, or 30% of the total available arable land, from agricultural production, according to the recent estimates (Quinton &

Fiener, 2023). It is estimated that approximately 1.96 billion hectares of the world's soils are moderately or excessively affected by water and wind erosion (Abdelrahman, 2023). The combined effect of limited soil resources for food production and accelerated soil degradation, caused by the constant growth of the global population, may have a greater negative impact on living conditions worldwide than the anthropogenic greenhouse effect (Lal, 2009). It is a common misconception that soil erosion is solely the result of an unfavourable climate. In fact, it can also be caused by inefficient land management and inappropriate policies (Martínez-Mena et al., 2020). The preservation of biodiversity is contingent upon the continued existence of agroecosystems (Altieri, 1999). The creation of multispecies agroecosystems through the use of sod-forming perennial grasses and grass-grain crop rotations represents a promising avenue for the development of strategies that simultaneously address soil conservation and biodiversity conservation (Lemaire et al., 2015).

The impact of human activity and agricultural practices on soil properties is evidenced by unsustainable changes in land use (Haghighi et al., 2010). The actual impact of the changes is contingent upon a number of factors, including the specific type of ecosystem that is being altered (Rhoades et al., 2000), initial soil properties, nature, duration and intensity of subsequent land use, and management practices (Zucca et al., 2010), long-term, site-specific factors such as climate, topography and parent rock (Khormali et al., 2009), soil type, mineralogy, texture, and depth of the soil (Bormann & Klaassen, 2008). The conversion of natural forests and pastures into agricultural land results in alterations to the physical and chemical properties of the soil. These changes include decrease in organic carbon content and shift in the distribution and stability of soil aggregates, which ultimately reduce crop yields (Haghighi et al., 2010). Decline in organic carbon content results in an increase in soil density and decrease in porosity, which in turn leads to reduction in soil infiltration (Wall & Heiskanen, 2003). In contrast to the conversion of forest and grassland to agricultural land, the conversion of forest to grassland does not result in a discernible pattern in soil carbon content and soil physical properties. The conversion of forest to grassland can lead to a reduction in organic carbon content (Powers, 2004), maintain it at its original level (Geissen et al., 2009), or even increase it (de Moraes et al., 1996).

The regions of Polissia and Forest-Steppe represent large areas of Ukraine with considerable potential for the advancement of agricultural and forestry activities. It is essential that any active economic utilisation of the territory is undertaken in a manner that ensures the continued sustainability of the ecological systems in question, whilst simultaneously supporting the fulfilment of the ecosystem functions. The effects of climate change and the impact of these processes, in addition to the intensity of soil erosion, have the potential to significantly affect the sustainability of agricultural production and forestry. The relationship between the productivity of soybean, sunflower, and winter rye cultivation and landscape diversity has been demonstrated for the Polissia and Forest-Steppe regions. The strongest statistical relationship between yields and landscape diversity indicators was identified for soybean yields, while sunflower yields exhibited the least dependence on landscape diversity. The majority of the relationships were nonlinear, indicating that there is an optimal level of landscape diversity that can be achieved to attain the highest possible crop yields (Zymaroieva et al., 2019; Zymaroieva et al., 2021). The climatic and soil conditions prevailing in the area exerted a considerable influence on the yield of sunflowers. The variation in the trend parameters of sunflower yield in Polissia and the Forest-Steppe was to a significant extent attributed to the edaphic and climatic factors, with the proportion of the variation explained ranging 34% to 58%. Among the edaphic factors that determine the variability of sunflower yields, soil texture and soil organic carbon content were of particular significance. The primary climatic determinants of sunflower yield were the continental climate and the degree of temperature variability during the growing season (Zymaroieva et al., 2021). The principal component analysis of variability in grain and legume yield identified seven principal components, which collectively accounted for 66.8% of the total yield variability. Crop yield fluctuations over a period of ten years or more may be attributed to climatic factors. Among the various agro-environmental factors, climate change has been identified as the primary driver of crop yield fluctuations (Zymaroieva & Zhukov, 2020). A common feature of temporal changes in soybean yields for the administrative regions of Polissia and Forest-Steppe is the presence of a trend that has an agroeconomic origin. The maximum rate of decline and the maximum rate of increase in yield are proposed as markers of the agroecosystem's resistance to agroeconomic factors. The southern and eastern regions of the study area exhibited the greatest sensitivity to agrotechnological and agroeconomic factors, while the northern and western regions demonstrated the lowest sensitivity (Zymaroieva et al., 2020). The yields of rapeseed in Polissia and Forest-Steppe during the period between 1991 and 2017 were influenced by a number of agroeconomic and agrotechnological factors, which can be identified as the determinants of the general trend observed. The mapping of maximum rates of yield decline and growth can indicate areas where yields exhibit a rapid response (either an increase or a decrease) to changes in agroeconomic and agrotechnological conditions. In addition, it allows designating areas where yields are more stable and change gradually. The shape of the yield trend is determined by the influence of agro-technological and agro-economic factors, which account for fluctuations in rapeseed yield to a significant extent, ranging 53% to 90% (Zymaroieva et al., 2020). The yield of corn is subject to the influence of spatially determined processes that exhibit oscillatory dynamics with varying periodicity. The analysis of geographically weighted principal components revealed the existence of spatially non-stationary environmental regimes that underpins the oscillatory component of temporal variation in corn yield (Zymaroieva, 2019). The analysis of the spatial and temporal dynamics of corn yields revealed the intricate nature of the underlying processes that determine it. A common feature of temporal changes in corn yields across all administrative regions is the presence of a trend that can be described by a fourth-degree polynomial. The characteristic points of the fourth-degree polynomial curve can be interpreted and used to describe the yield dynamics in a meaningful way. The regression analysis demonstrates that the overall trend in yield dynamics is determined by a combination of agrotechnological and agroeconomic factors. The coefficient of determination of the regression model can be interpreted as an indicator of the extent to which agrotechnological and agroeconomic factors influence the dynamics of yields. The northern and western districts of the region were observed to be the most susceptible to the influence of these factors, whereas the southern districts exhibited the least sensitivity (Zymaroieva, 2019a). The variability of climate also has an impact on corn yields in the Polissia and Forest-Steppe regions of Ukraine. The primary climatic factors that influence crop yields are the continental climate, temperature variability during extreme periods of the year, the degree of temperature variability, and the contrast of temperature conditions (Zymaroieva, 2019a). The dynamics of grain and legume yields were described by an absolute term that reflects the initial conditions of soil fertility in the initial period of research and the indicators of the maximum rate of yield decline in the 1990s and the maximum rate of yield growth in the 2000s. The indicators of the maximum rate of yield decline and the maximum rate of yield growth can be employed as markers of agroecosystem resilience to external factors. The agroecological systems in Ukraine's regions have not yet reached their maximum ecological capacity, and the current limitations are primarily due to agroeconomic and agrotechnological factors (Zymaroieva et al., 2019). The analysis of geographically weighted principal components revealed that soybean yields have been affected by four spatially determined processes that exhibit oscillatory dynamics with varying periodicity. The hypothesis that these oscillatory phenomena are of an environmental nature was validated. The application of geographically weighted principal component analysis has revealed the spatial units exhibiting comparable oscillatory components of soybean yield variation. In Polissia and Forest-Steppe, specific patterns of temporal dynamics of soybean yields were identified within homogeneous zones, which exhibited qualitative differences between them. It is proposed that territorial clusters within which the temporal dynamics of soybean yields are identical be considered as agroecological zones of soybean cultivation (Zymaroieva et al., 2019). The temporal dynamics of rye yields in the Polissyia and Forest-Steppe regions of Ukraine exhibit three distinct extreme points: two local maxima and one local minimum. The individual terms of the fourth-order polynomial curve can be interpreted and used to describe yield dynamics in a meaningful way. The free terms of the polynomial function indicate the initial productivity of the crop. The yield dynamics that can be explained by regression indicate that agrotechnological and agroclimatic conditions of agricultural production exert a pervasive influence on the presence of a general trend. The coefficient of determination of the general trend of the regression can be interpreted as an indicator of the role played by agrotechnological and agroeconomic factors in the dynamics of yields. The residuals of the trend regression model can be interpreted as representing the agroecological component of rye yield dynamics (Kunah et al., 2018). A model was constructed to examine the factors contributing to water erosion in the Volyn region. An increase in precipitation contrast in either space or time can result in heightened erosion processes, reaching a point where the precipitation intensity itself is affected by this contrast. The concurrence of elevated precipitation levels during the summer months and the presence of vegetative cover mitigate the effects of erosion. Nevertheless, sustained high precipitation levels at the outset of the harvesting period may result in heightened water erosion. (Matviichuk et al., 2023).

As a result, the regularities of spatial and temporal variability of crop yields have been identified for the territory of Polissia and the Forest-Steppe of Ukraine. Furthermore, approaches have been developed to differentiate the agroeconomic and agroecological components in the variability of the productive potential of the territories. Approaches to quantify the spatial and temporal variability of soil erosion have been developed for specific areas within the region. The issue of evaluating the influence of soil erosion processes on crop yields at the regional level remains unresolved. In order to address this issue, it is essential to first assess the diversity of landscape and soil cover in Polissia and Forest-Steppe of Ukraine, as presented in this article.

