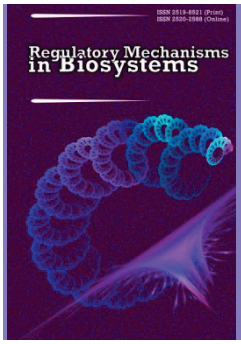

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Steppe vegetation islands in the gully landscape system: Hemeroby, naturalness and phytoindication of ecological regimes

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The article reveals the peculiarities of the vegetation cover of the gully system as a landscape where there are islands of steppe vegetation and their relationship with other types of natural and semi-natural vegetation. The steppe vegetation patches are islands of a vegetation type that was previously typical for a large geographically widespread physical and geographical zone. The steppe vegetation is a complex of species that is best adapted to climatic conditions and is a factor in ensuring the sustainable functioning of zonal landscape complexes. The limited nature of the remnants of steppe vegetation raises the issue of conservation of steppe vegetation and, if possible, restoration of their distribution. The field research was conducted in the Mayorska valley (Dnipropetrovska oblast, Ukraine) (48°16'41" N, 35°8'21.49" E). During the summer of 2023, the presence of all vascular plant species was recorded in 289 sample plots of 4 × 4 m in size. The vegetation cover of the gully system was represented by 263 plant species. The analysis of the synoptic phytosociological table allowed to determine that the vegetation cover of the studied gully system is represented by the six classes of vegetation. The highest level of species diversity was characteristic of *Festuco-Brometea*. A slightly lower number of species was observed for *Molinio-Arrhenatheretea* and *Agropyretalia intermedio-repentis*. The lowest number of species was observed in some associations of *Phragmito-Magnocaricetea*, as well as in *Galio-Urticetea* and *Onopordetalia acanthi*. The *Festuco-Brometea* steppe vegetation communities occur at the greatest distance from possible sources of anthropogenic impact, which are the slopes of the gully. The *Festuco valesiacae-Stipetum capillatae* associations were usually located in the upper third of the slopes, and the *Stipo lessingianae-Salvietum nutantis* and *Salvio nemorosae-Festucetum valesiacae* associations were usually located in the middle third of the gully slopes. The *Festuco-Brometea* steppe vegetation communities preferred habitats with the highest level of insolation compared to all others. All other syntaxon, with the exception of *Robinietea*, were in moderate insolation conditions and did not differ from each other in this respect. The class *Robinietea* was found under the lowest insolation level compared to all other syntaxon. The *Phragmito-Magnocaricetea* community prefers conditions with the highest level of topographic wetness index. The highest naturalness was found for such syntaxon as *Festuco-Brometea*, *Molinio-Arrhenatheretea* and *Phragmito-Magnocaricetea*. The lowest naturalness was found for such syntaxon as the class *Artemisietea vulgaris*. The hemeroby of the communities was negatively correlated with the number of species and the Shannon diversity index. The use of geomorphological variables, phytoindication assessments of environmental factors, naturalness and hemeroby as predictors allowed to discriminate syntaxon with an average accuracy of 85.5%. The leading gradient was a differential gradient that distinguishes biotopes with high insolation, variability of moisture conditions, high carbonate content, and high naturalness and low hemeroby from biotopes with higher levels of topographic moisture supply and phytoindication soil moisture estimates, higher soil nitrogen content, and higher ombroclimate indicators, and, accordingly, opposite indicators of naturalness and hemerobia. This gradient distinguishes between natural steppe (*Festuco-Brometea*) and meadow (*Molinio-Arrhenatheretea*) communities on the one hand and semi-natural and artificial ecosystems on the other. The practical significance of the study is that the role of hemerobia and naturalness indicators is emphasized for natural and semi-natural communities. Urban areas have been the usual testing ground for the use of hemeroby indicators. Our research indicates that in the context of significant anthropogenic transformation of the landscapes of the steppe zone of Ukraine, hemeroby and naturalness indicators can be applied to a wide range of ecosystem types. These indicators are appropriate for use in the practice of implementing projects to assess the environmental impact of planned activities. The assessment of hemeroby and naturalness of ecosystems based on botanical data should be recommended as a standard protocol for performing environmental impact assessments. It should also be noted that the spread of shelterbelts and artificial forest plantations within the gully systems is unacceptable. The reason for this is the provocation of erosion processes on the slopes of the gullies due to the destruction of steppe vegetation, which has the best erosion control capacity. Also, artificial forest plantations are a factor in the spread of invasive plant species, which is a negative factor that worsens the functional properties of plant communities and their diversity.

Keywords: diversity; plant community; landforms; anthropogenic transformation; discriminant analysis.

Introduction

Steppe landscapes play an important role in the creation of net primary production on a global scale. Due to high rates of anthropogenic transformation and widespread degradation, Palearctic steppes have become one of the most endangered terrestrial biomes in the world (Török et al., 2016). Steppes are increasingly declining due to local changes in management, often associated with land use intensification or abandonment. Steppes are often associated with fertile soils and are subject to widespread degradation and loss of area due to intensive crop cultivation or other forms of overuse. The steppe ecosystems are among the most threatened and least protected habitats in the world, so conservation and restoration of

steppe biodiversity, especially in agriculturally dominated landscapes, is a key priority for research and practical activities (Török et al., 2020). Steppes and semi-natural grasslands of the temperate zone are under great threat due to several global processes, such as climate change (Erdős et al., 2018), spread of invasive species (Holoborodko et al., 2022), land use changes and urbanization (Tsvetkova & Saranenko, 2007, 2010; Saranenko, 2011; Robinson, 2013; Faly & Brygadyrenko, 2014; Brygadyrenko, 2015; Tsvetkova et al., 2015). Arid and semi-arid steppes are particularly sensitive to climate change. The arid steppe with lower productivity is highly responsive to changes in precipitation, especially under warming conditions (Xu et al., 2016). Decreases in biodiversity and grassland productivity, as well as changes in the provision of ecosystem services in many regions due to changes in temperature and reduced water availability, have been documented (Lamarque et al., 2014). The total amount of precipitation during the growing season and the average temperature have an important influence on the annual net aboveground primary productivity of steppe plant communities (Dangal et al., 2016). A direct positive relationship between productivity and diversity was found for the Eurasian steppe. The strong positive linear relationship in this biome contradicts the conventional assumption that terrestrial ecosystems are dominated by a unimodal form of productivity-diversity relationship. The positive linear relationship was also found to be surprisingly robust to the effects of grazing. The explanation for this feature may be that precipitation has a greater influence on the relationship between productivity and diversity in steppe conditions than in herbaceous communities in other regions (Bai et al., 2007).

Species richness of herb communities is a complex phenomenon influenced by a number of abiotic and biotic environmental factors. The response of species richness to individual environmental factors depends both on the taxonomic group and on the combination of abiotic and biotic factors in the whole (Löbel et al., 2006). Temperate steppe landscapes are known to have a high, and in some cases extraordinary, small-scale vascular plant diversity (Wilson et al., 2012). Soil response and land use intensity are the most prominent factors affecting the species richness of Palaearctic grasslands (Dengler et al., 2014). European grassland plant species richness increases linearly with increasing soil pH (Schuster & Diekmann, 2003). The response of species richness to mean annual temperature is unimodal (Kuzemko et al., 2016). The type and intensity of land use strongly influence the phytodiversity of European grasslands. Extraordinarily high species richness is usually observed in semi-natural areas which are regularly mowed for a long time (Dengler et al., 2014). The heat index was found to negatively affect the species richness of steppe vegetation (Kuzemko et al., 2016). The heat load index had a negative impact on the diversity of herbaceous plant communities in the range of test plots sizes from 1 to 10 m^2 (Turtureanu et al., 2014). This is explained by the fact that the heat load reduces the availability of water (Pausas & Austin, 2001). The highest heat load is associated with very steep slopes where erosion is continuous. In turn, in northern central and northern Europe, where extreme summer drought is not a problem, solar radiation has been shown to have a positive effect on grassland diversity (Klimek et al., 2007). Climatic factors are important determinants of species richness. Species richness is strongly positively correlated with the average temperature of the coldest month. Species richness increases strongly with increasing annual precipitation. The type of bedrock and soil pH also have a significant impact on the richness of steppe communities (Palpurina et al., 2015). Environmental disturbance due to fires or grazing is a factor in increasing the species diversity of steppe communities (Kuzemko et al., 2016).

The steppe zone covers 39.4% of Ukraine's land area (Lyalko et al., 2017). Steppe vegetation was usually located on plateau areas within the steppe zone (Belgard, 1950). The landscape cover of the steppe zone is extremely transformed due to intensive agricultural development (Moon, 2016). The transformation of steppe into arable land took place in the steppe zone of Ukraine between 200 and 100 years ago (Lisetskii, 1992). Due to the fertile chernozem and chestnut soils and relatively flat terrain, vast areas of the steppe have been transformed into arable fields (Wesche et al., 2016). The area of agricultural land in the steppe zone of Ukraine is about 80% (Sudnik-Wójcikowska et al., 2006) which has led to the fact that only 1% of the country's natural steppe vegetation is preserved (Parnikoza & Vasiluk, 2011). The Ukrainian steppe is now preserved only in nature reserves, on the slopes of river valleys, forest gullys, old cemeteries and kurgans (Dembicz et al., 2021). The focus of natural vegetation in the steppe zone of Ukraine is river valleys, as they usually have steep slopes and are unsuitable or poorly suited for agricultural development (Lavrinenko et al., 2023). The kurgans are island habitats where a high diversity of steppe vegetation is preserved (Moysiyenko & Sudnik-Wójcikowska, 2006). For specialized species, the steppe "islands" clearly correspond to the theory of island biogeography, while for universal species the correspondence was less clear. The conservation value of the kurgans in the long term can only be achieved by increasing their area (Dembicz et al., 2021). The slopes of the right banks of the steppe rivers are crossed by gullys, on the slopes of which a high floristic and landscape diversity of steppe vegetation is also preserved.

Steppe vegetation centers are islands of a vegetation type that used to be typical for a large geographically widespread physical and geographical zone. The steppe vegetation is a complex of species that is best adapted to climatic conditions and is a factor in ensuring the sustainable functioning of zonal landscape complexes. The limited nature of the remnants of steppe vegetation raises the issue of conservation of steppe vegetation and, if possible, restoration of their distribution. The aim of this article was to reveal the peculiarities of the vegetation cover of the gully system as a landscape where there are islands of steppe vegetation and to identify their relationship with other types of natural and semi-natural vegetation.

Materials and methods

The field investigations were carried out in the Mayorska valley (Dnipropetrovska oblast, Ukraine) (48°16'41" N, 35°8'21.49" E). The climate is continental, with an average annual temperature of 9.9 ± 0.2 °C (in the range of 8.4–12.4 °C) over the period 2000–2022 with a temperature increase trend of 0.07 °C annually on average (Fig. 1). The average annual precipitation was 555 ± 17 mm (range 429–696 mm). The landscape is dominated by extensive, slightly undulating plains. Loess and loess-like loams are the most common geological surface rock, reaching a thickness of several tens of meters (Samoilych & Mokritskaia, 2016). The study area belongs to the Central Pontic herbaceous steppe zone (EuroVegMap). The natural vegetation is dominated by cereals and grasses.

