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Oscillatory spatial and temporal variability of precipitation in Polissia and Forest-Steppe and the impact of agricultural landscape transformation

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Abstract. The territories of Polissia and Forest-Steppe are of great importance to Ukraine, offering significant potential for the advancement of agriculture and forestry. In light of the pressing issue of global climate change, it is imperative that the active economic utilisation of these territories be guided by a commitment to the maintenance of ecological systems and the sustenance of ecosystem functions. The objective of this article was to ascertain the patterns of both spatial and temporal precipitation variability and to establish the impact of anthropogenic land transformation as a consequence of agricultural production. Within the study area, the average precipitation level was 625 ± 68 mm and ranged from 535 to 1,160 mm. During the study period (1960-2023), there was a trend of increasing and decreasing precipitation. The southeast of the region was characterised by a decreasing trend in precipitation, while in the northwest and north, the time trend showed an increase in precipitation. Precipitation in the Carpathian region is much higher than in other parts of the territory. The presence of an oscillatory regularity in precipitation rhythm allows for consideration of two practical aspects: the possibility of forecasting future precipitation dynamics based on available information from previous years, and accounting for the fluctuating precipitation dynamics when recommending optimal crop rotations and selecting the most suitable range of crop varieties for cultivation

Keywords: climate; spatial pattern; temporal dynamics; landscape diversity; land cover

INTRODUCTION

Increasing crop yields is a critical requirement to ensure food security in the face of a steadily growing global population. Climate change is increasing the frequency and intensity of extreme weather events, such as droughts, floods, storms, and forest fires, all of which can affect agricultural production. The loss of agricultural production is expected to progress in most European territories during the 21st century as a result of heatwaves, droughts, and an increased risk of water shortages. The water is the most important factor for growing various crops. Crop water requirements are highly vulnerable to the impacts of climate change. Water availability significantly affects all physiological and ecological processes in the plant world. The study

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of the spatial and temporal variability of precipitation, to ensure the conditions for sustainable agricultural production, represents a significant scientific challenge.

Precipitation is a critical factor in climate and hydrometeorology, and a major driver of hydrological processes, as well as the structure and function of terrestrial ecosystems, which determine the conditions for agricultural production, as discussed by M. Hernández-Rodríguez *et al.* (2023). Precipitation patterns are highly variable, with significant differences in frequency, duration, intensity, and overall trends over time, directly influencing the rhythm of water use by humans and ecosystems. Changes in precipitation significantly affect the hydrological cycle and human life, potentially leading to floods, droughts, biodiversity loss, reduced agricultural productivity, and soil erosion. According to T.T. Nguyen *et al.* (2019), an increase in extreme precipitation events will lead to a higher risk of flooding, especially with the rapid pace of urbanisation. High temperatures have a negative impact on yields due to heat stress and soil moisture deficits, and similarly, low precipitation leads to stomatal closure, reduced carbon uptake, and lower yields, as highlighted by E.P. Hendri & S. Fadhlia (2024). Modern statistical procedures provide powerful tools for predicting crop yields under global climate change, even when the model is based solely on climate variables such as temperature and precipitation (Leng & Hall, 2020).

According to S. Benziane (2024), precipitation forecasting is the process of using a range of models and data sources to accurately predict the amount and timing of precipitation, such as rain or snow, in a given area. Subsequent forecasts are based on historical data regarding precipitation dynamics. The author also explains that mathematical and statistical methods allow for the accurate prediction of future precipitation trends, enabling the identification of patterns, changes, and relationships in the data. Y.-F. Sang *et al.* (2020) highlight that the most common statistical methods are trend analysis, frequency or spatial analysis, regression models, and time series models. Additionally, they emphasise that identifying periodic rainfall fluctuations is the most important aspect of rainfall modelling and forecasting. According to O. Lobachevska & L. Karpinets (2024), the seasonality of the precipitation regime and the amount of precipitation allow for the identification of clear spatial structures, which have significant implications for livestock producers and future climate change assessments.

Precipitation is a distinct field of study within climatology and meteorology. However, precipitation constitutes an aspect of climate that affects biological systems and is therefore a climatope (Kyyak *et al.*, 2023). A climatope is a specific climatic regime that allows for the formation of a spatially regular fragment of landscape cover. Together with the edaphotope, it forms an ecotope. It must be emphasised that, just as an edaphic environment is not equivalent to soil, a climatological environment is not equivalent to climate. An edaphotope is how living organisms perceive soil. Similarly, the climatope is an aspect of how living organisms perceive climate. The system is becoming more complex. It is no longer sufficient to consider only the climatic component; the biotic component must also be taken into account. Conversely, a specific list of purely climatic issues recedes into the background. For example, this approach does not require an explanation of the mechanisms and processes of the dynamics of climatic phenomena. Climate can be considered purely phenomenologically or formally. This approach can be interpreted as ecological within the framework of ecological climatology. Thus, this study aimed to test the hypothesis that the climate of the area under investigation exhibits spatial and temporal regularity, which is hierarchically ordered. This enables the prediction of the state of the climate in the coming decades.

LITERATURE REVIEW

Effective water management is crucial for maximising crop yields, particularly in areas with varying rainfall patterns. Different crops have specific water requirements that are vital for their growth, with some being more drought-resistant, such as rye, and others requiring more moisture during key growth stages, such as potatoes and rapeseed. Understanding these seasonal water needs helps optimise crop production, as evidenced by the varying water demands across crops like soybeans, sugar beet, and sunflower.