Materials and methods

We analyzed the spatial variability of WRB soil reference groups, soil properties, and landscape cover structure within 10 administrative regions of northern and northwestern Ukraine (Fig. 1). This region includes the Polissia and Forest-Steppe geographical zones. The environmental characteristics were averaged within the administrative regions before the 2015–2022 reform of Ukraine's administrative and territorial structure. This is due to the fact that the area of “traditional” districts is smaller and more ecologically homogeneous than that of the new administrative units. It is also due to the fact that data on crop yields have been collected for a long time within the “old” administrative districts, which is very important for addressing the issue of the relationship between productive potential and soil and landscape conditions. Information on the spatial variability of the region's soil cover was obtained from the Harmonized World Soil Database (Version 2.0) (Aksoy et al., 2023). Information on soil properties was obtained from the SoilGRIDS database (www.isric.org/explore/soilgrids) using the geodata package (Hijmans et al., 2024).

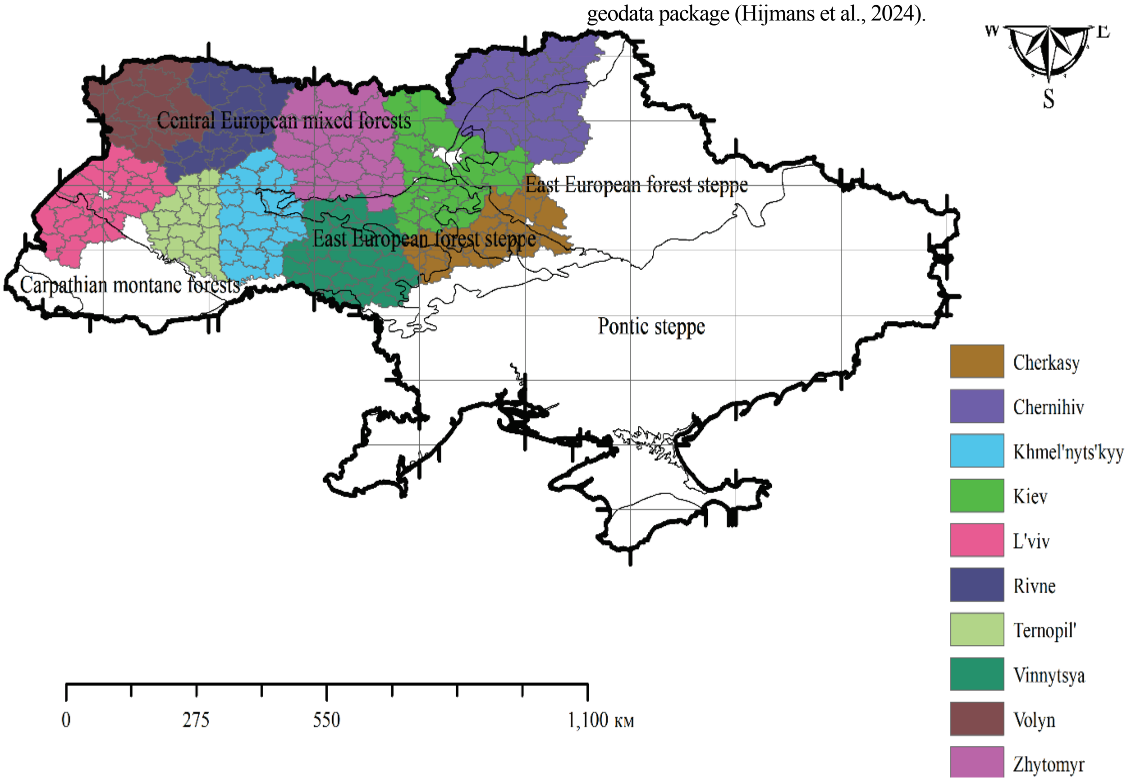

Fig. 1. Region of the study with the administrative regions of the country

Information on landscape cover types was obtained from the GlobCover land Cover Maps database (https://due.esrin.esa.int/page_globcover.php). Descriptive statistics, cluster, and discriminant analysis of streets were calculated in StatSoft 12.0.

Results

The research covered 10 administrative regions of the north and northwest of Ukraine, which are located mainly within mixed forests (Polissia) and the eastern European forest steppe (Forest-Steppe). Part of the territory is tangential to the Carpathian mountain forests and the Pontic steppe. Within the study area, 30 WRB soils were identified (Fig. 2). The largest area is occupied by Phaeozems Albic (21.7% of the total area of the region, Table 1). These soils are located mainly in the southern and central parts of the region. In the north of the region, Phaeozems Albic soils form an almost continuous cover, and to the north, the areas of these soils become island-like. Close to Phaeozems Albic are Phaeozems Luvic, which cover 12.1% of the region's territory. The Phaeozems group also included Phaeozems Gleyic (0.93%), Phaeozems Haplic (0.13%), and Phaeozems Sodic (1.78%). A significant part of the region's territory is occupied by Albeluvisols Umbric (17.1%). These soils occupy the north of the region and extend south along the Dnipro River floodplain. Spatially close to these soils were observed to be Albeluvisols Gleyic (12.8%). In the western part of the region, in Prykarpattia, there are Albeluvisols Stagnic soils (0.82%). The Chernic chernozems occupy 15.6% of the region's territory and are located in its central and southern parts. The Luvic chernozems (0.01%) were found as separate “islands” in the south. The cambisols group was represented by Cambisols Dystric (1.83%), Cambisols Eutric (< 0.01%), and Cambisols Gleyic (0.28%). These soils were found in the western part of the region in areas close to the Carpathians. Fluvisols are represented by Fluvisols Dystric (0.17%), Fluvisols Eutric (2.15%), Gleyic Fluvisols (0.01%), and Fluvisols Histic (3.06%). The fluvisols are located in river floodplains. Gleysols are represented by Gleysols Histic (0.16%), Gleysols Humic (2.38%), and Gleysols Sodic (0.36%). In Polissia, they were commonly found under waterlogged conditions. Histosols are represented by Histosols Fibric (1.54%), Histosols Sapric (1.16%), and Histosols Salic (0.46%), occupying the territory of peatlands of Polissia. Leptosols Rendzic soils were found to occupy 2.51% of the region's territory in the west, where Cretaceous marl outcrops are located. Haplic Luvisols are rarely found in the west of the region. Podzolic soils are represented by Podzols Entic (0.27%), Podzols

Haplic (0.04%), Leptic Podzols (0.01%), and Podzols Rustic (0.48%). Podzols are commonly found in the north of the region in Polissia. Umbrisols Gleyic soils occupy 0.26% of the territory and are found in floodplains.

The organic carbon content in the soils of the administrative districts of the region in the 0–5 cm layer measured 5.2 ± 3.3%, ranging 0.5% to 23.9% (Fig. 3). In the 5–15 and 15–30 cm layers, this figure decreased to 1.91 ± 1.1% and 1.90 ± 1.0%, respectively. In the 30–60 cm layer, the organic carbon content was 1.4 ± 0.8%, ranging 0.1% to 6.1%. The lowest organic carbon content was observed in the north central part of the region, and the highest content was found in the northeast and northwest of the region. In the south of the region, there is a strip of soils with moderate organic carbon content. The lowest content of organic carbon is characteristic of Albeluvisols and Podzols, which are located in the north of the region. In turn, the highest content of organic carbon is characteristic of organogenic Histosols, which, together with Albeluvisols and Podzols, form the basis of the soil cover structure of the territories in the northeast and northwest of the region. It should be noted that the agronomic role of these soils is insignificant, and their organic carbon content cannot be considered as a traditional indicator of fertility. Nevertheless, organic carbon is a reliable indicator of the anti-erosion properties of both natural and agricultural soils. The organic carbon content of Chernozems is quite high, which is a factor in the high fertility of these soils and their importance in agricultural production. The organic carbon content of Fluvisols and Gleysols is naturally high. The importance of these hydromorphic soils is due to their high productive potential, which ensures their use in agriculture. It is also worth noting their high seed protection potential. Phaeozems cover a large area of the region and contain a high level of organic carbon. These soils form the basis of agricultural production and forestry in the region. The silt content in the region's soils was found at the level of 45.6 ± 8.5%, ranging 19.1% to 57.6%. The north of the region is represented by soils with the lowest silt content (19–41%). In the center, in the west of the region, there is a zone with the highest silt content (53–58%). In other parts of the region, there are transitional levels of silt content in the soil. The clay content in the soils measured 30.7 ± 13.8%, ranging 7.4% to 36.0%. The zone with the lowest clay content in soils has formed in the north. The highest clay content in soils is typical for the southern part in the center of the region. The sand content in the soils is highest in the northern part of the region, and the lowest in the southwestern and southern parts. Under conditions of high sand content in the bedrock, such soils as Podzols, Histosols, and Albeluvisols have formed. High clay content ensures the formation of Chernozems, Cambisols, and Phaeozems. High silt content was observed in Podzols Leptic, Cambisols Gleyic, and Chernozems Chernic.