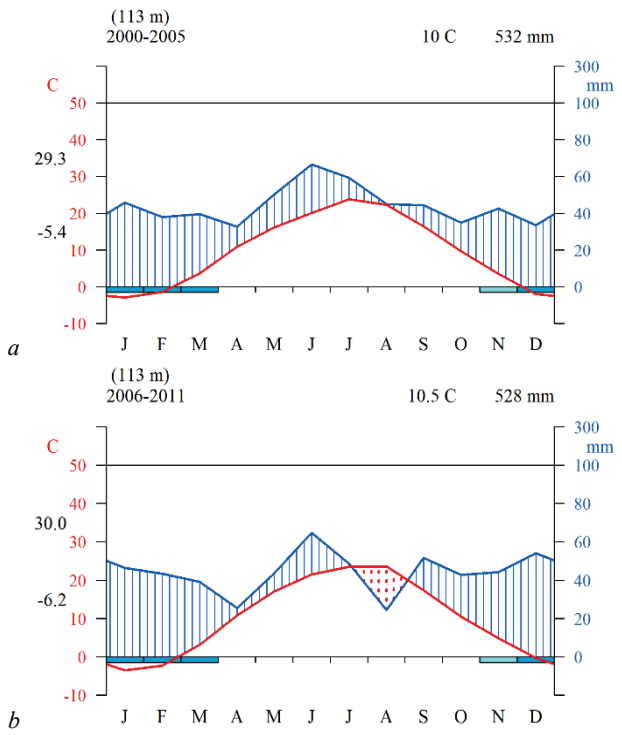


Fig. 1. Dynamics of the average annual temperature (*a*) and annual precipitation (*b*) according to the Dnipro weather station during 2000–2022: the abscissa is years, the ordinate is: (*a*) average annual temperature (°C); (*b*) total precipitation per year (mm)

The vegetation cover of the Mayorska valley is a combination of vegetation of different levels of anthropogenic transformation. The valley is surrounded by agricultural fields, which are usually bordered by artificial tree plantations. Tree plantations are also located on the slopes of the valley, with a particularly large area of artificial forest plantations on the slope of the northern exposure. Natural steppe vegetation is found on the gully's slopes. In some cases, steppe vegetation on the slopes of the gully borders directly on agricultural fields. In the areas disturbed by anthropogenic activity, invasive tree species or ruderal grass vegetation are spreading. Ruderal herbaceous vegetation also develops in the area of degradation of artificial tree plantations or along roads. In the lower thirds of the slopes and in the thalweg, there is meadow vegetation. Wetland vegetation is found in the thalweg. Shrubs are found on the slopes of the gully among the steppe vegetation.

Botanical data collection. During the summer of 2023, we recorded the presence of all vascular plant species in 289 sample plots of 4 × 4 m (Fig. 2). The projected species coverage was determined as a percentage. For the purposes of this study, we generally took infraspecific taxa as species. Critical specimens were collected and identified by microscopy. The sample plots were distributed throughout the study area and their exact location was determined using GPS (Garmin eTrex, ± 5 m). We tried to select samples that would represent the full range of community types and plot sizes within the gully system. Plant taxonomy was based on Euro+Med Plantbase (http://ww2.bgbm.org/EuroPlusMed). The vegetation was classified using the TWINSPAN software (Hill, 1979). The fidelity of diagnostic species for clusters was determined using the fidelity coefficient (phi coefficient) with a fidelity threshold of 25 (for highly diagnostic species – 50), species with a frequency of occurrence > 25% (for highly constant species > 50%) were considered constant, and species with projective coverage > 10% were considered dominant (Lavrinenko et al., 2023). The phi coefficient was calculated using the indicspecies library (Cáceres, 2013). Syntaxes were identified up to the association level; names of syntaxes are given according to the European Vegetation of Europe (Mucina et al., 2016) and the Prodromus of Vegetation of Ukraine (Dubina et al., 2019). Phytoindication assessment of environmental factors was carried out in accordance with the methodology of synphytoindication by Didukh (2011), and the calculations were made using the ideal indicator method (Buzuk, 2017). For clarity, the scores were converted to equivalent physical values. Descriptive statistics, ANOVA, analysis of components of relative variance, were calculated. The Walter-Lieth diagram (Walter & Lieth, 1960) was created using the climatol library based on data from The Center for Environmental Data Analysis (https://data.ceda.ac.uk). Habitat nomenclature is based on EUNIS (http://eunis.eea.europa.eu).

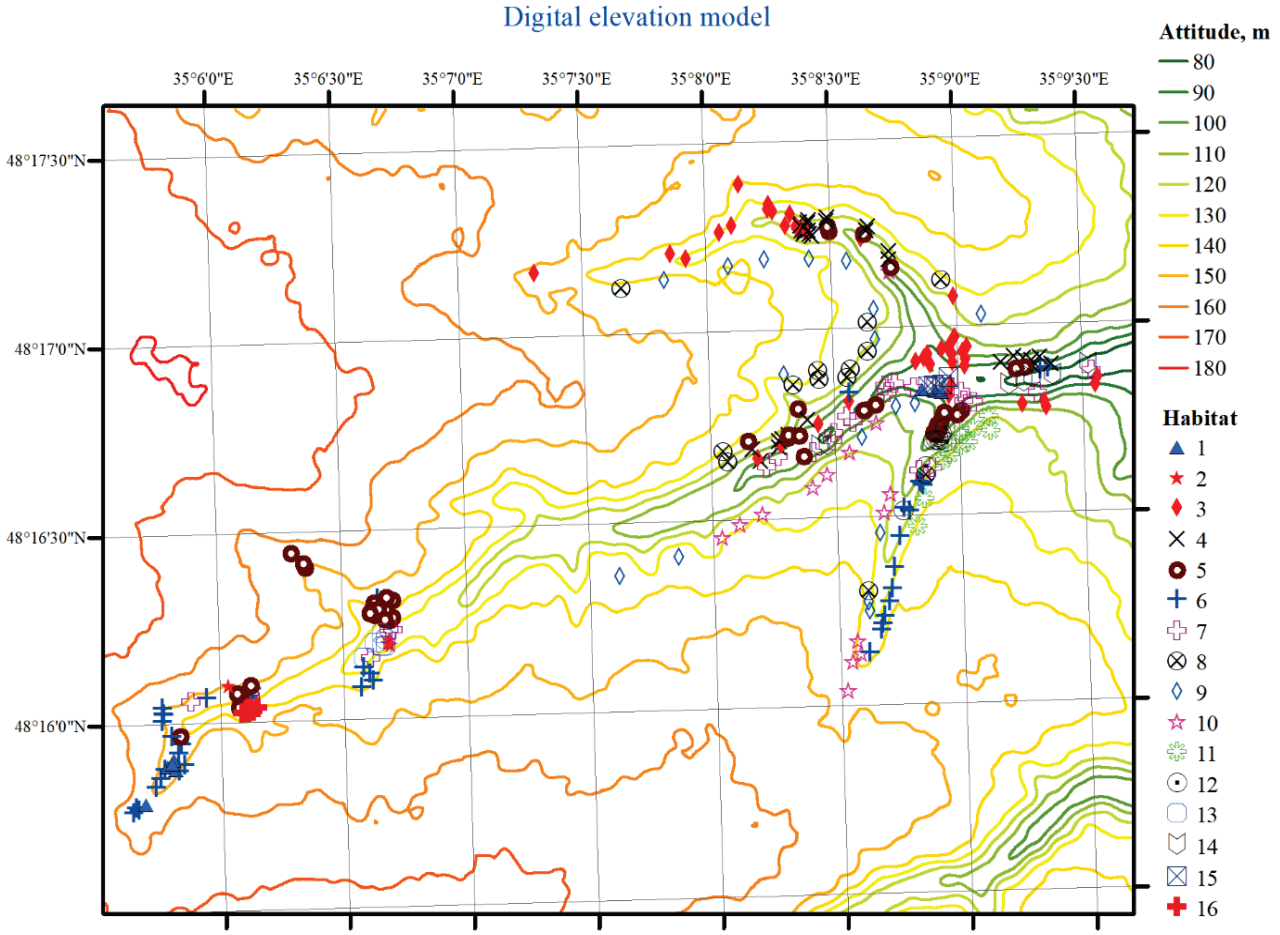


Fig. 2. Digital elevation model and locations of habitat types: * 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th.Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948)

Hemeroby, types of social behavior, and the value of plant naturalness. The Frank & Klotz (1990) scales were used to assess hemeroby. The original scales were converted by calculating the half-sum of the minimum and maximum values for each species, and then they were converted to a 100-point scale. The weighted average of the hemeroby scores, taking into account the projected plant cover, was used to characterize the hemeroby of each sample (Yorkina et al., 2022).

Types of plant social behavior are based on the role that plant species play in communities. They reflect the way in which the plant is connected to the habitat, as well as the informativeness and naturalness of this connection. The properties of the types found in a community can be used to infer the richness of ecological information in the community, its stability and naturalness, the degree of niche filling, the regeneration capacity or capacity of the community, and the degree of disturbance, transformation, or deviation from the natural state (Borhidi, 1995) (Table 1).

Table 1
Social types and value of plant naturalness (Borhidi, 1995)

	Social types	Naturalness
I.	Competitors (C)	
	A) Rare competitors (RC)	+5
	B) Unique competitors (UC)	+7
II.	Stress tolerant (ST)	
	A) Stress tolerant of narrow ecology: Specialists (S)	+9
	B) Rare specialist (RS)	+6
	C) Unique specialist (US)	+8
	D) Stress tolerant of wide ecology: Generalists (G)	+10
	E) Rare generalists (RG)	+4
	F) Unique generalists (UG)	+6
III.	Ruderals (R)	
	A) Plants of habitats disturbed by natural factors: Natural pioneers (NP)	+8
	B) Plants of habitats disturbed by human factors	+3
	1. Disturbance tolerant plants of natural habitats (T)	+2
	2. Anthropophilous elements of the native flora: native weed species (W)	+1
	3. Anthropogenic elements alien to the region	
	a) Introduced crops running wild (I)	–1
	b) Adventitious weeds (A)	–1
	4. Competitors of secondary habitats	
	a) Ruderal competitors of the natural flora (RC)	–2
	b) Alien competitors, aggressive invaders (AC)	–3

To analyze the naturalness of each sample, the weighted average of the scales of social behavior types was used, taking into account the projective coverage of plants (Yorkina et al., 2022).