The article by G. Bodner *et al.* (2015) suggests that seasonal crop water needs are essential for crop management, especially in dry years. For maximum tuber yield, potatoes require 500-700 mm of water per season. Rapeseed evaporates a large amount of water, with its transpiration coefficient in the range of 500-700 mm, and it needs 400-500 mm of rainfall during the growing season. High humidity during flowering is necessary for high yields. Excessive rainfall and low temperatures during the reproductive stage are unfavourable, as they reduce the number of flowers, the number and size of the capsules, and the seeds inside them (Moteva *et al.*, 2018). Rye grows well with annual rainfall of 600 to 1,000 mm and is relatively drought-resistant: it can tolerate dry conditions with annual rainfall as low as 400 mm (Basche *et al.*, 2016). Soybeans are water-efficient, depending on the weather and soil type, they use 400-700 mm of water, either from rainfall, irrigation, or the soil, to produce sufficient yields (Tacarindua *et al.*, 2013). Water is essential for many vital functions of sugar beet, which has a relatively low water consumption of between 500 and 800 mm, making it a suitable crop for regions with limited water resources. Sunflower is cultivated in a multitude of geographical regions worldwide, whether as a rain-fed, arid, or irrigated crop (Sposaro *et al.*, 2010). Sunflower requires about 500-670 mm of water during the growing season. According to FAO (Food and Agriculture Organization), guidelines for crop water requirements and drought sensitivity indicate that cabbage, walnut, and onion require 350-500 mm of water and are moderately sensitive to drought. Tomatoes require 400-800 mm of water and are moderately sensitive to drought, while peppers require 600-900 mm of water and are also moderately sensitive to drought. The quantity of water required by wheat varies depending on several factors, including the climate, the length of the growing season, soil conditions, and irrigation. In general, wheat requires between 400 and 650 mm of water for optimum yield (Tripathi & Mishra, 1986).

The regions of Polissia and Forest-Steppe represent significant areas of Ukraine with considerable potential for the advancement of agricultural and forestry activities. The active economic utilisation of these territories must be undertaken in a manner that ensures the sustainability of ecological systems and the maintenance of ecosystem functions. The issue of evaluating the impact of precipitation dynamics on crop yields at the regional level remains unresolved. Accordingly, the objective of this study was to identify patterns of spatial and temporal variability in precipitation and to ascertain the influence of anthropogenic landscape modification resulting from agricultural production.

MATERIALS AND METHODS

The spatial variability of annual precipitation within 10 administrative regions in the north and northwest of Ukraine between 1960 and 2023 was investigated (Fig. 1). The region encompasses both Polissia and Forest-Steppe geographical zones.

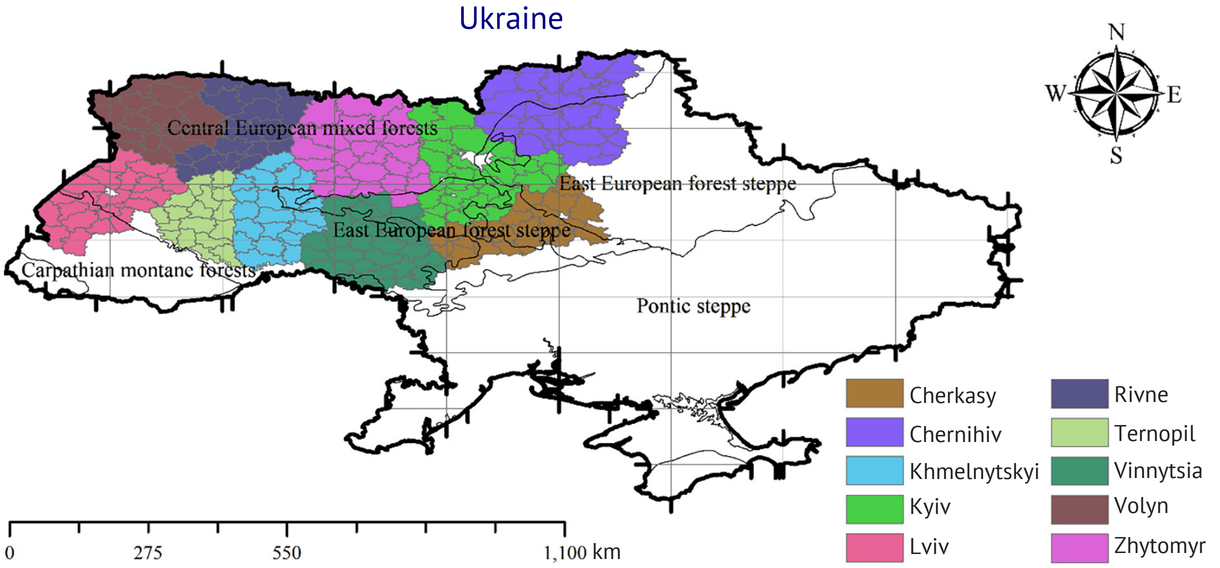

Figure 1. *The study area with the administrative regions of the country covered*

Source: *authors' development*

Prior to the 2015-2022 reform of Ukraine's administrative and territorial structure, the environmental characteristics were averaged across administrative districts. This is due to the fact that the area of "traditional" rayons is smaller and more ecologically homogeneous than that of the new administrative units. Furthermore, data on crop yields have been collected over an extended period within the "old" administrative districts, which is crucial for elucidating the relationship between productive potential and climatic conditions.

The historical data on the spatial variability of precipitation were obtained from the WorldClim (n.d.) website. A principal component analysis, Bartlett's test of sphericity, and the Monte Carlo test were conducted using the library stats (The R Project..., n.d.). The suitability of the precipitation data for the principal component analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) test (Kaiser, 1974), with the assistance of the KMOS function from the REdaS library (Maier, 2022) within the R computing environment. J.L. Horn's (1965) technique for evaluating the components in a principal component analysis was implemented through the paran function from the Paran library (Dinno, 2024). The spatial database was created in ArcGIS 10.0. Descriptive statistics, as well as cluster and cluster analysis, were performed in StatSoft 12.0.

RESULTS

Spatial and temporal dynamics of precipitation. The average precipitation level within the study area from 1960 to 2023 was 625 ± 68 mm, ranging from 535 to 1,160 mm. The lowest amount of precipitation was observed in 2005, amounting to 488 ± 59 mm, while the highest was recorded in 1980, with 803 ± 85 mm. The lowest precipitation level was recorded for the Chyhyryn District (535 ± 79 mm), and the highest in the Skole District (1,160 ± 151 mm).

A zone of local maximum precipitation is observed within the study region, extending diagonally from the northeast to the southwest (Fig. 2). Consequently, areas of local minima are located in the southeast and northwest of the region. The zone of highest precipitation levels is situated in the southwest and corresponds to the Precarpathian Upland. Precipitation levels in this zone range from 658 to 1,160 mm per year. Additionally, the central region exhibits elevated precipitation levels. The lowest precipitation levels are observed in the southeast, within the Forest-Steppe zone, where an average of 535-573 mm of precipitation falls per year. During the study period, a discernible trend of both increasing and decreasing precipitation was noted. The southeastern region exhibited a declining trend, whereas the northwestern and northern regions demonstrated an increasing trend.