The landscape cover of the region is represented by various types (Fig. 4, 5). Rainfed arable land accounts for 30.9 ± 12.1%, ranging 3.1% to 52.7%. The lowest proportion of this type of cover is found in the north of the region, and the highest is found in the south. The mosaic of vegetation cover with a predominance of arable land was 35.8 ± 7.5%. This indicator ranges 7.6% to 52.0%. The smallest proportion of the mosaic of vegetation cover with predominance of arable land in the structure of landscape cover is typical for the northwest of the territory, and the largest is found in the east and northeast of the territory. The mosaic of vegetation cover and arable land is 9.1 ± 3.9%, ranging 2.2% to 21.8%. The spatial pattern repeats the pattern of the previous type. The peculiarity lies in the high proportion of the mosaic of vegetation cover and arable land in the southwest of the territory. Broadleaf forests cover 14.3 ± 9.4% of the region's surface, ranging 1.2% to 41.4% across the administrative districts. The densest cover of broadleaf forests is observed in the west and northeast of the region, and the least dense is found in the southeast. Coniferous forests cover 1.8 ± 4.2% of the region's surface. This figure varies 0% to 26.6%. The densest cover of coniferous forests is observed in the north of the region. In the south, such forests are very rare. Sparse mixed forests cover 0.4 ± 0.7% of the region's territory. This figure varies 0% to 3.8%. This type of landscape cover is most common in the northeast of the region. Continuous mixed forests cover 4.9 ± 7.8% of the territory, ranging 0% to 35.3%. The densest cover of this type is observed in the north and northwest of the region. A mosaic of grassy cover, forests and shrubs, as well as pure grassy cover was most common in the southwest of the region. Sparse vegetation covers 0.32 ± 0.38% of the region's territory. The highest level of this type reaches 2.0%, observed in the south. Floodplain ecosystems are most common in the north of the region. Artificial cover is 0.3 ± 0.7% and can reach 5.8%. The highest rates for this type of cover coincide with the location of large cities in the region.

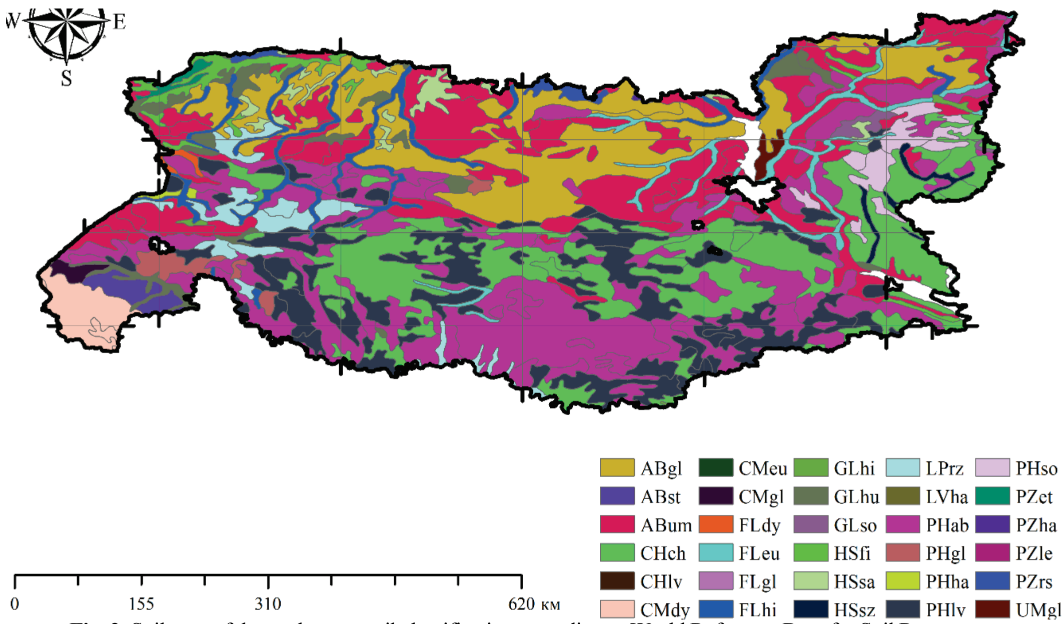

Fig. 2. Soil map of the study area: soil classification according to World Reference Base for Soil Resources:
ABgl is the Albeluvisols Gleyic; ABst is the Albeluvisols Stagnic; ABum is the Albeluvisols Umbric; CHch is the Chernozems Chernic; CHlv is the Chernozems Luvic; CMdy is the Cambisols Dystric; CMeu is the Cambisols Eutric; CMgl is the Cambisols Gleyic; FLdy is the Fluvisols Dystric; FLeu is the Fluvisols Eutric; FLgl is the Gleyic Fluvisols; FLhi is the Fluvisols Histic; GLhi is the Gleysols Histic; GLhu is the Gleysols Humic; GLso is the Gleysols Sodic; HSfi is the Histosols Fibric; HSsa is the Histosols Sapric; HSsz is the Histosols Salic; LPrz is the Leptosols Rendzic; LVha is the Haplic Luvisols; PHab is the Phaeozems Albic; PHgl is the Phaeozems Gleyic; PHha is the Phaeozems Haplic; PHlv is the Phaeozems Luvic; PHso is the Phaeozems Sodic; PZet is the Podzols Entic; PZha is the Podzols Haplic; PZle is the Leptic Podzols; PZrs is the Podzols Rustic; UMgl is the Umbrisols Gleyic

The cluster analysis of administrative districts based on information on soil properties and vegetation structure allowed us to identify three homogeneous clusters (Fig. 6). These clusters can be distinguished using two discriminative roots (Table 2). Root 1 differentiates clusters 2 and 3, which correspond to the mixed forest and forest-steppe zones, respectively (Fig. 7). Root 2 differentiates clusters 2 and 3 on the one hand and cluster 1 on the other. Cluster 1 marks the transition zone between Mixed Forest and Forest Steppe. Root 1 contrasts forest ecosystems of different composition and agricultural lands. Accordingly, forest ecosystems predominate in the Polissia zone, and agricultural lands predominate in the Forest-Steppe zone. The organic carbon content is not an informationally valuable indicator for determining root 1. In Polissia, there is a mosaic of soils with low and very high organic carbon content, while in the Forest-Steppe soils this indicator has an intermediate value. Polissia soils are generally characterized by a higher content of sand, while Forest-Steppe soils are characterized by a higher content of silt and clay. Polissia and the Forest-Steppe do not differ in terms of urbanization. The loss of coniferous forests from the vegetation structure defines the transition zone between Polissia and Forest-Steppe. In addition to broadleaf forests, coniferous forests are also replaced by a grassy cover or a mosaic of forests and shrubs. The transition zone has a higher proportion of artificial cover and a higher content of organic carbon. Soils contain more silt but less clay and sand.