Digital elevation model and derived geographic information layers. A digital elevation model (DEM) is a digital representation of the earth's surface. The data from the Advanced Land Observation Satellite – ALOS (www.eorc.jaxa.jp/ALOS/en/index.htm) were used to create the digital elevation model. The spatial resolution for this model is 12.5 meters. The DEM was resampled to a resolution of 1 m using the kriging procedure (Susetyo, 2016). The kriging procedure also made it possible to obtain a DEM appropriate for computing derived layers, such as the topographic wetness index and erosion coefficient (Zhukov et al., 2021).

The concept of the topographic moisture index (TWI) was first proposed by Beven & Kirkby (1979) which can be calculated using the formula:

$$TWI = ln(a/\tan\beta),$$

where a is the area of elevation per unit length of the contour, β is the local slope. TWI has no unit. High TWI values indicate an area with an increased potential for accumulated surface runoff.

Terrain erosion potential (LS) is one of the components of the Universal Soil Loss Equation (USLE). LS is the product of L- and S-factors. The L-factor represents the length of the slope and the S-factor represents the steepness of the slope. The LS-factor is dimensionless and has values equal to or greater than 0 (Panagos et al., 2015). The TWI and LS-factor were calculated in this study using the SAGA software (Conrad et al., 2015).

Results

Climate change during the 21st century. The analysis of Walter-Lieth diagrams indicates a trend of climate aridization that has occurred during the 21st century (Fig. 3). The duration of the dry period in late summer at the beginning of the century was insignificant. At the end of August, there was a short dry period, which ended with a characteristic period of autumn rains. The increase in average annual air temperature was accompanied by an increase in temperatures in late summer and early fall and a decrease in precipitation during this period. After 2006, the dry period took place from late July to early September. In the period 2012–2017, the start of the dry period shifted to almost the beginning of July, and the end shifted to mid-September. In the period 2018–2023, the dry period became even more extreme and occurred between August and the end of September.

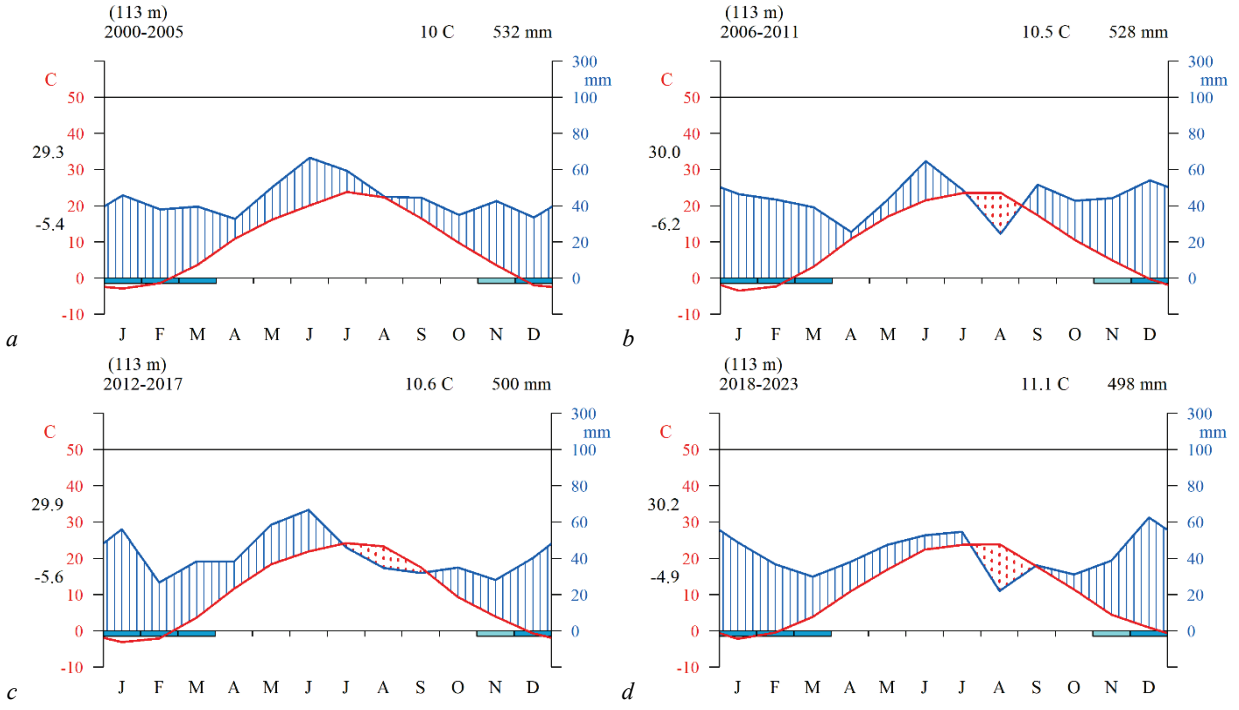


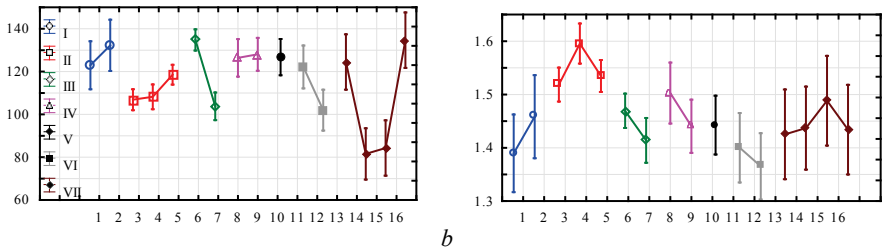
Fig. 3. Walter- Lieth diagram for the periods 2000–2005 (*a*), 2006–2011 (*b*), 2012–2017 (*c*), 2018–2023 (*d*): the humid period is shown in blue, the dry period is shown in red

Vegetation cover. The vegetation cover of the gully system was represented by 263 plant species. The analysis of the synoptic phytosociological table (Table 2) allowed to find out that the vegetation cover of the studied gully system is represented by six classes of vegetation.

Class Festuco-Brometea Br.-Bl. et R.Tx. in Br.-Bl. 1949
Oder *Festucetalia valesiacae* Soó 1947
Union *Festucion valesiacae* Klika 1931
Association *Festuco valesiacae-Stipetum capillatae* Sill 1931
Association *Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997
Union *Astragalo-Stipion* Knapp 1944
Association *Stipo lessingianae-Salvietum nutantis* Vynokurov 2014
Class *Molinio-Arrhenatheretea* Tx. 1937
Oder *Galietalia veri* Mirkin et Naumova 1986
Union *Agrostion vinealis* Sipaylova et al. 1985
Association *Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986
Association *Poëtum angustifoliae* Shelyag-Sosonko et al. 1986
Class *Artemisietea vulgaris* Lohmeyer et al. in Tx. 1950
Oder *Onopordetalia acanthii* Br.-Bl. et Tx. ex Klika et Hadač 1944
Union *Arction lappae* Tx. 1937
Association *Arctietum lappae* Felföldy 1942
Union *Dauco-Melilotion* Görs ex Rostański et Gutte 1971
Association *Asclepiadetum syriacae* Láníková in Chytrý 2009
Oder *Agropyretalia intermedio-repentis* T. Müller et Görs 1969
Union *Convolvulo arvensis-Agropyrion repentis* Görs 1967
Association *Melico transsilvanicae-Agropyretum* Th.Mull. in Gors 1966
Association *Convolvulo arvensis-Agropyretum repentis* Felföldy 1943
Class *Galio-Urticetea* Passarge ex Kopecký 1969
Oder *Galio-Alliarietalia* Oberd. in Görs et T. Müller 1969
Union *Geo urbani-Alliarion officinalis* Lohmeyer et Oberd. in Görs et T. Müller 1969
Association *Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973
Class *Robinietea* Jurko ex Hadač et Sofron 1980
Oder *Chelidonio-Robinietalia pseudoacaciae* Jurko ex Hadač et Sofron 1980
Union *Chelidonio-Acerion negundi* L. Ishbirdina et A. Ishbirdin 1991
Association *Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991
Union *Chelidonio majoris-Robinion pseudoacaciae* Hadač et Sofron ex Vitková in Chytrý 2013
Association *Chelidonio-Robinietum* Jurko 1963
Class *Phragmito-Magnocaricetea* Klika in Klika et Novák 1941
Oder *Phragmitetalia* Koch 1926
Union *Phragmition communis* Koch 1926
Association *Phragmitetum australis* Savič 1926
Association *Typhetum latifoliae* Soo 1927
Association *Typhetum angustifoliae* Pignatti 1953
Union *Eleocharito palustris-Sagittarion sagittifoliae* Passarge 1964
Oder *Oenanthetalia aquaticae* Hejný ex Balátová-Tuláčková et al. 1993
Association *Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948

Relief elevation and insolation within communities. The Class and Association variables were able to explain 39% of the variation in relief height ($R_{adj}^2 = 0.39$, $F = 13.0$, $P < 0.001$). The results of the nested hierarchical ANOVA analysis showed that the variable "Class of syntax" was not a statistically significant predictor, and the predictor "Association" explained 43.8% of the variation in relief altitude ($F = 14.9$, $P < 0.001$). The associations within each class are located at different elevations, which explains why the variable "Syntaxon class" was not a statistically significant predictor (Fig. 4). The *Phragmito-Magnocaricetea* associations were found in the upper part of the gully thalweg, where the elevation is high, and also occurred in the lower part of the gully, where the elevation is low. The *Molinio-Arrhenatheretea* meadow communities are located in close proximity to the *Phragmito-Magnocaricetea* communities, so they show similar patterns of elevation. The syntaxons of semi-natural vegetation (*Onopordetalia acanthi*, *Agropyretalia intermedio-repentis*, and *Galio-Urticetea*) occur in close proximity to artificial tree plantations on the plateau, where anthropogenic disturbance creates conditions for their development. Therefore, the elevations of the relief level where these communities are found were relatively high. The Robinietea tree communities occupy a wide range of altitudinal conditions within the gully. The *Chelidonio-Robinietum* association was typically found on the plateau or in the upper third of the slope, and the *Chelidonio-Aceretum negundi* association was typically found in the lower third of the slopes or even in the thalweg of the gully.

The steppe vegetation communities of *Festuco-Brometea* occur at the greatest distance from possible sources of anthropogenic impact, which are the slopes of the gully. The *Festuco valesiacae-Stipetum capillatae* associations were usually located in the upper third of the slopes, and the *Stipo lessingianae-Salvietum nutantis* and *Salvio nemorosae-Festucetum valesiacae* associations were usually located in the middle third of the gully slopes.