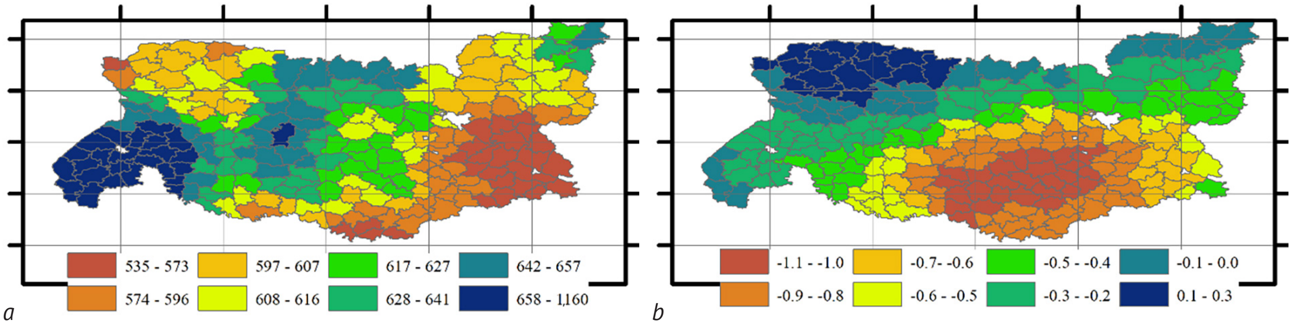

Figure 2. *Spatial variation of mean annual precipitation (mm, 1960-2023) (a) and temporal trend of precipitation variability (b)*

Source: *authors' development*

Global principal component analysis. Linear regression can explain some of the variance in precipitation over time. Further analysis uses the residuals of the regression model of precipitation versus time. The variability of these residuals is also likely to be complex in nature. The variation in the residuals of a linear regression model contains random noise associated with inherent errors in the original data. Additionally, a component associated with regular factors that may have environmental effects can be expected in the regression residuals. Bartlett's test of sphericity ($P < 0.05$) indicates that principal component analysis can be applied to such data. Global principal component analysis identified six statistically significant principal components, which together explained 84.8% of the variation in the detrended precipitation data (Table 1).

Table 1. *Results of the global principal component analysis*

Principal component	Adjusted eigenvalue*	Eigenvalue	Shift	Explained variation	Standard deviation
1	20.35	21.66	1.31	33.84	4.64
2	14.54	15.73	1.19	24.57	3.96
3	9.06	10.16	1.10	15.87	3.18
4	4.47	5.49	1.02	8.58	2.34
5	2.40	3.35	0.95	5.24	1.83
6	1.37	2.26	0.89	3.53	1.50

Notes: ** – according to J.L. Horn (1965)*

Source: *authors' development*

Years of research into the principal component space have revealed certain patterns. The properties of the principal components can be better understood by presenting their variability in both time (Fig. 3) and space (Fig. 4). Each principal component contrasts a particular sequence of years with another sequence in terms of precipitation, which has a distinct spatial structure. Principal Component 1 accounts for 33.8% of the variation in precipitation and is the most sensitive to fluctuations in precipitation, with autocorrelation lags of 5 and 9 years. Spatially, this principal component contrasts the precipitation rhythm in the eastern part of the region with that of the western part.