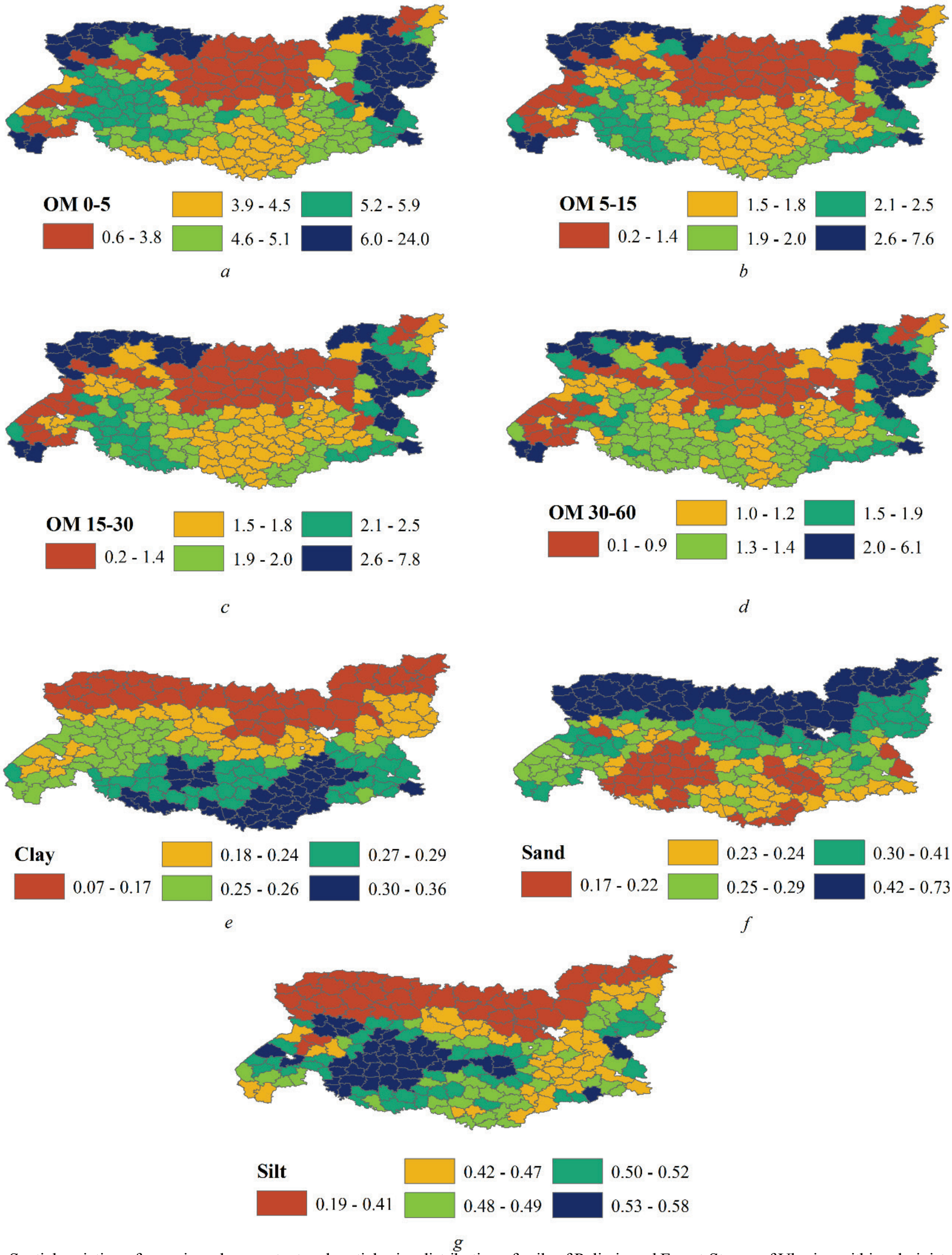

Fig. 3. Spatial variation of organic carbon content and particle size distribution of soils of Polissia and Forest-Steppe of Ukraine within administrative districts: *a* is the organic carbon of soil at the depth of 0–5 cm (g/kg); *b* is the organic carbon of soil at the depth of 5–15 cm (g/kg); *c* is the organic carbon of soil at the depth of 15–30 cm (g/kg); *d* is the organic carbon of soil at the depth of 30–60 cm (g/kg); *e* is clay (< 0.002 mm) in fine earth, proportion; *f* is sand (> 0.05 mm) in fine earth, proportion; *g* is silt (0.002–0.05 mm) in fine earth, proportion

Table 1
Organic carbon content in granulometric fractions in the soils of the region (in the profile with a thickness of 0–60 cm)

Soil	Area, %	Soil organic carbon, %				Silt, %	Sand, %	Clay, %
		0–5 cm	5–15 cm	15–30 cm	30–60 cm			
Albeluvisols Gleyic	12.76	0.7 ± 0.2	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	34.8 ± 9.1	51.0 ± 12.8	14.2 ± 4.4
Albeluvisols Stagnic	0.82	0.6 ± 0.1	0.2 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	49.6 ± 3.1	27.0 ± 2.9	23.5 ± 1.4
Albeluvisols Umbric	17.07	0.7 ± 0.2	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	38.4 ± 9.0	44.4 ± 13.3	17.2 ± 5.6
Chernozems Chernic	15.61	5.4 ± 1.1	4.0 ± 0.4	3.0 ± 0.2	1.4 ± 0.4	51.1 ± 4.4	21.9 ± 5.1	27.0 ± 4.6
Chernozems Luvic	0.01	4.5 ± 0.8	3.2 ± 0.5	3.1 ± 0.5	1.5 ± 0.2	47.9 ± 1.8	16.2 ± 1.0	35.9 ± 1.6
Cambisols Dystric	1.83	7.8 ± 1.8	3.0 ± 0.8	3.0 ± 0.8	1.9 ± 0.7	43.0 ± 2.8	31.4 ± 3.7	25.5 ± 2.6
Cambisols Gleyic	0.28	5.1 ± 0.6	1.9 ± 0.3	1.9 ± 0.3	1.2 ± 0.3	52.6 ± 2.2	22.7 ± 2.1	24.7 ± 2.4
Fluvisols Dystric	0.17	5.7 ± 0.5	1.5 ± 0.2	1.5 ± 0.2	1.1 ± 0.2	42.6 ± 9.5	33.2 ± 11.3	24.3 ± 2.9
Fluvisols Eutric	2.15	7.5 ± 1.8	2.5 ± 0.9	2.5 ± 0.9	2.0 ± 0.9	39.9 ± 6.3	42.2 ± 11.0	17.8 ± 6.4
Fluvisols Gleyic	0.01	6.7 ± 0.6	2.1 ± 0.4	2.1 ± 0.4	1.5 ± 0.3	39.9 ± 10.6	39.4 ± 14.8	20.7 ± 5.1
Fluvisols Histic	3.06	6.6 ± 1.5	2.3 ± 0.8	2.3 ± 0.8	1.7 ± 0.8	35.3 ± 10.2	47.3 ± 16.3	17.4 ± 7.1
Gleysols Histic	0.16	7.4 ± 1.8	2.5 ± 0.8	2.5 ± 0.8	2.0 ± 0.9	41.9 ± 4.7	38.0 ± 6.9	20.1 ± 6.6
Gleysols Humic	2.38	6.7 ± 1.7	2.3 ± 0.8	2.3 ± 0.8	1.7 ± 0.8	35.9 ± 11.1	48.5 ± 16.9	15.7 ± 6.8
Gleysols Sodic	0.34	8.7 ± 0.7	3.1 ± 0.7	3.1 ± 0.7	2.4 ± 0.8	47.2 ± 2.5	34.4 ± 3.8	18.4 ± 3.1
Histosols Fibric	1.54	46.6 ± 7.3	14.9 ± 4.5	15.3 ± 4.7	11.0 ± 4.2	25.0 ± 8.4	63.7 ± 14.2	11.3 ± 6.4
Histosols Sapric	1.16	45.5 ± 8.2	15.4 ± 4.8	15.9 ± 4.9	11.6 ± 4.6	26.0 ± 7.8	63.4 ± 11.4	10.6 ± 4.2
Histosols Salic	0.46	43.0 ± 7.0	15.3 ± 4.7	15.8 ± 4.9	11.4 ± 4.3	48.5 ± 4.0	28.7 ± 4.4	22.9 ± 3.2
Leptosols Rendzic	2.51	5.5 ± 0.8	3.1 ± 0.4	2.1 ± 0.4	1.5 ± 0.4	45.4 ± 7.3	30.1 ± 9.8	24.4 ± 4.1
Luvisols Haplic	0.01	5.2 ± 0.3	1.5 ± 0.2	1.5 ± 0.2	1.1 ± 0.2	40.3 ± 5.4	33.9 ± 6.0	25.8 ± 1.7
Phaeozems Albic	21.65	5.4 ± 1.4	3.0 ± 0.5	2.0 ± 0.5	1.4 ± 0.5	48.7 ± 4.7	25.0 ± 7.6	26.3 ± 5.3
Phaeozems Gleyic	0.93	5.0 ± 0.5	2.9 ± 0.3	1.9 ± 0.3	1.1 ± 0.4	51.1 ± 2.4	24.8 ± 3.3	24.2 ± 2.3
Phaeozems Haplic	0.13	5.3 ± 0.5	2.7 ± 0.3	1.7 ± 0.3	1.2 ± 0.3	46.2 ± 5.7	27.7 ± 5.9	26.1 ± 1.9
Phaeozems Luvic	12.12	4.9 ± 0.7	2.9 ± 0.3	1.9 ± 0.3	1.4 ± 0.3	50.2 ± 4.3	21.4 ± 4.3	28.5 ± 4.1
Phaeozems Sodic	1.78	7.5 ± 1.1	3.5 ± 0.8	2.5 ± 0.8	2.0 ± 0.7	49.3 ± 3.9	30.5 ± 4.7	20.2 ± 2.9
Podzols Entic	0.27	0.8 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	20.1 ± 2.6	70.8 ± 4.4	9.1 ± 2.2
Podzols Haplic	0.04	0.7 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	28.2 ± 1.7	59.1 ± 2.9	12.7 ± 1.8
Podzols Leptic	0.01	0.6 ± 0.1	0.2 ± 0.1	0.2 ± 0.0	0.1 ± 0.0	53.3 ± 2.2	21.6 ± 2.0	25.3 ± 1.4
Podzols Rustic	0.48	0.8 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	24.0 ± 4.9	67.5 ± 6.9	8.5 ± 2.7
Umbrisols Gleyic	0.26	8.0 ± 0.9	2.2 ± 0.5	2.2 ± 0.5	1.7 ± 0.5	36.3 ± 3.0	48.2 ± 4.5	15.6 ± 2.7