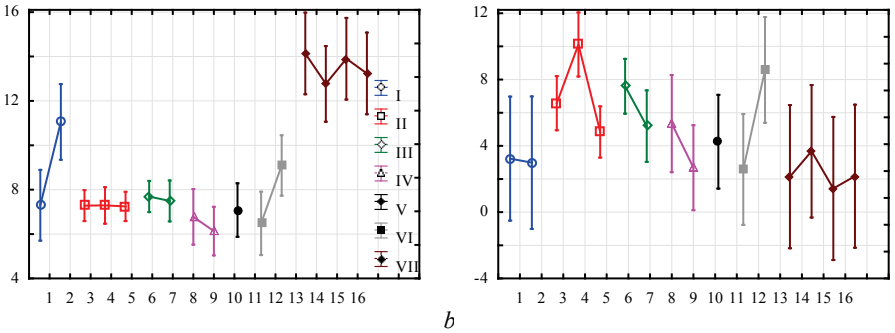
a *b*

Fig. 4. Relief altitude, m (*a*) and solar insolation, MWh/m^2 (*b*) within vegetation syntaxons: I – *Onopordetalia acanthi*; II – *Festuco-Brometea*; III – *Molinio-Arrhenatheretea*; IV – *Agropyretalia intermedio-repentis*; V – *Galio-Urticetea*; VI – *Robinietea*; VII – *Phragmito-Magnocaricetea*; 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th. Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948)

The variables class and association were able to explain 22% of the variation in insolation within communities ($R_{adj}^2 = 0.22$, $F = 6.6$, $P < 0.001$). The results of the nested hierarchical ANOVA analysis showed that the predictor "Syntaxon class" explained 21.9% of the variation in the number of species ($F = 14.2$, $P < 0.001$), and the predictor "association" explained 5.3% of the variation in the number of species ($F = 2.3$, $P = 0.017$). The steppe vegetation community *Festuco-Brometea* preferred habitats with the highest insolation compared to all others (Planned comparison $F = 73.4$, $P < 0.001$). All other syntaxon, with the exception of *Robinietea*, were in the moderate insolation conditions and did not differ

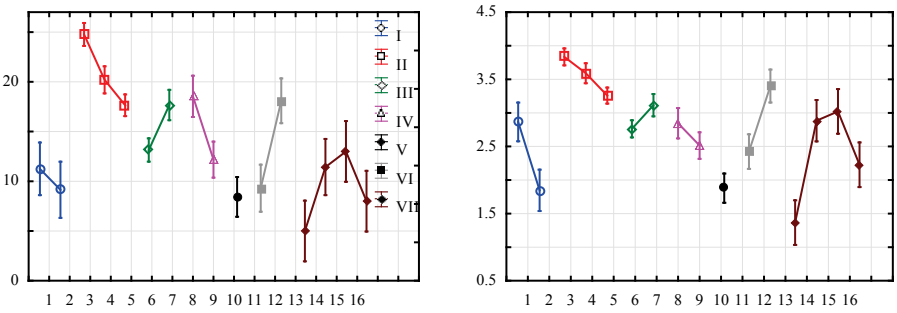
from each other in this indicator (Planned comparison F = 0.89, P = 0.34). The class *Robinietea* occurred under conditions of low insolation compared to all other syntaxon (Planned comparison F = 10.8, P < 0.002). The association *Chelidonio-Aceretum negundi* was found at the lowest insolation level.

Topographic wetness index and erosion index. The variables class and association were able to explain 39% of the variation in the topographic wetness index within plant associations (R_{adj}^2 = 0.39, F = 10.1, P < 0.001). The results of the nested hierarchical ANOVA analysis showed that the predictor "syntaxon class" explained 41.6% of the variation in the topographic wetness index (F = 29.6, P < 0.001), and the predictor "association" explained 3.4% of the variation in the number of species (F = 2.1, P = 0.028). The *Phragmito-Magnocaricetea* community favored the conditions with the highest topographic wetness index (Fig. 5). Associations within the *Festuco-Brometea*, *Molinio-Arrhenathereteа* and *Agropyretalia intermedio-repentis* syntaxons occupy uniform conditions in terms of the topographic wetness index within the respective syntaxon. The associations within *Onopordetalia acanthi* and *Robinietea* differed significantly in terms of the topographic wetness index. Within the order *Onopordetalia acanthi*, the association *Asclepiadetum syriacae* differed in that it preferred conditions with a significantly higher level of topographic wetness than the association *Arctietum lappae* from the same order. Within the *Robinietea* class, the association *Chelidonio-Aceretum negundi* was much more hygrophilous than *Chelidonio-Robinietum*.



a *b*

Fig. 5. Topographic wetness index (*a*) and erosion index (*b*) within vegetation syntaxons: I – *Onopordetalia acanthi*; II – *Festuco-Brometea*; III – *Molinio-Arrhenathereteа*; IV – *Agropyretalia intermedio-repentis*; V – *Galio-Urticetea*; VI – *Robinietea*; VII – *Phragmito-Magnocaricetea*; 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th. Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948)



a *b*

Fig. 6. Species richness (*a*) and Shannon index (*b*) of vegetation syntaxons: I – *Onopordetalia acanthi*; II – *Festuco-Brometea*; III – *Molinio-Arrhenathereteа*; IV – *Agropyretalia intermedio-repentis*; V – *Galio-Urticetea*; VI – *Robinietea*; VII – *Phragmito-Magnocaricetea*; 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th. Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948)

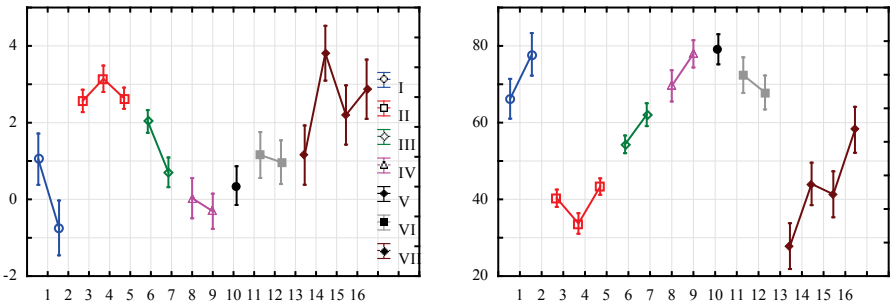
The variables class and association were able to explain 12% of the variation in the erosion index within plant associations (R_{adj}^2 = 0.12, F = 3.6, P < 0.001). The results of the nested hierarchical ANOVA analysis showed that the predictor "syntaxon class" explained 2.2% of the variation in the erosion index (f = 4.5, p < 0.001), and the predictor "association" explained 11.3% of the variation in the number of species (F = 3.3, P = 0.028). The most at risk from the point of view of the development of erosion processes of the soil cover are such associations as *Stipo lessingianae-Salvietum nutantis* and *Chelidonio-Aceretum negundi*. In the most erosive

locations, there were communities of such syntaxons as *Festuco-Brometea*, *Molinio-Arrhenathеretea* and *Robinietea*.

Species diversity of communities. The variables class and association were able to explain 64% of the variation in the number of species (R_{adj}^2 = 0.64, F = 35.7, P < 0.001). The results of the nested hierarchical ANOVA analysis revealed the predictor "syntax class" explained 37.9% of the variation in the number of species (F = 60.6, P < 0.001), and the predictor "association" explained 30.9% of the variation in the number of species (F = 18.5, P < 0.001). The highest level of species diversity was observed in the *Festuco-Brometea*. A slightly lower number of species was observed for *Molinio-Arrhenathеretea* and *Agropyretalia intermedio-repentis* (Fig. 6). The lowest number of species was observed in some *Phragmito-Magnocaricetea* associations, as well as in *Galio-Urticetea* and *Onopordetalia acanthi*.

The variables class and association were able to explain 67% of the variation in Shannon's index (R_{adj}^2 = 0.67, F = 39.5, P < 0.001). The results of the nested hierarchical ANOVA analysis indicated that the predictor "syntax class" explained 41.4% of the variation in the Shannon index (F = 70.9, P < 0.001), and the predictor "association" explained 29.6% of the variation in the Shannon index (F = 19.2, P < 0.001). The pattern of the Shannon index reproduces the pattern of species richness (r = 0.86, P < 0.001), indicating that the number of species is the main driver of variability in species diversity of plant communities.

Naturalness and hemeroby of communities. The variables class and association were able to explain 58% of the variation in the naturalness of plant communities (R_{adj}^2 = 0.58, F = 28.1, P < 0.001). The results of the nested hierarchical ANOVA analysis showed that the predictor "syntax class" explained 50.6% of the variation in naturalness (F = 58.9, P < 0.001), and the predictor "association" explained 14.7% of the variation in naturalness of the community (F = 8.5, P < 0.001). The highest naturalness was found for such syntaxons as *Festuco-Brometea*, *Molinio-Arrhenathеretea*, and *Phragmito-Magnocaricetea* (Fig. 7). The lowest naturalness was found for such syntaxon as the class *Artemisietea vulgaris* (orders *Onopordetalia acanthi* and *Agropyretalia intermedio-repentis*). The naturalness was positively correlated with the number of species (r = 0.28, P < 0.001) and the Shannon diversity index (r = 0.39, P < 0.001).



a *b*

Fig. 7. Species naturalness (*a*) and hemeroby (*b*) of vegetation syntaxons: I – *Onopordetalia acanthi*; II – *Festuco-Brometea*; III – *Molinio-Arrhenathеretea*; IV – *Agropyretalia intermedio-repentis*; V – *Galio-Urticetea*; VI – *Robinietea*; VII – *Phragmito-Magnocaricetea*; 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th. Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948)

The variables class and association were able to explain 80% of the variation in plant community hemeroby (R_{adj}^2 = 0.80, F = 76.7, P < 0.001). The results of the nested hierarchical ANOVA analysis showed that the predictor "syntaxon class" explained 71.1% of the variation in hemeroby (F = 181.1, P < 0.001), and the predictor "Association" explained 10.7% of the variation in hemeroby (F = 8.5, P < 0.001). The hemeroby score divided the syntaxons into three almost homogeneous groups. The first group contains *Festuco-Brometea* and *Phragmito-Magnocaricetea* with the lowest level of hemeroby. The second group contains *Molinio-Arrhenathеretea* with a transitional level of hemeroby. And the third group contains all semi-natural communities with the highest level of hemeroby. Among the semi-natural communities, the highest hemeroby was found for the syntaxon *Galio-Urticetea*. The hemeroby was negatively correlated with the number of species (r = –0.38, P < 0.001) and Shannon's diversity index (r = –0.48, P < 0.001).

Phytoindication assessment of ecological regimes. The content of productive moisture in the soil, estimated on the basis of phytoindication, varied from 36.9 ± 1.6 mm in the meter layer of soil within the associations belonging to the class *Festuco-Brometea* to 107.9 ± 19.0 mm in the associations belonging to the class *Phragmito-Magnocaricetea* (Table 2). The content of productive moisture within the classes *Molinio-Arrhenathеretea*, *Galio-Urticetea* and the order *Agropyretalia intermedio-repentis* did not differ and amounted to 42.7 ± 2.0 mm. The moisture content within the artificial tree plantations of the *Robinietea* class was 51.7 ± 4.5%. The weedy vegetation of the order *Onopordetalia acanthii* was usually located under conditions of high soil moisture content, which amounted to 81.7 ± 12.9 mm. The vegetation class and association were able to explain 81.4% of the variation in the phytoindicator score of moisture regime (F = 85.2, P < 0.001). The class of vegetation explained 45.7% of the variation in this indicator, and the association as a nested variable was able to explain 38.6% of the variation in the moisture regime (Fig. 8). The highest soil moisture content is naturally observed within the *Phragmito-Magnocaricetea* vegetation class, and the lowest content was observed for plant communities within the *Festuco-Brometea* class. Within the *Phragmito-Magnocaricetea* class, significant differences in soil moisture levels are observed. The association *Typhetum latifoliae* was characterized by the lowest level of edaphic moisture, and the association *Butomo-Alismatetum plantaginis-aquaticae* was characterized by the highest level of moisture. The associations did not differ by the level of moisture within the classes *Festuco-Brometea* and *Molinio-Arrhenathеretea*. Significant differences within the class are observed for the classes *Artemisietea vulgaris* and *Robinietea*.