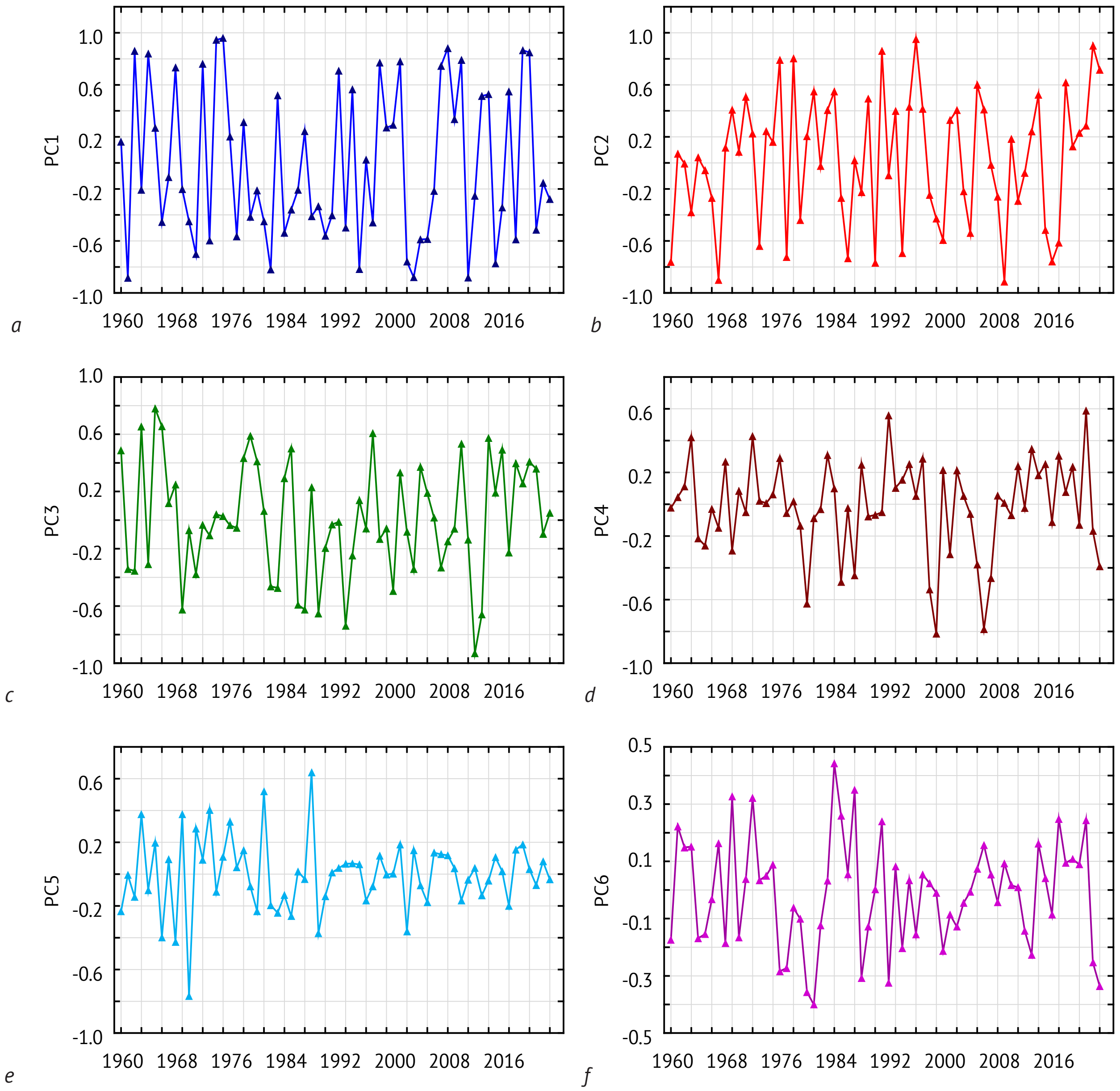

Figure 3. *Time variation of the loadings of principal components 1-6*

Notes: *a – Principal Component 1 (autocorrelation: -0.13 ± 0.11 for lag 5, 0.13 ± 0.11 for lag 9, and 0.90 ± 0.08 for lag 12); b – Principal Component 2 (autocorrelation: -0.22 ± 0.12 for lag 3, 0.12 ± 0.09 for lag 4, and -0.15 ± 0.12 for lag 11); c – Principal Component 3 (autocorrelation: -0.26 ± 0.12 for lag 8, 0.19 ± 0.09 for lag 13); d – Principal Component 4 (autocorrelation: -0.18 ± 0.09 for lag 12, -0.26 ± 0.09 for lag 15); e – Principal Component 5 (autocorrelation: -0.39 ± 0.12 for lag 1, 0.22 ± 0.12 for lag 2, and -0.26 ± 0.12 for lag 3); f – Principal Component 6 (autocorrelation: -0.25 ± 0.12 for lag 5, -0.20 ± 0.12 for lag 7, and 0.21 ± 0.12 for lag 12)*

Source: *authors' development*

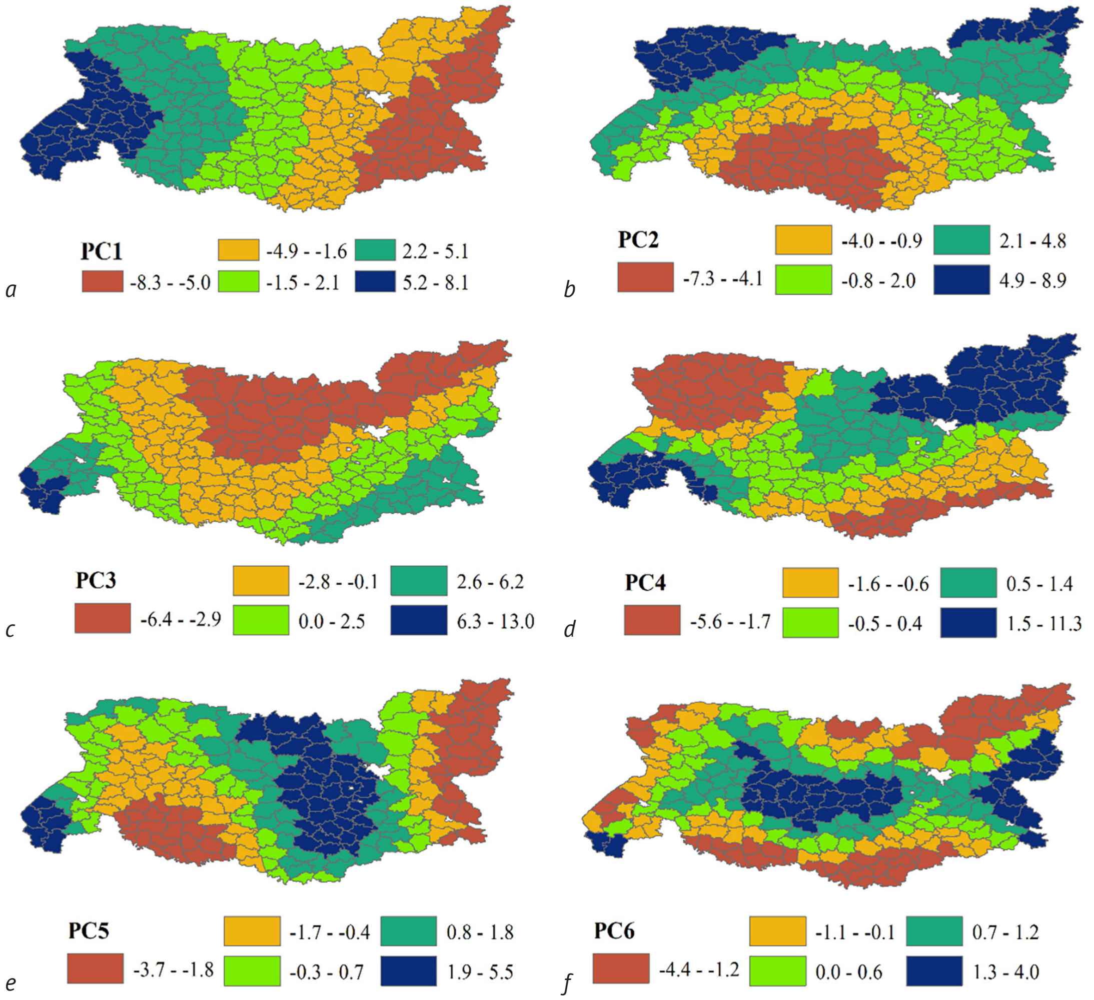

Figure 4. *Spatial variability of the principal component scores 1-6*

Notes: *a – Principal Component 1 (λ = 20.35, 33.84% of the explained variation); b – Principal Component 2 (λ = 14.54, 24.57% of the explained variation); c – Principal Component 3 (λ = 9.06, 15.87% of the explained variation); d – Principal Component 4 (λ = 4.47, 8.58% of the explained variation); e – Principal Component 5 (λ = 2.40, 5.24% of the explained variation); f – Principal Component 6 (λ = 1.37, 3.53% of the explained variation)*