Discussion

In the region, the main reference soil groups are Phaeozems (36.6% of the region), Albeluvisols (30.7%), Chernozems (15.6%), Fluvisols (5.4%), and Histosols (3.2%). Other reference soil groups (Gleysols, Leptosols, Cambisols, Podzols, Umbrisols, Luvisols) cover less than 3% of the territory each. The landscape and soil indicators allowed us to identify three soil-landscape complexes that correspond well to the traditional division of this region into Polissia, Forest-Steppe, and interzonal territory. The most prevalent soil types in Polissia are Albeluvisols, Histosols, Gleysols, and Fluvisols. It should be noted that Fluvisols is an azonal soil type that occurs in areas where rivers are present. Albeluvisols (included in Retisols in the modern classification) are soils that have formed in areas where surface waterlogging has occurred. They are characterised by the presence of loose sediments, which may have been deposited by glaciers, lakes or rivers, or by eolian processes, such as accumulation of loess. These soils are formed on hilly plains under coniferous or mixed forests in boreal and temperate climates with cold winters and short, cool summers, with total precipitation of 500–1,000 mm per year (Schad, 2023). The erosion of Albeluvisols results in significant alterations of the essential physicochemical and biological properties of these soils, which are crucial for optimal crop production. Topsoil is typically characterised by an enrichment of organic matter and the presence of granular aggregates, which serve to create larger soil pores, reduce soil density and enhance water infiltration and aeration. The erosion of Albeluvisols topsoil results in decrease in yields, due to loss of nutrients and deterioration of physical properties of soil. The loss of topsoil and its impact on yields is particularly pronounced on steep slopes. The process of erosion alters the physical properties of Albeluvisols, primarily by removal of the surface layer of soil that is rich in organic materials, thus exposing the underlying soil layers. The bulk density and saturated hydraulic conductivity of the soil demonstrated a slight increase with rising erosion rates (Arriaga & Lowery, 2003). Soil peds are defined as complex and dynamic systems of micro- and macro-aggregates, which exert a significant influence on a range of soil physical properties and microbiological processes.

The implementation of grassland crop rotations and sod-forming perennial grasses has been observed to mitigate the erosion of Albeluvisols, thereby indicating an enhancement in soil structure. These alterations correlated with increase in organic carbon content (Jankauskas et al., 2006). The low aggregate stability and high dispersion of Albeluvisols with low organic matter content led to the formation of a dense and thick crust for all sizes of soil aggregates (Lado et al., 2004). The high aggregate stability and low dispersion of soils with high organic matter content resulted in the limited formation of compaction. The integration of multi-species agroecosystems comprising sod-forming perennial grasses and grass-grain rotations represents a promising avenue for the development of sustainable conservation strategies for Albeluvisols. Such practices can increase soil carbon stocks, improve the soil physical properties (e.g., overall porosity, water retention, soil structure, and aggregate stability), and reduce the risk of soil erosion and associated water pollution in terrestrial and marine aquatic ecosystems (Jankauskas et al., 2006).

The Albeluvisols Umbric reference group is characterised by soddy-weakly podzolic sandy and clay-sandy soils. This is one of the most prevalent soil types in Polissia. These soils are formed primarily on light water-glacial and ancient alluvial deposits of plains and ancient terraces. In some areas, these soils are underlain by moraine, which is a weathering product of carbonate and igneous rocks. Soils of a sandy nature are typically associated with hilly uplifts of Aeolian origin and are consequently referred to as 'boron sands'. The presence of a light particle size distribution results in an excessively high water permeability and a concomitant low moisture capacity (Glina et al., 2013). The soil exhibits a high degree of aeration, which, in conjunction with its limited capacity to retain water, results in the accelerated decomposition of organic matter (Minasny & McBratney, 2018). These soils can exhibit thin humus horizon, low humus content (0.6-0.9%), low absorption capacity and water capacity, unsaturated bases, lack of nutrients, and as a result, low fertility. Given that Albeluvisols are typically low-fertile and unsuitable for crop production, the relatively high proportion of commercial crops may be the result of intensive cultivation driven by economic incentives rather than a search for the most suitable crops (Tóth et al., 2020). The implementation of appropriate agricultural methodologies has resulted in the generation of substantial yields of potatoes and winter rye (Jankauskas & Otabbong, 2004). Soils with high sand content are unsuitable for agricultural use and are better suited to forestry (Kalinina et al., 2013). The presence of perennial grasses is an effective method of preventing water erosion of these soils. The proportion of clay-dusty and clay fractions in the arable soil horizon increases, while the overall porosity and water-holding capacity of the soil decreases in conjunction with rising soil erosion. The introduction of phytocoenoses, in particular sod-forming perennial grasses and grass crop rotations, results in alterations to the physical properties of eroded soils. The volume weight of the soil is reduced, while the percentage of total porosity and moisture capacity are increased. The implementation of cereal-tilled crop rotations and sod-forming perennial grasses demonstrated effective mitigation of soil erosion, thereby contributing to the erosion control and environmental sustainability of Albeluvisols within a vulnerable hilly and undulating landscape (Jankauskas et al., 2008).

Albeluvisols Gleyic soils are representative of soddy-low podzolic and soddy-medium podzolic clayey soils. These soils are prevalent in areas of low relief with a high groundwater table (Kawalko et al., 2021). A typical feature of these soils is a humus horizon depth of 20–40 cm with a crumbly and structureless profile. Another distinctive feature of these soils is soil glazing (Špulák et al., 2023). The higher the intensity of glaze and the greater the extent of the profile it covers, the poorer the agronomic characteristics of these soils (Medvedev & Plysko, 2016). These soils are suitable for cultivation of crops across all the zones. Albeluvisols Stagnic soils are analogous to the soddy-medium and heavily podzolic surface-ash soils of the Prykarpattia region. These soils are common on elevated swale-like plains and slopes under conditions of excessive atmospheric moisture (over 700 mm of precipitation per year). Their profiles are clearly differentiated into humus-eluvial, eluvial, and illuvial horizons. The latter is dense and waterproof, which leads to surface glazing. The reaction of the soil solution is very acidic. In order to maintain these soils, it is necessary to implement water management and fertilisation (Šiaudinis et al., 2020).

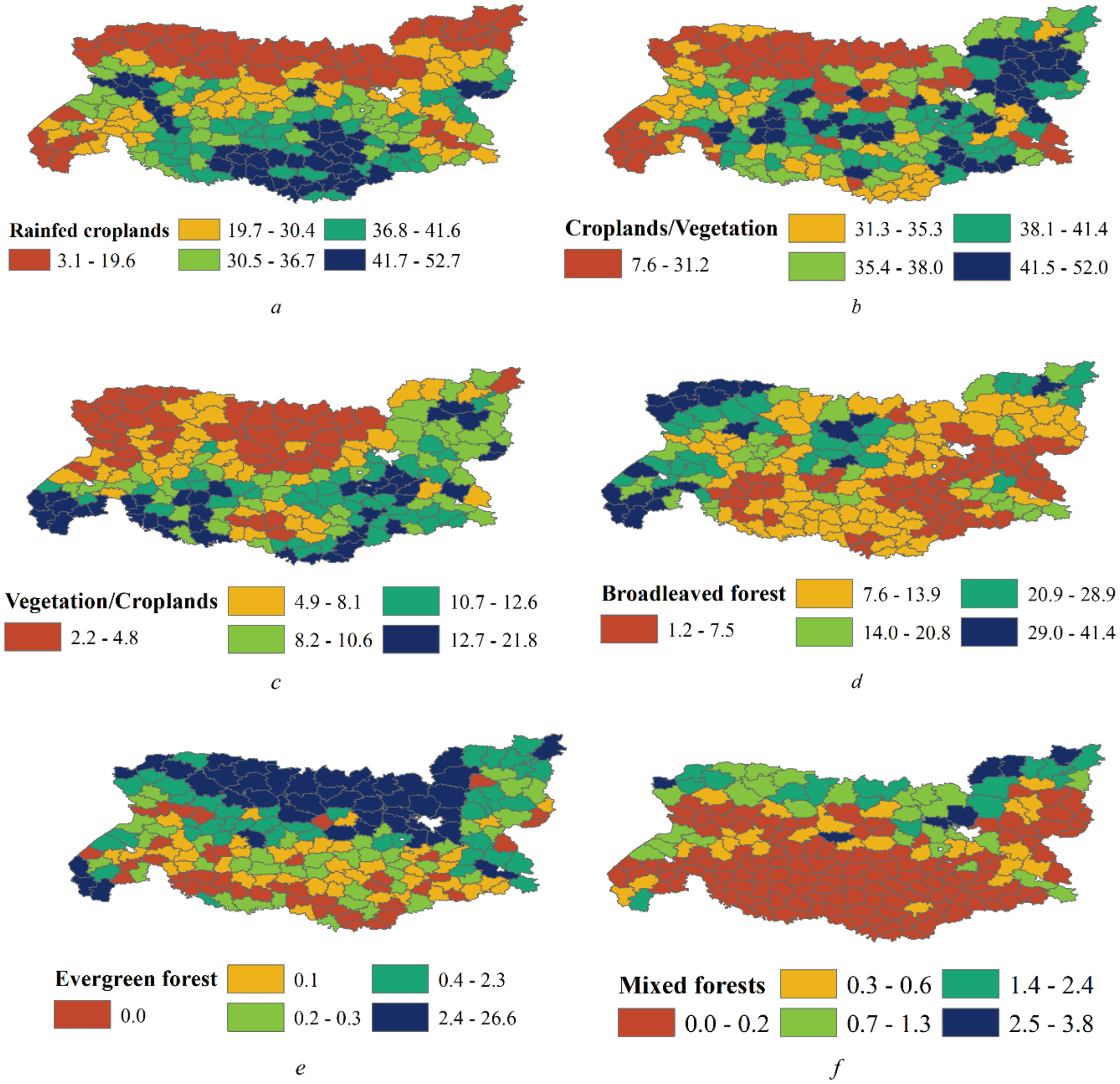

Fig. 4. Spatial variation in the proportion of landscape cover types (in the range from 0 to 1): *a* is the rainfed croplands, *b* is the mosaic croplands (50 is the 70%) / vegetation (grassland/shrubland/forest) (20 is the 50%); *c* is the mosaic vegetation (grassland/ shrubland/ forest) (50 is the 70%) / cropland (20 is the 50%); *d* is the closed (>40%) broadleaved deciduous forest (>5 m); *e* is the closed (>40%) needleleaved evergreen forest (>5 m); *f* is the open (15 is the 40%) needleleaved deciduous or evergreen forest (>5 m)