The variable Class was not a statistically significant predictor of moisture regime variability (F = 0.91, P = 0.53) and 44.2% of the variation in this indicator was determined by plant association (F = 15.1, P < 0.001). The largest range of moisture contrast conditions was covered by *Phragmito-Magnocaricetea* associations from the most constant *Typhetum latifoliae* (ω = 0.12 ± 0.02) to the most contrasting *Butomo-Alismatetum plantaginis-aquaticae* (ω = 0.29 ± 0.03). Among the associations of the *Festuco-Brometea* class, the most constant water regime was within the

Festuco valesiacae-Stipetum capillatae (ω = 0.20 ± 0.01), and the most contrasting regime was within the *Salvio nemorosae-Festucetum valesiacae* (ω = 0.27 ± 0.01). The associations of *Robinietea* did not differ in contrast regime (ω = 0.17 ± 0.02).

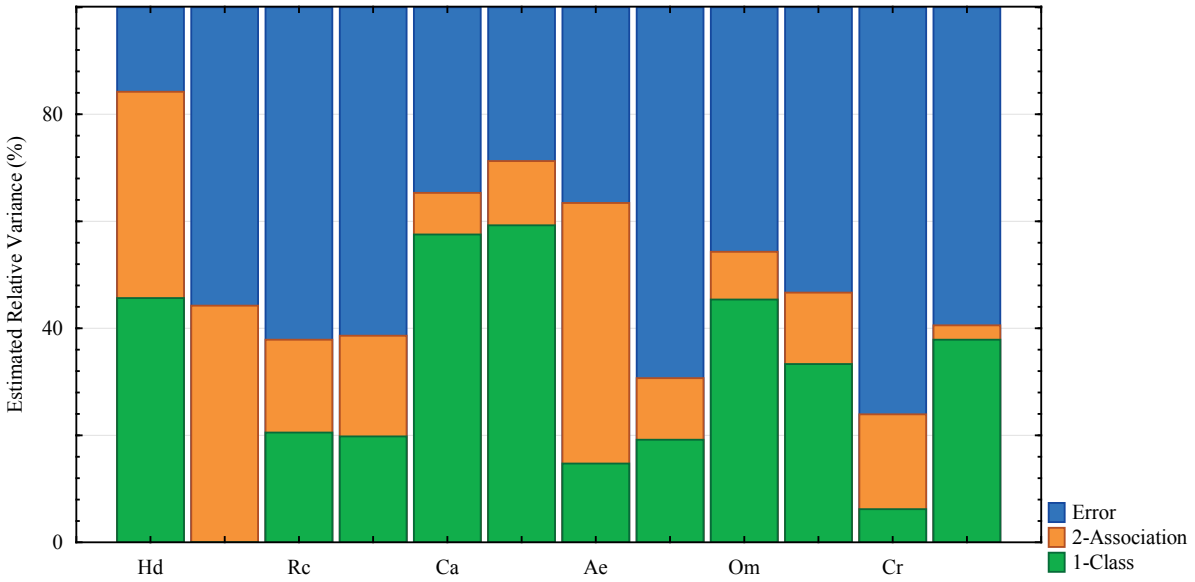


Fig. 8. Fractionation of variation of phytoindication estimates of ecological regimes between classes and associations of vegetation cover: Hd is the content of productive moisture in the meter-long soil layer (mm); fH is the ω coefficient of moisture unevenness; Rc is the negative logarithm of the concentration of hydrogen ions in the soil solution (pH); Sl is the content of salts in the soil solution (μg/L); Ca is the content of carbonates (in terms of calcium and magnesium oxides, %); Nt is the content of nitrogen in the soil (g/kg); Ae is the aeration aperture (% of the total volume of the aeration space in the soil); Tm is the radiation balance (gJ/m^2 year); Om is the difference between the amount of precipitation on average per year in terms of a day to evaporation from the open water surface for the same period (mm); Kn is the Ivanov continental scale; Cr is the average temperature of the coldest month of the year; Lc is the lighting regime

The variable class was able to explain 20.5% of the variability in soil acidity, and the association was able to explain 17.3% of the variation in this indicator. The most acidic soils were found within the *Agropyretalia intermedio-repentis* order (pH = 6.7 ± 0.05), and the most alkaline soils were characteristic of the *Festuco-Brometea* class (pH = 7.0 ± 0.01). The vegetation class was able to explain 19.8% of the variability in the content of dissolved salts in soil aqueous solution, and the Association was able to explain 18.8% of the variation in this indicator. Within the plant associations within the syntaxon *Robinietea*, *Agropyretalia intermedio-repentis* and *Galio-Urticetea*, the content of dissolved salts in the soil aqueous solution was the lowest and amounted to 20.1 ± 2.2 μg/L. The content of dissolved salts in the soil aqueous solution was 30.5 ± 2.4 μg/L in the plant communities *Phragmito-Magnocaricetea*. In the *Molinio-Arrhenatheretea* and *Onopordetalia acanthii* syntaxon communities it was higher and amounted to 35.7 ± 3.5 μg/L. The highest content of dissolved salts in the soil aqueous solution was within the associations of the *Festuco-Brometea* class and amounted to 38.4 ± 1.1 μg/L.

The carbonate content of the soil differed significantly by vegetation class, which explained 57.5% of the variation in this indicator. The association accounted for 7.8% of the variation in carbonate content. The lowest carbonate content was determined within the *Phragmito-Magnocaricetea* communities, where it was 1.3 ± 0.3%. The *Festuco-Brometea* plant communities were formed under conditions of the highest carbonate content, where they amounted to 5.6 ± 0.1 %. Other vegetation types had transitional levels of carbonate content in the soil. The nitrogen content was largely dependent on the vegetation class. The vegetation class was able to explain 59.3% of the variation in this indicator. The association was able to explain 12.0% of the variation in nitrogen content. The *Festuco-Brometea* plant communities were formed under conditions of the lowest soil nitrogen content (0.75 ± 0.04 g/kg). Within the *Molinio-Arrhenatheretea* meadow communities, the nitrogen content in the soil was slightly higher (1.23 ± 0.11 g/kg). Among the ruderal communities, the nitrogen content was the lowest within the *Agropyretalia intermedio-repentis* (1.91 ± 0.21 g/kg). Within the *Galio-Urticetea* and *Onopordetalia acanthii* communities, an increase in soil nitrogen content was observed (2.73 ± 0.37 and 3.10 ± 0.33 g/kg, respectively). The highest nitrogen content in the soil was found within the tree plantations of *Robinietea* (3.56 ± 0.23 g/kg). Within the *Phragmito-Magnocaricetea* class, the nitrogen content in the soil varied greatly. The lowest nitrogen content was found within the *Phragmitetum australis* association (1.75 ± 0.33 g/kg), and the highest within the *Typhetum angustifoliae* association (4.33 ± 0.33 g/kg). As we can see, the level of variation in nitrogen content among the associations of the *Phragmito-Magnocaricetea* class is commensurate with the variability of this indicator between other classes of vegetation cover.

The importance of features between associations was more important in generating variation in soil aeration than differences between land cover classes. The associations determined 48.7% of the variability in soil aeration, while the classes determined 14.7% of the variation in this indicator. The main source of this pattern was the associations of the *Phragmito-Magnocaricetea* class. The soil aeration within this class varied from very high within the *Typhetum angustifoliae* association (83.1 ± 1.8%) to the lowest level of aeration within the *Phragmito-Magnocaricetea* association (9.1 ± 1.8%). The level of aeration was very high among the vegetation classes *Festuco-Brometea* (72.8 ± 0.7%) and *Molinio-Arrhenatheretea* (77.9 ± 1.1%). The level of aeration was in the range of 63–69% in the semi-natural communities.

Unexplained variance for soil properties using plant class and association was in the range of 15.8–62.1%. Unexplained variance for climate scales was even higher, ranging from 36.6–76.1%. The vegetation class was able to explain 14.7% of the variation in thermal regime, and the association was able to explain 48.7% of the variation in this indicator. The phytoindication assessment provided the highest value of the radiation balance within the Phragmito-Magnocaricetea plant community (2.10 ± 0.02 gJ/m year). However, the estimates of the radiation balance within this class should be noted to vary greatly between the associations. The highest radiation balance was estimated based on the data obtained from *Typhetum latifoliae*, and the lowest was obtained from *Phragmito-Magnocaricetea* (Table 3). A relatively high level of radiation balance was found for the *Festuco-Brometea* communities (2.05 ± 0.01 gJ/m year). The radiation balance for other plant communities was in the range of 1.83–1.95 gJ/m year.

The vegetation class was able to explain 45.4% of the variation in the ombroclimate, and the associations were able to explain 8.9% of the variation in this indicator. The estimate of the ombroclimate was the lowest for

the Festuco-Brometea class (–1.49 ± 0.04 mm). The estimate of the ombroclimate was somewhat higher for plant communities of the *Molinio-Arrhenatheretea* class (–1.15 ± 0.07 mm). The highest estimate of the ombroclimate was for the *Galio-Urticetea* communities (–0.14 ± 0.11 mm). For other communities, this indicator was in the range of –0.86 to –0.43 mm. The variation of the continentality score is explained by vegetation class (33.3%) and association (13.3%). The highest continentality scores were found for the *Festuco-Brometea*, *Molinio-Arrhenatheretea*, and *Agropyretalia intermedio-repentis*. Cryoclimate can be mostly explained by association (17.7%), while the explanatory power of vegetation class is much lower (6.2%). Cryoclimate scores were lowest for the *Festuco-Brometea* and highest for *Galio-Urticetea*. The lighting regime was most strongly related to vegetation class (37.9%), and the value of the association as a predictor was not statistically significant (F = 1.8, P = 0.07). The lighting regime was high for all communities. A decrease in this indicator was found for Robinietea, and the highest level of light reduction was in the *Phragmito-Magnocaricetea* communities.