Source: *authors' development*

Principal Component 1 is not statistically significantly correlated with soil properties (Table 2). The values of this principal component are higher in landscapes where the proportion of broadleaf and mixed forests and meadows is greater, and the proportion of agricultural areas is smaller. Principal Component 2 accounted for 25.6% of the variability in precipitation and is sensitive to the variability components with autocorrelation lags of 3, 4, and 11 years. This principal component differentiates the southwestern part of the region from other areas. Principal Component 2 is positively correlated with soil organic matter and sand but negatively correlated with clay and silt. Higher values of this principal component are found in landscapes with a greater proportion of coniferous, broadleaved, or mixed forests, and a smaller proportion of agricultural areas or sparse vegetation.

Table 2. *Correlation between principal components and ecological properties of the territories (correlation coefficients are statistically significant for P < 0.05)*

Variables	Principal components					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Soil properties						
Organic matter (OM)	–	0.41	0.19	-0.24	-0.23	–
Clay	–	-0.74	0.51	–	–	–

Table 2, Continued

Variables	Principal components					
	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Sand	–	0.71	−0.41	–	0.18	-0.15
Silt	–	-0.60	0.28	0.20	-0.25	0.24
Types of landscape cover (GlobCover)						
Rainfed croplands	-0.15	-0.64	0.23	-0.27	-0.14	–
Mosaic croplands (50-70%) / Vegetation (grassland/shrubland/forest) (20-50%)	-0.38	-0.25	-0.18	–	-0.35	–
Mosaic vegetation (grassland/shrubland/forest) (50-70%) / Cropland (20-50%)	-0.23	-0.27	0.53	0.33	–	–
Closed (>40%) broadleaved deciduous forest (>5m)	0.44	0.49	–	–	–	–
Closed (>40%) needle-leaved evergreen forest (>5m)	–	0.30	-0.35	0.15	0.28	–
Open (15-40%) needle-leaved deciduous or evergreen forest (>5m)	–	0.49	-0.33	0.23	–	-0.28
Closed to open (>15%) mixed broadleaved and needle-leaved forest (>5m)	0.14	0.50	-0.38	–	0.29	–
Mosaic grassland (50-70%) / Forest or shrubland (20-50%)	0.47	–	0.44	0.30	–	–
Closed to open (>15%) herbaceous vegetation (grassland, savannas, or lichens/mosses)	0.28	–	0.35	0.24	0.21	–
Sparse (<15%) vegetation	-0.29	-0.48	0.17	-0.21	–	-0.29
Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil – fresh, brackish or saline water	–	–	-0.19	–	–	–
Artificial surfaces and associated areas (urban areas >50%)	–	–	–	–	–	–

Source: *authors' development*

Principal Component 3 accounted for 15.9% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 8 and 13 years. It contrasts the dynamics of oscillatory processes in the northern region with those in the central part of the area. Principal Component 3 is positively correlated with soil organic carbon, clay, and silt content, and negatively correlated with sand content. Higher values of this principal component are found in landscapes with a greater proportion of meadow and shrub vegetation and a smaller proportion of agricultural land, coniferous, or mixed forests.

Principal Component 4 accounted for 8.6% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 12 and 15 years. It contrasts the dynamics of oscillatory processes along a diagonal from the northeast to the southwest, compared with those in the northwest and southeast. Principal Component 4 is positively correlated with silt content and negatively correlated with organic carbon content. It is negatively correlated with the proportion of rainfed land or sparse vegetation cover and positively correlated with the proportion of meadows, coniferous, or mixed forests.

Principal Component 5 accounted for 5.4% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 1, 2, and 3 years. It contrasts the dynamics of oscillatory processes in the centre of the region with those in other areas. Principal Component 5 is negatively correlated with organic carbon and silt content but positively correlated with sand content. This component is negatively correlated with the proportion of agricultural land but positively correlated with the proportion of coniferous forests, mixed forests, and herbaceous vegetation.

Principal Component 6 accounted for 3.5% of the variability in precipitation and was sensitive to variability components with autocorrelation lags of 5 and 7 years. It contrasts the dynamics of oscillatory processes in the centre of the region with the rhythm of processes in the north and south. Principal Component 6 is negatively correlated with sand content and positively correlated with silt content in the soil. This component is negatively correlated with the proportion of mixed forests and sparse vegetation.

Geographically weighted principal component analysis (GWPCA). The Monte Carlo test was conducted to determine whether the eigenvalues of the data matrix are characterised by a spatial component of variation. The *P*-value for testing the standard deviation of the local eigenvalues based on the GWPCA results is 0.01. This value indicates that the hypothesis of spatial invariance of local eigenvalues can be statistically significantly rejected; in other words, there is a high level of spatial non-stationarity represented in the data on the precipitation erosion factor. Before determining the optimal pass-through window, it is necessary to decide how many principal components to retain (Harris *et al.*, 2011; Gollini *et al.*, 2015). The results of the preliminary global principal components analysis indicate that the first two components together account for 58.4% of the variation in the data structure. Accordingly, it is reasonable to retain these two components for the subsequent GWPCA procedure. In the process of adaptive window selection, an optimal window of 220 nearest neighbours was established for performing the GWPCA procedure. To obtain the corresponding results of the global principal component analysis, only the first two principal components, GWPC 1 and GWPC 2 were interpreted for comparison purposes.

The results of the GWPCA procedure can be visualised and interpreted by focusing on two key aspects: firstly, how the dimensionality of the data varies spatially, and secondly, how the original variables influence the principal components. The proportion of spatial variation in the total variation exhibits a notable degree of variability, with spatially homogeneous clusters emerging in the meridional direction (Fig. 5). In comparison to global principal component analysis, GWPCA has been demonstrated to be an effective and efficient method for analysing spatial patterns of regional precipitation variability, through the mapping of the spatial variability of principal components. The first two principal components extracted from the global principal component analysis were found to be capable of explaining 58.4% of the variability in precipitation. The GWPCA explained between 60.7 and 69.2% of the precipitation variability. The nearest neighbours were selected for the GWPCA procedure. To facilitate comparison with the results of the global principal component analysis, only the first two principal components, GWPC 1 and GWPC 2, were interpreted.