Gleysols are defined as meadow soils. These are exemplified by meadow-boggy soils (Gleysols Histic), meadow saline soils (Gleysols Sodic), and meadow humic soils (Gleysols Humic). Gley soils are hydromorphic soils, characterised by a subsoil layer that is consistently wet for the majority of the year. Consequently, maize, a crop with high demands on soil water and nutrients, is deemed to be pedologically suitable for cultivation on sites with light, medium, or medium-heavy textures. The cultivation of maize on gley soils can be successful due to the ability to provide water from groundwater sources even during critical periods in July and August, when climatic drought is frequent and maize's demand in water is at its highest. The preference for maize over cereals on glacial soils is also attributable to pedoclimatic factors. Gley soils are among the most susceptible to excess water, particularly during the early spring period, which presents a significant risk for corn cultivation. This risk can be mitigated by the cultivation of spring crops with a sowing time subsequent to the wettest period. Consequently, maize represents an optimal alternative to winter crops for cultivation on Gleysols. The period of highest risk of inland flooding coincides with the time of sowing corn. Therefore, growing corn on Gleysols can be considered a mutually beneficial outcome (Tóth et al., 2020). Gleysols are very sensitive to soil erosion (Molla & Sisheber, 2017).

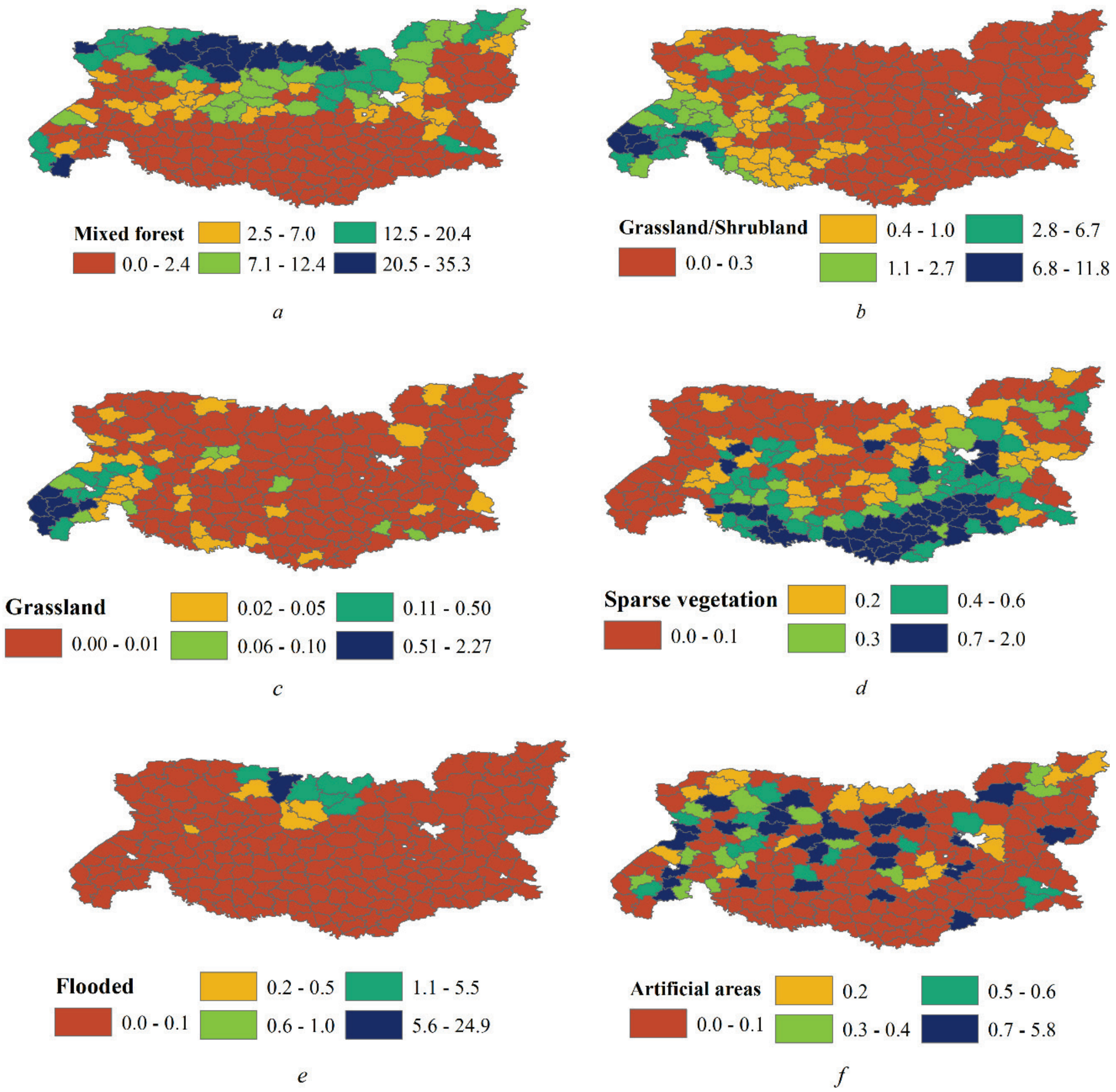

Fig. 5. Spatial variation in the proportion of landscape cover types (in the range from 0 to 1): *a* is the closed to open (>15%) mixed broadleaved and needleleaved forest (>5 m), *b* is the mosaic grassland (50 is the 70%) / forest or shrubland (20 is the 50%); *c* is the closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses); *d* is the sparse (<15%) vegetation; *e* is the closed to open (>15%) grassland or woody vegetation in regularly flooded or waterlogged soil in fresh, brackish or saline water; *f* is the artificial surfaces and associated areas (urban areas >50%)

Histosols are peat soils. They are found in river floodplains, on closed and flowing depressions of Polissya and Forest-Steppe. They often form a combination with mineral soils, which differ significantly in properties. Their density is 2.5–10.0 times lower. These soils have reduced reserves of the main biogenic elements (except for carbon). The chemical composition is determined by the conditions of water and mineral nutrition. Almost half of the total area of peatlands has been drained and put to use in fodder and field crop rotations. Under conditions of overdrying and intensive use, such soils can degrade rapidly. This reduces the capacity and mineralisation of the peat layer. The peculiarity of crop cultivation on Histosols is largely due to the relatively high proportion of root crops grown on this soil type, which occupies a significantly larger area compared to other soil types (Tóth et al., 2020). Histosols are soils with a loose structure that is conducive to the growth of root crops. It is therefore recommended that root crops be cultivated on this soil in accordance with good agronomic practice. Compared to corn and, to a certain extent, oilseeds, root crops are the preferred type in these soils. The cultivation of potatoes is particularly prevalent among root crops. This crop is particularly selective regarding its precursors, with a recommended minimum interval of four years between crops (Camacho et al., 2024). The high spatial extent of root crops in Histosols indicates that farmers strive to achieve maximum root crop production in these soils, taking into account the agronomic possibilities (Tóth et al., 2020).

In Polissia, there are Umbrisols Gleyic soils, which correspond to meadow soils. These soils are predominantly found on low-lying topographical features, with a relatively close proximity (1.5–3.0 m) to fresh groundwater. They typically develop in cool and humid climates (Jenčo et al., 2018). The formation of Umbrisols is contingent upon the availability of organic matter, which can only be provided by the rich herbaceous undergrowth of pine and mixed pine-oak forests. In Polissia, these soils have a relatively short profile, whereas in the Forest-Steppe and Steppe, they have a deep, well-developed profile with indications of glazing in the lower portion. The constant moisture content of the soil is maintained by capillary water rise. With the exception of soils with a high clay content, soils of a light texture in Polissia are distinguished by favourable properties, high fertility, and suitability for the cultivation of vegetables and fodder crops (Wawire et al., 2021).