Dependence of plant community diversity on environmental factors and the level of anthropogenic impact. The correlation analysis showed that the number of species negatively depends on the elevation of the relief where the association was located, the topographic wetness index, the level of habitat moisture, soil nitrogen content, cryoclimate index, and the level of hemeroby (Table 4). The number of species increased with increasing insolation, contrast of moisture regime, pH (increasing alkalinity), increasing mineralization of soil solution and calcium content, and increasing soil aeration. The species diversity of plant communities was positively influenced by such microclimatic factors as the thermal climate, continentality, and lighting conditions. The ombroclimate and cryoclimate had a negative impact on species diversity.

The correlations between environmental factors and species diversity had their own peculiarities within individual syntaxons. The sample size for individual synthaxons was much smaller, so the number of statistically significant correlation coefficients was smaller. The species diversity within the class *Festuco-Brometea* increased with the increase of moisture regime and its contrast, as well as with the increase of soil solution mineralization. The diversity of steppe coenoses was negatively affected by the growth of continentality and cryoclimate. The species diversity within the *Molinio-Arrhenatheretea* class increased with the level of habitat moisture. The species diversity was negatively affected by altitude and insolation, soil alkalinity, cryoclimate index, and naturalness. The diversity of *Phragmito-Magnocaricetea* communities decreased with the height of the relief. The diversity of these communities was higher under conditions of higher moisture contrast and higher soil nitrogen content. An increase in calcium content, on the contrary, was accompanied by a decrease in community diversity. The increase in diversity was positively correlated with the naturalness of the communities. The patterns of response of species diversity in the order Artemisietea vulgaris to the influence of environmental factors differed greatly. The communities of the order *Onopordetalia acanthii* responded negatively to the relief altitude and insolation level. Also, a negative correlation was found for the diversity of communities of this order and the content of dissolved salts and calcium in the soil. The level of light in the community had a negative effect on diversity. The diversity of *Onopordetalia acanthii* communities increased with increasing naturalness. The diversity of *Agropyretalia intermedio-repentis* communities responded positively to an increase in erosion risks and negatively to an increase in humidity, cryoclimate, and hemeroby. The diversity of artificial woody plantations of the *Robinietea* class decreased with increasing relief height and increasing hemeroby of the community. There was a positive correlation between diversity and phytoindication assessment of the thermal climate. The diversity of *Galio-Urticetea* communities responded positively to the level of insolation and negatively to the increase in the contrast of moisture conditions.

Table 2

Phytoindication assessment of soil properties within plant associations (mean ± SE)

Syntaxon	Association	Phytoindication scales**						
		Hd	fH	Rc	Sl	Ca	Nt	Ae
Onopordetalia acanthii	1	77.80 ± 6.57	0.19 ± 0.03	6.51 ± 0.09	22.06 ± 2.93	3.44 ± 0.52	3.86 ± 0.33	71.39 ± 2.90
	2	40.37 ± 5.63	0.26 ± 0.01	7.01 ± 0.10	51.37 ± 8.71	5.44 ± 0.27	2.23 ± 0.40	57.64 ± 5.55
Festuco-Brometea	3	35.06 ± 0.44	0.27 ± 0.01	6.92 ± 0.02	42.76 ± 1.86	5.26 ± 0.18	0.81 ± 0.06	73.02 ± 1.27
	4	34.41 ± 0.50	0.24 ± 0.01	7.01 ± 0.02	39.86 ± 2.13	5.62 ± 0.12	0.66 ± 0.07	74.18 ± 1.87
	5	32.60 ± 0.41	0.20 ± 0.01	6.99 ± 0.02	33.47 ± 1.32	5.99 ± 0.10	0.76 ± 0.07	71.73 ± 0.97
Molinio-Arrhenatheretea	6	34.18 ± 0.55	0.19 ± 0.01	6.92 ± 0.02	33.60 ± 2.23	5.11 ± 0.20	1.02 ± 0.12	78.72 ± 1.28
	7	37.81 ± 1.21	0.22 ± 0.01	6.77 ± 0.03	35.19 ± 3.15	4.64 ± 0.27	1.58 ± 0.19	76.39 ± 2.05
Agropyretalia intermedio-repentis	8	37.87 ± 1.37	0.21 ± 0.01	6.69 ± 0.04	17.49 ± 1.82	3.57 ± 0.27	1.39 ± 0.25	66.06 ± 3.80
	9	44.98 ± 2.62	0.23 ± 0.01	6.66 ± 0.09	21.87 ± 2.34	3.60 ± 0.39	2.30 ± 0.29	72.16 ± 2.58
Galio-Urticetea	10	50.03 ± 3.51	0.17 ± 0.01	6.75 ± 0.06	20.13 ± 2.18	3.30 ± 0.68	2.73 ± 0.37	67.23 ± 1.61
Robinietea	11	57.45 ± 3.60	0.17 ± 0.02	6.72 ± 0.08	19.15 ± 3.56	1.23 ± 0.32	3.59 ± 0.32	60.96 ± 4.08
	12	75.20 ± 9.03	0.18 ± 0.01	6.77 ± 0.05	22.00 ± 2.05	2.39 ± 0.60	3.53 ± 0.35	65.28 ± 3.56
	13	52.47 ± 1.07	0.12 ± 0.02	6.89 ± 0.03	24.35 ± 2.69	3.26 ± 0.98	1.75 ± 0.33	52.32 ± 8.92
Phragmito-Magnocaricetea	14	106.65 ± 7.67	0.20 ± 0.02	6.77 ± 0.04	19.01 ± 0.39	1.33 ± 0.31	4.34 ± 0.14	83.05 ± 1.75
	15	181.28 ± 13.88	0.28 ± 0.01	6.97 ± 0.02	42.41 ± 3.89	0.40 ± 0.07	2.83 ± 0.16	33.64 ± 2.72
	16	227.10 ± 41.36	0.29 ± 0.03	6.82 ± 0.09	37.97 ± 4.10	0.34 ± 0.07	3.64 ± 0.16	9.13 ± 1.81
Total		48.86 ± 2.34	0.22 ± 0.01	6.87 ± 0.01	32.52 ± 0.84	4.44 ± 0.12	1.61 ± 0.08	69.91 ± 0.89

Notes: 1 – E5.1 Anthropogenic herb stands (association *Arctietum lappae* Felföldy 1942); 2 – E5.1 Anthropogenic herb stands (association *Asclepiadetum syriacae* Láníková in Chytrý 2009); 3 – E1.2D3 Pontic Eastern steppes (*Salvio nemorosae-Festucetum valesiacae* Korotchenko et Didukh 1997); 4 – E1.2D3 Pontic Eastern steppes (*Stipo lessingianae-Salvietum nutantis* Vynokurov 2014); 5 – E1.2D2 Sarmatic steppes (*Festuco valesiacae-Stipetum capillatae* Sill 1931); 6 – E2.251 Ponto-Pannonic mesophile hay meadows (*Festuco valesiacae-Poetum angustifoliae* Mirkin in Denisova et al. 1986); 7 – E2.251 Ponto-Pannonic mesophile hay meadows (*Poëtum angustifoliae* Shelyag-Sosonko et al. 1986); 8 – E1.D Unmanaged xeric grassland (*Melico transsilvanicae-Agropyretum* Th.Mull. in Gors 1966); 9 – E1.D Unmanaged xeric grassland (*Convolvulo arvensis-Agropyretum repentis* Felföldy 1943); 10 – I1.5 Bare tilled, fallow or recently abandoned arable land (*Myosotido sparsiflorae-Alliarietum petiolatae* Gutte 1973); 11 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Robinietum* Jurko 1963); 12 – G1.C Highly artificial broadleaved deciduous forestry plantations (*Chelidonio-Aceretum negundi* L. Ishbirdina et A. Ishbirdin 1991); 13 – D5.1 Reedbeds normally without freestanding water (*Typhetum latifoliae* Soo 1927); 14 – C3.2 Water-fringin greedbeds and tall helophytes other than canes (*Phragmitetum australis* Savič 1926); 15 – D5.2 Beds of large sedges (*Typhetum angustifoliae* Pignatti 1953); 16 – C3.1 Species-rich helophyte beds (*Butomo-Alismatetum plantaginis-aquaticae* Slavnic 1948); Hd is the content of productive moisture in the meter-long soil layer (mm); fH is the ω coefficient of moisture unevenness; Rc is the negative logarithm of the concentration of hydrogen ions in the soil solution (pH); Sl is the content of salts in the soil solution (μg/L); Ca is the content of carbonates (in terms of calcium and magnesium oxides, %); Nt is the content of nitrogen in the soil (g/kg); Ae is the aeration aperture (% of the total volume of the aeration space in the soil).

Discriminative analysis of syntaxones. The application of geomorphological variables, phytoindication assessments of environmental factors, naturalness and hemeroby as predictors allowed us to discriminate syntaxones with an average accuracy of 85.5% (Table 5). The *Phragmito-Magnocaricetea* communities were discriminated with an accuracy of 100%. Also, a high level of discrimination was observed for the *Festuco-Brometea* communities (92.4%).

The Root 1 denotes a differential gradient that distinguishes habitats with high insolation, variable moisture conditions, high carbonate content, and high naturalness and low hemeroby from habitats with higher topographic moisture supply and phytoindication soil moisture estimates, higher soil nitrogen content, and higher ombroclimate indicators, and, accordingly, opposite naturalness and hemeroby indicators (Table 6).

Table 3
Phytoindication assessment of microclimatic conditions within plant associations (mean ± SE)

Syntaxon	Associations *	Phytoindication scales**				
		Tm	Om	Kn	Cr	Lc
Onopordetalia acanthii	1	1.89 ± 0.07	–0.28 ± 0.20	144.28 ± 8.36	3.18 ± 1.30	8.75 ± 0.10
	2	1.99 ± 0.05	–1.11 ± 0.27	110.85 ± 12.03	–2.70 ± 1.83	8.95 ± 0.01
	3	2.09 ± 0.02	–1.34 ± 0.06	147.79 ± 1.49	–4.18 ± 0.41	8.94 ± 0.02
Festuco-Brometea	4	2.00 ± 0.02	–1.33 ± 0.08	151.50 ± 2.10	–3.90 ± 0.36	8.92 ± 0.02
	5	2.03 ± 0.02	–1.73 ± 0.07	156.27 ± 1.37	–2.26 ± 0.43	8.96 ± 0.01
	6	1.98 ± 0.02	–1.26 ± 0.08	159.44 ± 2.03	–1.22 ± 0.69	8.97 ± 0.02
Molinio-Arrhenatheretea	7	1.91 ± 0.02	–0.96 ± 0.11	145.20 ± 3.43	–4.49 ± 0.73	8.90 ± 0.04
	8	1.89 ± 0.04	–0.76 ± 0.09	157.67 ± 3.55	–4.93 ± 1.03	8.99 ± 0.12
Agropyretalia intermedio-repentis	9	1.80 ± 0.05	–0.94 ± 0.12	140.82 ± 5.72	–0.47 ± 1.41	8.87 ± 0.14
Galio-Urticetea	10	1.91 ± 0.09	–0.14 ± 0.11	113.99 ± 9.13	1.62 ± 1.08	8.15 ± 0.16
Class *Robinietea*	11	1.84 ± 0.05	–0.46 ± 0.16	116.00 ± 11.96	1.01 ± 0.75	8.43 ± 0.12
	12	2.06 ± 0.03	–0.42 ± 0.13	130.02 ± 5.85	0.54 ± 1.00	8.70 ± 0.11
	13	2.20 ± 0.02	–0.43 ± 0.07	135.90 ± 4.46	–2.09 ± 4.36	8.96 ± 0.01
Phragmito-Magnocaricetea	14	2.16 ± 0.04	–0.47 ± 0.09	110.08 ± 6.92	0.39 ± 0.99	8.72 ± 0.15
	15	2.07 ± 0.01	–0.67 ± 0.27	122.86 ± 2.92	–0.41 ± 0.78	8.69 ± 0.02
	16	2.00 ± 0.06	–0.61 ± 0.13	131.53 ± 3.96	–5.17 ± 0.67	8.62 ± 0.04
Total		1.99 ± 0.01	–1.08 ± 0.04	144.60 ± 1.32	–2.17 ± 0.25	8.85 ± 0.02

Notes: see Table 2; Tm is the radiation balance (gJ/m^2 year); Om is the difference between the amount of precipitation on average per year in terms of a day to evaporation from the open water surface for the same period (mm); Kn is the Ivanov continental scale; Cr is the average temperature of the coldest month of the year; Lc is the lighting regime.