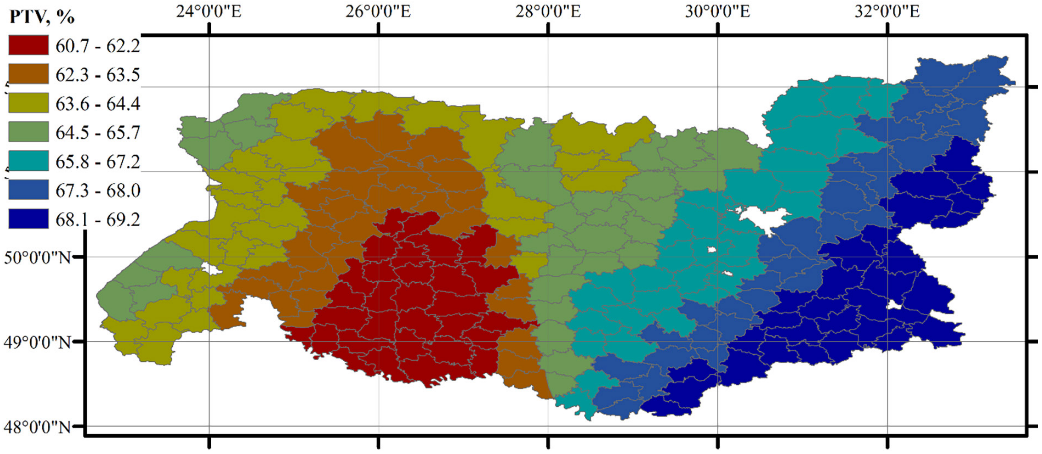

Figure 5. *Spatial variation of the percentage of total variation of the first two principal components*
Notes: *PTV – percentage of total variation*
Source: *authors' development*

The application of cluster analysis to the administrative districts based on the GWPC 1 factor loadings enabled the identification of two distinct clusters (Fig. 6). The aforementioned clusters bisect the study area along the median meridian, delineating the eastern and western regions. The oscillatory process of precipitation variability within Cluster 1 exhibits autocorrelation lags of 1 and 6, whereas precipitation variability within Cluster 2 follows an oscillatory process with autocorrelation lags of 3 and 10 (Fig. 7). The primary distinction between the oscillatory processes observed in the two clusters is the presence of three dominant oscillation periods in the density spectrum of the oscillatory process within Cluster 1, in contrast to the two most prominent periods observed in the spectrum of the oscillatory process in Cluster 2. Furthermore, the oscillatory processes of precipitation variability in Clusters 1 and 2 occur with a phase shift.

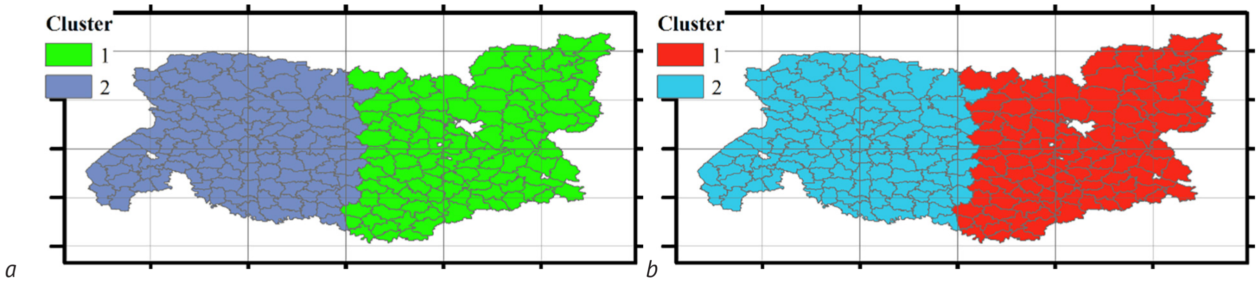

Figure 6. *The spatial location of clusters obtained based on factor loadings GWPC 1 (a) and GWPC 2 (b)*
Source: *authors' development*