Rivers exert a profound influence on natural and human ecosystems, providing fertile soil and water for irrigation and consumption in rural and urban areas. Fluvisols are formed in river floodplains on alluvial deposits and are subject to periodic flooding by floodwaters (Saint-Laurent et al., 2010). The organic matter content and other properties exhibit considerable variation. The chemical and physical properties of Fluvisols vary broadly, strongly influenced by application of management practices and the depth of the soil profile (Šimanský, 2018). It is not uncommon to encounter saline soils among the floodplain soils of the forest-steppe and steppe zones. The variability in the characteristics of Fluvisols necessitates a differentiated approach to their utilisation. Fluvisols are used for a variety of human activities, including agriculture, mining, industry, service provision, urban development, and construction of reservoirs (Rodrigo-Comino et al., 2021).

Fluvisols make a significant contribution to the provision of water-retaining hydrological ecosystem services in floodplain ecosystems (Kanianska et al., 2022). The loss of nutrients from Fluvisols due to wind necessitates additional fertiliser costs to ensure the economic viability of the crop (Segovia et al., 2017).

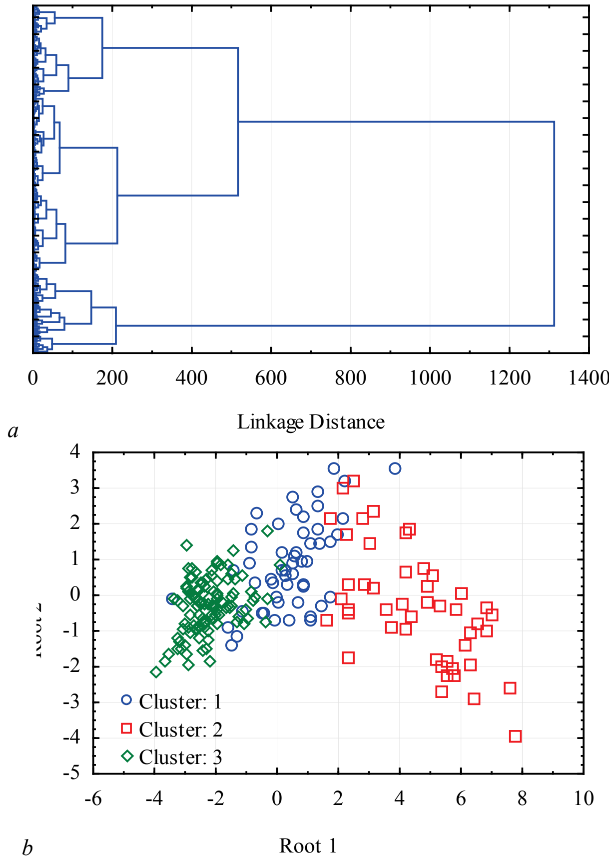

Fig. 6. Cluster analysis of administrative districts by soil and landscape features (*a*) and location of the three identified clusters in the space of discriminant functions (*b*)

The forest steppe soil cover within the study area is typified by the presence of Phaeozems, Chernozems, Leptosols, and Cambisols (in the west). Phaeozems constitute approximately 1.5% of the Earth's continental land area and account for 3% of Europe's soil cover. They are particularly prevalent in humid steppe regions (Kunzová & Hejcman, 2010). These soils are found in association with chernozems, but in wetter climatic conditions (over 550 mm of precipitation per year) that results in the absence of calcium carbonate or salt accumulation in the subsurface layers. However, in some cases, a clay accumulation layer may be observed. The surface layers of these soils typically exhibit higher humus content compared to black soils. Phaeozems are distinguished by a surface layer that is rich in humus, which is naturally covered by a profusion of herbaceous or deciduous forest vegetation (Spaargaren, 2008).

Table 2
Factor structure of the discriminant roots (statistically significant correlation coefficients for $P < 0.05$ are shown)

Variables	Root 1	Root 2
Organic matter at the depth 0–5 cm	–	–0.11
Organic matter at the depth 5–15 cm	–	–0.14
Organic matter at the depth 15–30 cm	–	–0.14
Organic matter at the depth 30–60 cm	–	–0.16
Clay	–0.34	–
Sand	0.39	–0.17
Silt	–0.33	0.26
Rainfed croplands	–0.70	–0.26
Mosaic Croplands (50–70%) / Vegetation (grassland/shrubland/forest) (20–50%)	–0.23	0.18
Mosaic vegetation (grassland/ shrubland/ forest) (50–70%) / cropland (20–50%)	–0.15	0.21
Closed (>40%) broadleaved deciduous forest (>5 m)	0.32	0.25
Closed (>40%) needleleaved evergreen forest (>5 m)	0.25	–0.30
Open (15–40%) needleleaved deciduous or evergreen forest (>5 m)	0.32	–0.23
Closed to open (>15%) mixed broadleaved and needleleaved forest (>5 m)	0.55	–0.61
Mosaic grassland (50–70%) / forest or shrubland (20–50%)	–	0.42
Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	–	0.23
Sparse (<15%) vegetation	–0.16	–0.19
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – Fresh, brackish or saline water	–	–0.12
Artificial surfaces and associated areas (Urban areas >50%)	–	0.17

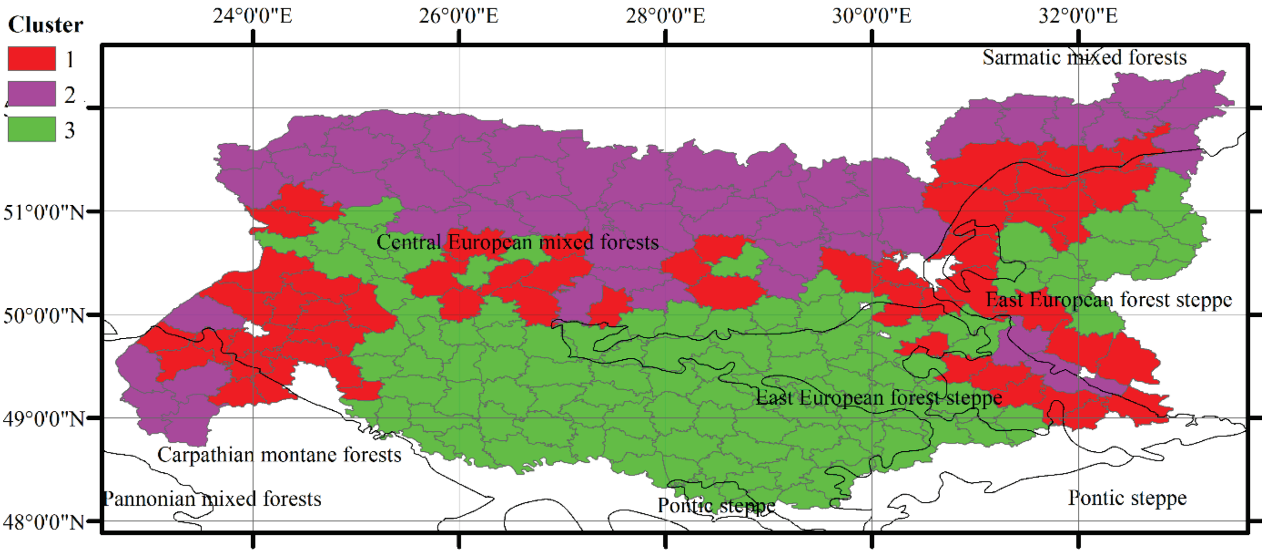

Fig. 7. Soil and landscape complexes: *1* is the interzonal transition area; *2* is Polissia; *3* is the forest-steppe

The humus content of Phaeozems represents a pivotal factor influencing both the total phosphorus content and the available phosphorus resources. The restoration of humus reserves in the soil is a prerequisite for the reclamation of phosphorus depletion. This process should be carried out concurrently with the application of phosphate fertilisers (Spychalski et al., 2018). Phaeozems are found on plains, valleys, forests, and low hills with a temperate continental climate. Soil-forming materials are Pliocene and Quaternary sediments, loess, and loess-like clays (Hristov, 2020). These soils are characterised by high fertility and are utilised for the cultivation of wheat, soybeans, and pasture for livestock, in addition to wood and fuel production. The long-term sustainability of winter wheat production on Phaeozems can be ensured by implementing a crop rotation incorporating legumes and root crops, even in the absence of fertilisation (Kunzová & Hejcman, 2010). Phaeozems are characterised by high concentration of available calcium ions bound to soil particles, which facilitates the formation of a highly permeable and well-aggregated structure (Spychalski et al., 2018).

Phaeozems Albic soils correspond to light gray, gray, and dark gray podzolic soils according to the national classification (Rudenko, 2007). Dark grey podzolised soils are used in agricultural practices for the cultivation of crops and for horticulture. The increasing pressure from human activities has led to the emergence of degradation phenomena resulting from prolonged and intensive soil use. The deterioration of soil quality is evidenced by a number of observable phenomena, including over-compaction, destructuring, dehumidification and an increased propensity for water erosion. A reduction in soil carbon, nutrients, and microbial communities poses a significant risk to crop production (Karahan, 2020). Soil erosion results in considerable losses of organic carbon when soil cultivation is not properly managed over an extended period. This ultimately endangers the ecological functions of soil biota (Liu et al., 2024). The degradation processes have had a deleterious impact on the morphological characteristics, physical and physicochemical properties of the soil. This has resulted in a decline in soil fertility and an overall deterioration of the environmental situation in the region (Haskevych, 2016).