Table 4
Correlation of the number of species in the community with geomorphological variables, phytoindicative assessments of environmental factors, and naturalness and hemerobia (correlation coefficients are given, which are significant for $P < 0.05$)

Variable	Total	*Festuco–Brometea*	*Molinio–Arrhenatheretea*	*Phragmito–Magnocaricetea*	*Artemisietea vulgaris*		*Robinietea*	*Galio-Urticetea*
					Onopordetalia acanthii	*Agropyretalia intermedio–repentis*		
Alitude	–0.28	–	–0.48	–0.85	–0.74	–	–0.69	–
Insolation	0.19	–	–0.41	–	–0.55	–	–	0.57
TWI	–0.23	–	–	–	–	–	–	–
LS	0.16	–	–	–	–	0.47	–	–
Hd	–0.29	0.23	0.38	–	–	–0.57	–	–
fH	0.31	0.36	–	0.43	–	–	–	–0.79
Rc	0.24	–	–0.31	–	–	–	–	–
Sl	0.24	0.29	–	–	–0.66	–	–	–
Ca	0.38	–	–	–0.48	–0.53	–	–	–
Nt	–0.40	–	–	0.50	–	–	–	–
Ae	0.23	–	–	–	–	–	–	–
Tm	0.16	–	–	–	0.52	–	0.51	–
Om	–0.33	–	–	–	–	–	–	–
Kn	0.29	–0.21	–	–0.59	–	–	–	–
Cr	–0.36	–0.33	–0.27	–	–	–0.51	–	–
Lc	0.30	–	–	–	–0.54	–	–	–
Naturalness	0.28	–	–0.29	0.58	0.53	–	–	–
Hemeroby	–0.38	–	–	–	–	–0.37	–0.65	–

Notes: alitude is the elevation above sea level according to digital elevation model data (m); insolation is the solar insolation (MWh/m^2); TWI is the topographic wetness index; LS is the erosion index; Hd is the content of productive moisture in the meter-long soil layer (mm); fH is the ω coefficient of moisture unevenness; Rc is the negative logarithm of the concentration of hydrogen ions in the soil solution (pH); Sl is the content of salts in the soil solution (μg/L); Ca is the content of carbonates (in terms of calcium and magnesium oxides, %); Nt is the content of nitrogen in the soil (g/kg); Ae is the aeration aperture (% of the total volume of the aeration space in the soil); Tm is the radiation balance (gJ/m^2 year); Om is the difference between the amount of precipitation on average per year in terms of a day to evaporation from the open water surface for the same period (mm); Kn is the Ivanov continental scale; Cr is the average temperature of the coldest month of the year; Lc is the lighting regime.

Table 5
Classification matrix based on the results of discriminant analysis of syntaxones using geomorphological variables, phytoindication assessments of environmental factors, naturalness and hemeroby as predictors

Syntaxons (observable)	% of correct classifications	Syntaxons (according to the results of discrimination)						
		1	2	3	4	5	6	7
1 *Festuco-Brometea*	92.4	110	9	–	–	–	–	–
2 *Molinio-Arrhenatheretea*	75.4	7	49	–	3	–	6	–
3 *Phragmito-Magnocaricetea*	100.0	–	–	25	–	–	–	–
4 *Onopordetalia acanthii*	73.3	–	1	–	11	3	–	–
5 *Robinietea*	85.7	–	2	–	1	18	–	–
6 *Agropyretalia intermedio-repentis*	76.7	–	3	–	1	1	23	2
7 *Galio-Urticetea*	78.6	–	–	–	1	1	1	11
Total	85.5	117	64	25	17	23	30	13

This gradient distinguished between natural steppe (*Festuco-Brometea*) and meadow (*Molinio-Arrhenatheretea*) communities on the one hand and semi-natural and artificial ecosystems on the other. The pole of the most anthropogenically transformed communities was occupied by the *Robinietea* and *Galio-Urticetea*. Thus, Root 1 can be identified as a gradient of the naturalness/hemeroby regime. It should be noted that the hygrophilous *Phragmito-Magnocaricetea* community occupied a wide area along this gradient, indicating that these communities are under different levels of anthropogenic transformation. The Root 2 clearly distinguished the *Phragmito-Magnocaricetea* community from all others. It is natural that semi-aquatic communities differed from all others by a higher level of moisture and a lower position within the relief. The *Phragmito-Magnocaricetea* communities were characterized by lower variability of moisture conditions and lower levels of carbonate content in the soil. A higher level of moisture was accompanied by less soil aeration but a higher level of soil nitrogen supply. The Root 3 differentiated between the semi-natural communities *Galio-Urticetea* on the one hand and *Agropyretalia intermedio-repentis* on the other. Other communities occupied a transitional position between these groups of associations. The *Galio-*

Urticetea communities covered semi-natural communities formed by highly and moderately herbivorous species on nitrogen-enriched edge habitats. In turn, the *Agropyretalia intermedio-repentis* associations covered rhizome cereal communities of disturbed ecotopes on dry soils. The *Galio-Urticetea* communities were characterized by a higher content of nitrogen, carbonates, and soluble salts in the soil, as well as a higher pH value and lower light. The *Agropyretalia intermedio-repentis* community, on the contrary, was more illuminated, grew under conditions of better soil aeration and greater variability in moisture conditions. The Root 4 contrasted the *Molinio-Arrhenatheretea* community on the one hand and the *Agropyretalia intermedio-repentis* on the other. Other communities occupied a transitional position between these groups of associations. The *Molinio-Arrhenatheretea* associations were characterized by higher moisture levels and lower moisture variability, higher dissolved salt content in the soil, and better soil aeration. The *Agropyretalia intermedio-repentis* community was characterized by a higher level of insolation.

Table 6
Factor structure matrix

Predictors*	Root 1	Root 2	Root 3	Root 4
Altitude	–0.24	–0.18	–0.17	0.19
Insolation	0.17	–	–	–0.53
TWI	–0.19	0.33	–0.28	0.27
LS	–	–	0.17	0.12
Hd	–0.16	0.70	–0.23	0.19
fH	0.32	–0.30	–0.34	–0.52
Rc	–	–	0.42	–
Sl	–	–	0.16	0.59
Ca	0.32	–0.14	0.26	–
Nt	–0.33	0.19	0.14	–
Ae	–	–0.16	–0.15	0.45
Tm	–0.12	0.23	0.17	–
Om	–0.40	–0.11	0.15	–
Kn	0.14	–0.33	–0.34	–
Cr	–	–	–	–
Lc	–	–	–0.63	0.22
Naturalness	0.21	–0.25	0.44	0.34
Hemeroby	–0.48	–0.82	0.16	0.24

Discussion

The vegetation cover of the studied gully is a combination of natural, anthropogenic and naturalized vegetation types. The sources of anthropogenic impact within the gully are agricultural activities, activities related to planting artificial tree plantations, the impact of the road that passes through the gully, grazing and haying. The overall level of anthropogenic impact is very high, resulting in the focus of natural steppe vegetation in areas that are most shielded from anthropogenic impact. Such centers are areas on the steepest slopes of the gully (Tutova et al., 2022). These habitats should be noted to be not fully typical of the steppe vegetation, although they nevertheless provide a fairly high level of conservation of steppe floristic complexes. An important feature of the conditions where *Festuco-Brometea* communities were found was a significant level of insolation. There are two reasons for this feature. The first is the ecological characteristics of steppe vegetation, which is naturally adapted to high levels of insolation (Benaradj et al., 2022). The second reason is that the slopes of the northern exposure gully, which receive less insolation due to geomorphological factors, are planted with artificial tree plantations, and the natural steppe vegetation there has been artificially destroyed (Zhukov et al., 2017). Nevertheless, the role of the insolation factor is very significant (Major, 1963), which is emphasized by the specificity of the solar regime, which is typical for individual plant syntaxons.

The moisture conditions are the leading factor affecting the structure of the vegetation cover (Lozano-Parra et al., 2018). The analysis of climate data indicates an increase in summer drought conditions, which further emphasizes the role of topography as a factor that redistributes climate resources (Yakovenko et al., 2023). Our results are in line with studies that show that in the Steppe zone of Ukraine, the average annual air temperature increased by 3.5 °C between 1945 and 2019. The amount of annual precipitation decreased by 40%. An 18.7% increase in solar radiation to the soil surface and a 26.0% decrease in climatic losses on soil formation have reduced the rate of natural soil fertility reproduction. In particular, plant bioproductivity has decreased by 62.0%, and it is expected to decline further by 20% (Pichura et al., 2022).

Topography is an important determinant of soil moisture distribution and thus determines the functioning of terrestrial ecosystems, including the composition and structure of vegetation (Kopecký & Čížková, 2010). There is evidence that the topographic wetness index explains soil moisture better than photoinitiation estimates (Raduła et al., 2018). The topographic wetness index was found to be an informationally valuable predictor that allows to differentiate hygrophilous *Phragmito-Magnocaricetea* communities from all others. The fact that many syntaxons are very homogeneous within their boundaries in terms of topographic wetness index values also emphasizes the importance of this indicator as a predictor of the spatial distribution of plant communities. The semi-natural communities were the most heterogeneous. This heterogeneity should be considered as a result of the evolutionary youth of semi-natural plant associations and the eclecticism of their composition (Agrawal et al., 2006). In addition, such communities are composed largely of adventive species, which by definition are highly environmentally resistant and able to spread in a wide range of environmental conditions.