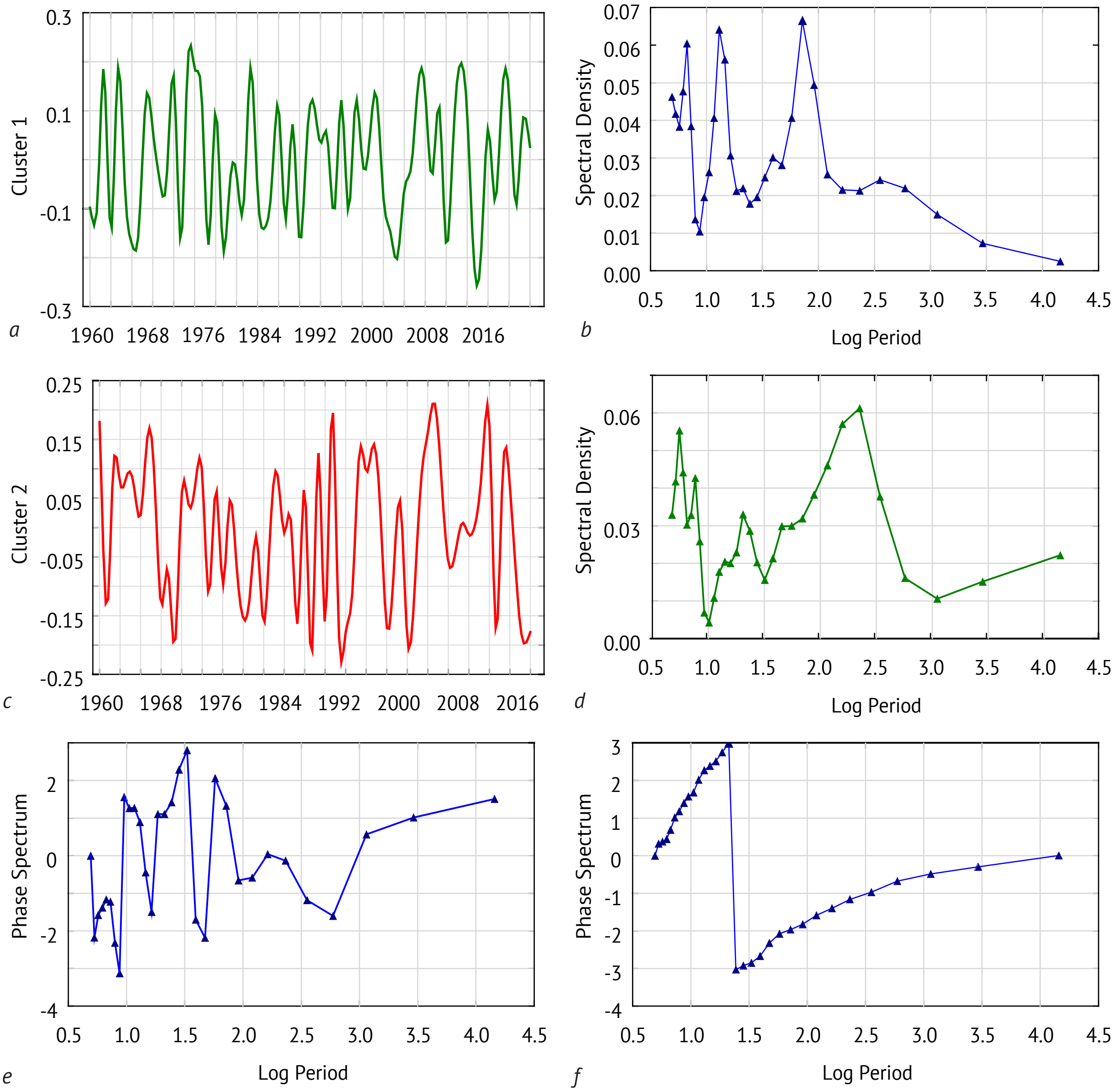

Figure 7. *Time variation of the loadings of the principal component GWPC 1 for Clusters 1 and 2*
Notes: *a – Cluster 1 (autocorrelation: -0.14 ± 0.09 for lag 1, 0.12 ± 0.08 for lag 6, and -0.19 ± 0.11 for lag 8); b – Spectral Density of the oscillatory process for Cluster 1; c – Cluster 2 (autocorrelation: -0. 22 ± 0.11 for lag 3, 0.10 ± 0.07 for lag 10, and -0.21 ± 0.11 for lag 14); d – Spectral Density of the oscillatory process for Cluster 2; e – Phase Spectrum of oscillatory processes within Cluster 1 and 2; f – Phase Spectrum of oscillatory processes with a shift of 3 lags between them*
Source: *authors' development*

The application of cluster analysis to the administrative districts, based on the values of the GWPC 2 factor loadings, enabled the identification of two distinct clusters. The aforementioned clusters delineate the study area along the median meridian, resulting in the division of the area into eastern and western sections. The oscillatory process of precipitation variability within Cluster 1 exhibits autocorrelation lags of 4 and 11, whereas precipitation variability within Cluster 2 follows an oscillatory process with autocorrelation lags of 4, 5, and 9 (Fig. 8).