Phaeozems Luvic correspond to light gray podzolic soils according to the national classification (Rudenko, 2007). These soils provide favorable conditions for the development of forest vegetation (Velychko, 2005). A great area of these soils in the region is degraded due to erosion. The humus content is less than 1.1% in 4% of light gray podzolic soils in Rivne region, 60% of the area contains 1.1–2.0% and 36% of the area contains 2.1–3.0% humus (Furman et al., 2018). According to our results, the content of organic carbon in these soils is somewhat lower, which can be explained by the fact that light gray podzolic soils in Rivne region are at the northern edge of their distribution, and a significant area within the region of these soils is located in more southern areas, where conditions for humus accumulation are better. Phaeozems Gleyic correspond to dark gray podzolic soils, and Phaeozems Haplic correspond to gray podzolic soils (Rudenko, 2007). Phaeozems Sodic correspond to meadow chernozem surface and deeply saline soils. They are found mainly on the loess terraces of the Dnipro and its left-bank tributaries, in low-lying depressions, and slopes. They receive additional water nutrition from mineralized groundwater, so they are saline to varying degrees. Phaeozems Sodic show signs of salinity and glazing. As a result, they are only slightly suitable for growing some crops (Rudenko, 2007). These soils are found mainly in Kyiv and to a large extent in Chernihiv region within the study area.

Chernozems Chernic correspond to podzolic chernozems, typical chernozems, and regular chernozems. These soils dominate large areas of the Forest-Steppe and Steppe zones (Strouhalová et al., 2019). Chernozems are formed mainly on loess that almost completely cover interfluvial plateaus and upper river terraces. Chernozems are classified as steppe soils, characterized by pedogenesis that primarily involves the accumulation of humus. This process is influenced by a dry continental climate and steppe vegetation, along with key factors such as carbonate parent material and bioturbation (Eckmeier et al., 2007). The granulometric composition of these soils varies from coarse dusty light loam in the north of the distribution area to heavy loam and light clay in the south of the distribution area (Borek, 2019). The depth of the humified layer ranges 70 to 120 cm (Yakovenko & Zhukov, 2021). The humus content in the upper horizon of low-humus soils is 3.5–5.5%, and in medium-humus soils is 5.5–6.5%. The latter are more common in the eastern regions of the Forest-Steppe and Steppe. The reaction of the soil solution is slightly acidic or close to neutral. The water and physical properties are generally favorable for agriculture (FAO, 2020). The moisture content is subject to significant seasonal and annual fluctuations. Groundwater is generally located 5 meters below the surface and does not affect soil formation (Labaz et al., 2018). The moisture is unevenly distributed across the soil profile, and more than 90% of the active moisture is accumulated in the depth range of 0 to 150 cm (Kotovych et al., 2019). Chernozems have high potential fertility, suitable for growing most crops (Stepan Pozniak, 2019). The predominant factors of erosion of Chernozems are water and wind. Intensive plowing leads to a significant intensification of erosion processes. In general, eroded arable land in Ukraine accounts for 30% of all arable land, and in the Black Earth zone this figure is about 25%, of which 18% of land is slightly eroded, 5% is moderately eroded, and 2% is highly eroded. Erosion causes loss of habitat, decrease in humus content, degradation and overall decrease in fertility of Chernozems. The intensive deterioration of the Chernozems structure leads to the formation of large soil clods. Erosion has also caused irreparable damage to the environment and led to significant negative environmental impacts. In Ukraine, 130 years after the monumental research by V. Dokuchaev, the average annual humus loss in the upper horizons of chernozems ranges 21 to 40%, i.e. 0.5–0.9 t/ha (Kravchenko et al., 2012). It should be noted that this trend is typical for black soil agrosoils. In natural soils, an average increase in total humus content of 0.8% has occurred over 130 years. In agrogenic soils, the humus content decreased by an average of 1.1% (Ponomarenko et al., 2022).

Cambisols Dystric corresponds to the brown mountain-forest and soddy brown soils of the Carpathians (Pozniak & Barannyk, 2017). These soils were primarily formed from the eluviated and deluviated materials of dense rocks under conditions of an intensive seasonal flushing water regime (Barannyk & Pozniak, 2017). Cambisols Dystric are predominantly loamy, loose soils. The humus content in these soils varies from 2.0–2.5% on slopes below 800 m above sea level to 7–9% above 800 m above sea level. Cambisols Dystric are characterized by high acidity (Sparchez et al., 2017). These soils are used in field and fodder crop rotations and as natural pastures. As a result of anthropogenic soil transformation, the composition indicators have undergone distinct changes – soil of genetic horizons with a decrease in total porosity; the structure of the humus-accumulative horizon of virgin soil has undergone transformation and is characterized as prismatic (Pozniak & Barannyk, 2017).

Leptosol Rendzins are classified as sod-carbonate soils. They develop from massive rocks rich in calcite, dolomite, or gypsum, often containing admixtures of glacial or periglacial materials, at all stages of development (Kohlhepp et al., 2017). The humus horizon reaches 20 to 40 cm, with a humus content of up to 3.5% (Kabała, 2018). Rendzin soils are distinguished by high calcium and magnesium content, a neutral to alkaline pH, and high base saturation throughout the soil profile. However, individual soil subtypes exhibit considerable variation in their suitability for agricultural and forestry applications, contingent on the thickness of the soil profile (i.e., depth to hard rock or extremely skeletal subsoil), stoniness, texture, and humus content (Kabała, 2018).

The specificity of the inter-zonal transition area lies largely in the quantitative differences in soil properties and landscape cover. The Polissia zone naturally has a higher proportion of mixed forests, while the Forest-Steppe zone is characterized by a larger area of agricultural land. The organic carbon content is not a differentiating indicator, as in Polissia the forest soils with very low humus content coexist with bog soils with very high organic matter reserves. It should be noted that the low content of organic matter in Polissia forest soils is also associated with the high level of drainage of these soils and, accordingly, moisture deficit during very important periods of agricultural crops, which explains their low fertility. Bog soils are formed under conditions of excessive moisture, poor aeration, and high acidity, which also negatively affects the fertility of these soils in Polissia. Formally, the humus content in the Forest-Steppe soils is in a transitional position compared to the organic matter content of Polissia soils. However, the acidity of the soils, which is close to neutral, the heavier mechanical composition, and climatic conditions create conditions more favorable for high crop yields.

The inter-zonal transition area is characterized by higher humus content, which is probably due to the higher silt content in the soil. Changes in distribution of soil particle size due to geomorphological reasons provide conditions that are favorable for greater accumulation of organic matter in the soils of the transition zone compared to Polissia. This transition is not accompanied by significant changes in the clay content of the soil, which is what makes it only transient. These changes in soil conditions immediately affect the growth of soil fertility and increase the proportion of agricultural land in the landscape cover structure. In addition, the share of broadleaf forests increases in the transition zone at the expense of a decrease in the share of coniferous and mixed forests. The transition zone is spatially limited, but it is an area of concentrated artificial cover, mainly in cities. Therefore, it requires special attention to ensure the sustainability of ecological processes.

Conclusion

Landscape and soil indicators revealed three soil-landscape complexes that correspond to the traditional division of this region into Polissia, Forest-Steppe and interzonal territory. In the region, the main reference soil groups are Phaeozems (36.6% of the region's area), Albeluvisols (30.7%), Chernozems (15.6%), Fluvisols (5.4%), and Histosols (3.2%). Other reference soil groups (Gleysols, Leptosols, Cambisols, Podzols, Umbrisols, Luvisols) each occupy less than 3% of the territory. Typical components of the soil cover of Polissia are Albeluvisols, Histosols, Gleysols, and Fluvisols. Deficit or excess moisture and associated changes in acidity, aeration, and trophicity lead to a significant deterioration of soil conditions for agricultural production in Polissia. Anthropogenic transformation can significantly increase the risk of soil erosion in this geographic area. Typical components of the Forest-Steppe soil cover within the study area are Phaeozems, Chernozems, Leptosols, and Cambisols (in the west). Soils in the Forest Steppe have a higher fertility potential and erosion control capacity, but more intensive agriculture is a significant factor in increasing erosion risks in this geographic area. The inter-zonal transition area is characterized by quantitative differences in soil properties and landscape cover. The inter-zonal transition area is characterized by higher humus content in the soil compared to Polissia, which is due to an increase in the silt content in the soil. Improved trophic conditions provide for the existence of a larger area of megatrophic broadleaf forests compared to oligotrophic coniferous or mesotrophic mixed forests. The transition zone is an area of concentrated artificial land cover, mostly in cities. Therefore, it requires special attention to ensure the sustainability of ecological processes.

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