The location of steppe vegetation on slopes coincides with the area of greatest erosion risks. On the other hand, steppe vegetation should be considered as an almost perfect soil protector against erosion. Erosion phenomena should also be noted to have different scales of organization, which are larger or smaller than the scale of the digital research model used in the study. Semi-natural and artificial forest plantations are planted in the area of possible erosion risks (Zhukov et al., 2023), and can also be factors of erosion processes due to the disturbance of the natural steppe cover (Fig. 9).

The steppe communities of the class *Festuco-Brometea* are focuses of species diversity with a high level of naturalness. Obviously, their high conservation value is combined with their functional significance for preserving soil cover and preventing the intensification of erosion. In terms of species diversity, steppe communities significantly outnumber all other types of communities found in the gully. The steep slopes of the gully make it difficult to access for grazing and haying, so the role of the factor of variability of projective cover is secondary in the formation of species diversity patterns, which are mainly determined by the variability of the number of species.

The dimensions of naturalness and hemeroby are to some extent symmetrically opposed, although each of them carries a certain amount of specific information. The naturalness is assessed through the ratio of different life strategies of plants, and hemeroby is assessed through a scoring measure of the plant's ability to exist under certain conditions of anthropogenic transformation of the community (Kunakh et al., 2021). The level of class/order of syntaxons should be noted to be the leading one for determining the naturalness and hemeroby of plant communities, while the level of individual association is much lower for differentiating naturalness and the hemeroby. The naturalness and hemeroby correlate with the number of species in the community and the Shannon index. The higher the diversity of the community, the lower the hemeroby and the higher the naturalness. This result once again emphasizes the role of biodiversity as a marker of the level of anthropogenic transformation. It is worth noting that the correlation of the Shannon index was higher in the model than the correlation of naturalness and hemeroby with the number of species. This suggests that the Shannon index is a better proxy for naturalness/hemeroby than the number of species. Nevertheless, species diversity indices as parameters of the level of transformation of plant communities should be treated with caution because diversity indices are sensitive to a range of environmental factors and, moreover, the response patterns of species diversity indices are dependent on the type of plant community. The diversity of communities varies depending on geomorphological variables, environmental factors, and the level of anthropogenic transformation of the environment.

The results of the study of steppe vegetation in the valley of the Southern Bug River revealed that phytoindication assessments of soil moisture, nitrogen content, and aeration regime are positively correlated in pairwise (Lavrinenko et al., 2023). Our results confirm a positive correlation between moisture content and nitrogen content, while aeration is negative-

ly correlated with moisture content and nitrogen content. The negative correlation between moisture content and aeration is natural, as air (aeration) and water content (soil moisture) are antagonists as they compete for cavity space in the soil. The increase in soil moisture naturally leads to a decrease in the air content of the soil (Jiang et al., 2022). The instrumental methods of measuring the moisture content and mineral forms of nitrogen in the soil also indicate that as the water content increases, the concentration of nitrogen in the soil also increases (Zhang & Wienhold, 2002). The relationship between aeration and the content of mineral forms of nitrogen compounds is complex (Kunakh et al., 2023). Thus, under conditions of excessive moisture, the content of ammonium nitrogen in the soil is not related to the level of aeration, but the content of nitrate nitrogen was inversely related to the degree of filling the space of the soil pores with water (Girsang et al., 2020). The increase in inorganic nitrogen content may be due to an increase in nitrifier activity as a response to improved oxygen availability in the soil (Gebauer et al., 1996). The positive correlation between aeration and nitrogen content was found for *Phragmito-Magnocaricetea* communities with excessive moisture levels. The correlation was negative for other communities. Improved aeration can provide better consumption of nitrogen compounds by the plant root system, which can lead to a decrease in its content in the soil (Zhu et al., 2015).

a *b*

Fig. 9. Expansion of the gully system due to intensification of erosion processes induced by disturbance of the steppe cover as a result of creation of artificial tree plantations: *a* – association *Chelidonio-Aceretum negundi* in the thalweg of a gully; *b* – association *Chelidonio-Robinietum* on a plateau near agricultural fields

A significant influence on the differentiation of steppe vegetation was proved to be caused by the contrast of soil moisture regime (Lavrinenko et al., 2023). The authors made this conclusion based on an assessment of the variability of the corresponding phytoindicator. Our results also confirm the great differential importance of the contrast of moisture conditions for the structuring of vegetation cover in the steppe, but we came to this conclusion based on the results of a discriminant analysis, which is specifically designed to find out the differential capabilities of reliable predictors (Adebiyi et al., 2022). The contrast of moisture conditions makes a significant contribution to the formation of the first four discriminant roots, indicating a high differential ability of this predictor.

An inverse linear relationship with salt and acid regimes was observed for soil moisture, nitrogen content, and aeration regime of steppe ecosystems (Lavrinenko et al., 2023). Our results indicate that moisture shows a unimodal response in the gradient of soil solution mineralization conditions. Very low mineral salts in the soil and very high mineral salts are observed at very low soil moisture levels. A moderate level of soil solution mineralization is observed under high moisture conditions. This pattern is formed due to the positive correlation between moisture and mineral content in the soil within the *Phragmito-Magnocaricetea* communities. There is no correlation between these indicators in other synthaxons. According to our data, acidity and mineral content are strongly correlated, so these indicators show similar patterns of correlation with other indicators.

Lavrinenko et al. (2023) conclude that the general salt and acid regimes affect vegetation differentiation less than other soil factors. This is fully confirmed by our results. These factors have a certain differential value, but they contribute to the formation of discriminant roots 3 and 4, which are of secondary importance for structuring the vegetation cover. The high level of anthropogenic transformation of the studied area is confirmed by the fact that the results of the discriminant analysis revealed that the indicators of naturalness and hemeroby are the most important for determining discriminant roots. The absolute value of the factor coefficients decreases for roots 3 and 4, while for roots 1 and 2 the role of naturalness and hemeroby indicators is leading. It should be noted that the discriminative capacity of the roots decreases with their order, so hemeroby and naturalness are the factors that determine the differentiation of vegetation cover. The variability of vegetation cover initiated by anthropogenic transformation factors is accompanied by changes in other environmental factors.

The discriminant root 1 is denoted by the intuitively understandable opposite dynamics of naturalness and hemeroby, which indicates that the greater the naturalness of a grouping, the lower its hemeroby. However, discriminant roots 2, 3, and 4 are characterized by the contribution of naturalness and hemeroby of the same sign, which does not quite correspond to the idea of the relationship between these properties of plant communities. This situation can be explained by the fact that, under certain circumstances, more natural plants can gain a competitive advantage in the face of greater anthropogenic pressure. Less natural species are not "universal soldiers" that always win the competition, otherwise natural species would not have a chance. It can be assumed that even natural species may have an advantage at a certain level of anthropogenic pressure. It is this mechanism that can explain the same sign of the contribution of naturalness and hemeroby to the discriminant root, which should have different signs. It should also be emphasized that such a pattern is observed only for minor roots (of order two or more), i.e., those calculated after the leading discriminant trend has been previously extracted. The practical significance of the study is that the role of hemeroby and naturalness indicators is also

emphasized for natural and semi-natural communities. Urbanized areas have been the usual testing ground for the use of hemeroby indicators. Our research indicates that in the context of significant anthropogenic transformation of the landscapes of the steppe zone of Ukraine, hemeroby and naturalness indicators can be applied to a wide range of ecosystem types. These indicators are appropriate for use in the practice of implementing projects to assess the environmental impact of planned activities. The assessment of hemeroby and naturalness of ecosystems based on botanical data should be recommended as a standard protocol for performing environmental impact assessments.

It should also be noted that the spread of shelterbelts and artificial forest plantations within the gully systems is unacceptable. The reason for this is the provocation of erosion processes on the slopes of the gullies due to the destruction of steppe vegetation, which has the best erosion control capacity. Also, artificial forest plantations are a factor in the spread of invasive plant species, which is a negative factor that worsens the functional properties of plant communities and their diversity.

In terms of further research, the following issues should be addressed: 1) to determine the features of soil cover depending on vegetation types and the level of anthropogenic impact; 2) to determine the correlation of hemeroby phenomena between vegetation cover and soil macrofauna; 3) to establish patterns of variability in the diversity of plant communities at different hierarchical levels; 4) to establish the role of artificial woody plantations as a factor in the spread of invasive plant species and a factor in the activation of soil erosion processes.

Conclusion

The vegetation cover of the gully system was represented by 263 plant species. The vegetation cover of the studied gully system is represented by six vegetation classes. Steppe vegetation communities are representted by the class *Festuco-Brometea*. The species diversity of steppe vegetation significantly exceeds the level of biodiversity of all other vegetation types identified in the gully. A significant level of anthropogenic transformation of the steppe zone of Ukraine has led to the fact that the steppe vegetation pockets have been preserved in fragments, mainly in geomorphological conditions that are not typical for this type of vegetation. Usually, these are the slopes of gully systems, where human economic activity is very complicated, and that is why steppe communities are still preserved there. Steppe vegetation pockets remained in the habitats with the highest levels of insolation and a high risk of erosion. The beam systems are surrounded by agricultural fields. The forest protection artificial tree plantations are included in the diversity of the gully vegetation and occur in different geomorphological conditions. The location of artificial tree plantations on the slopes of gullies is a wrong decision, as the destruction of steppe vegetation significantly increases the risk of erosion, as evidenced by the increased spread of the gully system in the area of artificial plantations. The artificial plantations also trigger the expansion of invasive species, including aggressive weeds. The dynamics of climatic conditions indicates a trend of climate aridization, which manifests itself in an increase in the duration and scale of the dry period in late summer. This is a phenological period of vegetation depression, and only the steppe cover is able to counteract soil erosion, both wind and water. The location of the steppe cover and the steep slopes of the gullies draws attention to the steppe vegetation as a center of biodiversity and a condition for counteracting soil erosion. The vegetation classes *Festuco-Brometea*, *Molinio-Arrhenatheretea*, and *Phragmito-Magnocaricetea* were the least anthropogenically transformed in the naturalness/hemeroby gradient. The markers of the largest anthropogenic transformation were the communities of the *Artemisietea vulgaris* class. Species richness and Shannon's index are strongly correlated with indicators of naturalness and hemeroby, which indicates that diversity is an important structural feature of communities that is undergoing changes under the influence of anthropogenic activities. Indicators of species diversity are sensitive to the influence of other environmental factors in a contextualized manner depending on the type of vegetation, so they may not be an ideal indicator of the level of anthropogenic transformation of ecosystems. Geomorphological variables, phytoindication assessments of environmental factors, naturalness and hemeroby can provide a good differentiation of vegetation cover syntaxons. The leading one is the differential gradient that distinguishes biotopes with high insolation, variable moisture conditions, high carbonate content, and high naturalness and low hemeroby from biotopes with higher levels of topographic moisture supply and phytoindication soil moisture assessments, higher soil nitrogen content, and higher ombroclimate indicators. This gradient distinguishes between natural steppe (*Festuco-Brometea*) and meadow (*Molinio-Arrhenatheretea*) communities on the one hand and semi-natural and artificial ecosystems on the other.

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