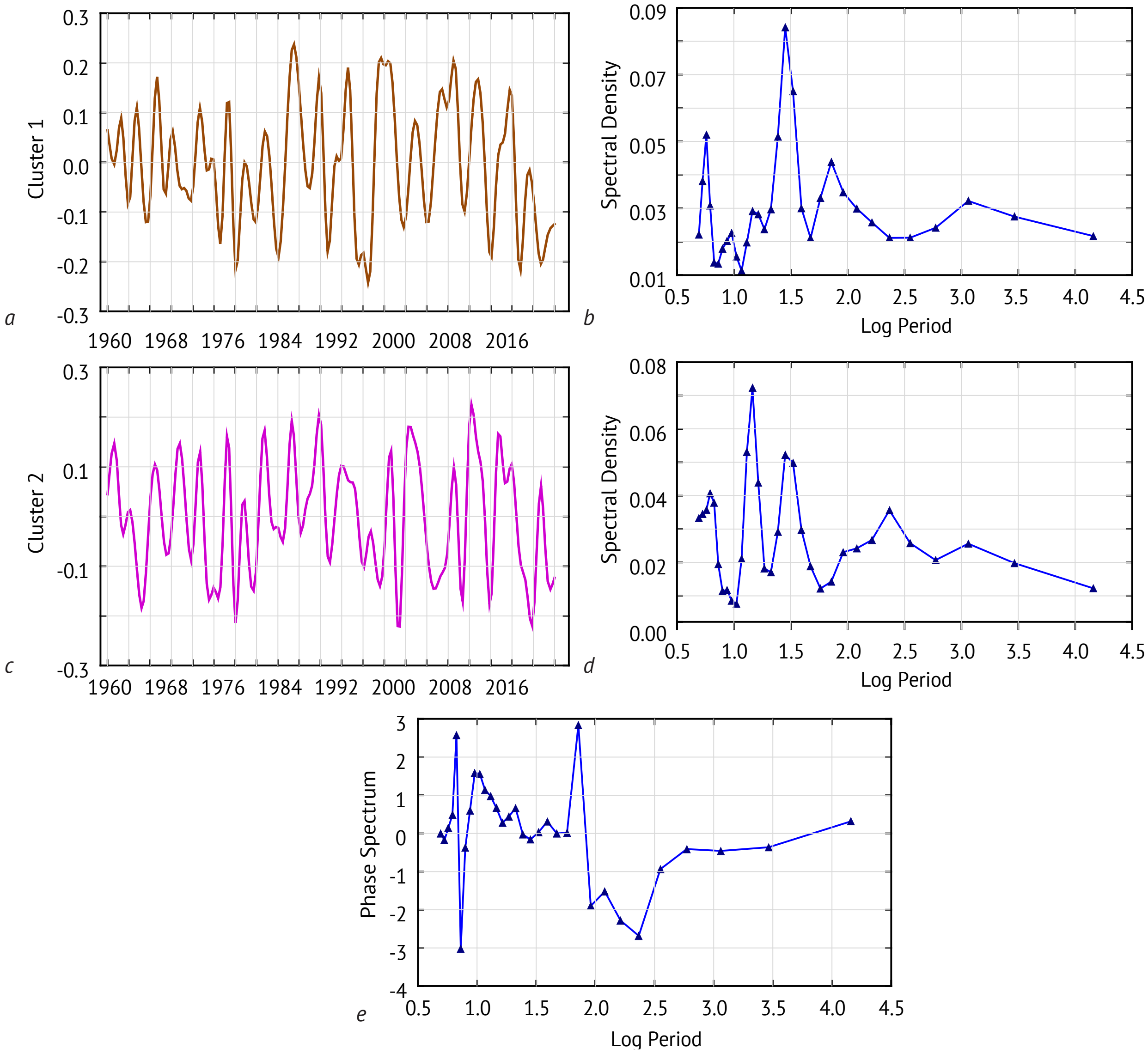

Figure 8. *Time variation of the GWPC 2 principal component loadings for Clusters 1 and 2*

Notes: *a – Cluster 1 (autocorrelation: 0.17 ± 0.09 for lag 4, -0.21 ± 0.08 for lag 11 and 0.27 ± 0.11 for lag 13); b – Spectral Density of the oscillatory process for Cluster 1; c – Cluster 2 (autocorrelation: 0.11 ± 0.07 for lag 4, -0.16 ± 0.07 for lag 5, and 0.18 ± 0.11 for lag 9); d – Spectral Density of the oscillatory process for Cluster 2; e – Phase Spectrum of oscillatory processes within Clusters 1 and 2*

Source: *authors' development*

The primary distinction between the oscillatory processes observed in the two clusters is that the density spectrum of the oscillatory process within Cluster 1 encompasses the three most prominent oscillation periods, whereas the lags of these oscillatory processes are shifted to the left in the spectrum of the oscillatory process observed in Cluster 2. Furthermore, the oscillatory processes of precipitation variability in Clusters 1 and 2 occur with a phase shift.

DISCUSSION

The distribution of total precipitation in the area under study is the result of a combination of processes that reflect the patterns of geographical and altitudinal zonation, as well as geographical sectorality (meridional zonation). The Forest-Steppe zone is characterised by a naturally lower level of precipitation compared to Polissia. The Carpathian region exhibits considerably higher precipitation levels than other areas within the territory. Polissia displays a contrast in moisture conditions, ranging from regionally high to regionally low levels. In the central part of the region, from the north to the centre and southwest, a zone of increased precipitation is formed, exhibiting signs of sectoral variability. The Forest-Steppe fraction of the study area is included in the sub-zone of sufficient moisture, with an average annual precipitation of 570 to 600 mm.

The phenomenon of climate change is impacting the global water cycle, with implications for both the total amount of precipitation and extreme precipitation events. It is expected that total precipitation will increase by approximately 2-3% for each degree Celsius of global warming. Additionally, estimates indicate that extreme precipitation may become more intense by approximately 7% for each degree Celsius of warming (Allen & Ingram, 2002). It is anticipated that the projected changes in daily temperature, precipitation, wind, relative humidity, and global radiation will result in a decline in maize yields in Europe, with an estimated reduction of between 1 and 22% by 2050. Furthermore, wheat yields in Southern Europe are anticipated to decline by 49%. Nevertheless, in Northern Europe, some of the adverse effects of climate change on yields may be mitigated by elevated CO_2 concentrations in the atmosphere and alterations in precipitation patterns (Hristov *et al.*, 2020). A decline in total annual precipitation has been observed in the Forest-Steppe zone of Ukraine, with a reduction from 616 to 584 mm from 1990 to 2010. An evaluation of water losses due to evaporation demonstrates that even with annual precipitation exceeding 500 mm, a moisture deficit can occur. This phenomenon is observed in the Forest-Steppe zone with a frequency of approximately 60% of the cases studied (Petrychenko *et al.*, 2018). These findings align with the temporal precipitation trends previously identified in the Forest-Steppe segment of the study area. It should be noted, however, that this trend does not extend across the entire territory. In contrast, the Polissia segment of the region exhibits a reversal in the trend of precipitation variability over time. In particular, the northwest region exhibits a pronounced trend of increasing precipitation. It is also noteworthy that the diagonal zone within the study area represents the boundary between the opposing trends in precipitation over time. Consequently, this zone can be considered to exhibit a relatively constant temporal trend.

The findings highlight an additional dimension of precipitation variability that extends beyond a mere directional trend over time. Precipitation dynamics over time exhibit several distinct spatial patterns, which are identified by principal components that are statistically independent of one another. This indicates that disparate spatial and temporal patterns of precipitation arise as a consequence of the influence of different factors. It is also important to note that the contribution of the respective patterns to the overall precipitation rhythm decreases in the corresponding principal component series. Consequently, their direct impact on ecological processes and agricultural production conditions also diminishes. If the "first" principal components are the result of geographical factors that are regular in space and time, then the subsequent factors in their genesis can be considered to be generated by factors of local environmental and landscape character.

Principal Component 1 reflects the meridional sectoral variability of precipitation rhythms. An increase in precipitation in the eastern region is accompanied by a decrease in precipitation in the western region, and vice versa. Therefore, the remote sensing data reveal a distinct meridional zonation of the marine ecosystem structure, with a markedly higher density of phytoplankton in coastal and Atlantic waters. This structure correlates well with the complex hydrographic circulation observed in the region (Mitchell *et al.*, 1991). The meridional zonation of phytoplankton productivity characteristics was identified through an analysis of the spatial distribution of primary production in the world ocean. The latitudinal zonation of vegetation is complemented by a meridional zonation, which should be taken into account when identifying biogeographic regions. The results demonstrate a distinct form of zonation, characterised by rhythmic patterns. Zonation can be defined as a sequence of geographically ordered areas of the Earth's surface that are quantitatively distinct in terms of specific properties. In this instance, the focus is on the cyclical variability of properties over time, which is characterised by a sectoral spatial organisation. Principal Components 2 and 3 show a spatial organisation that closely resembles geographic zonation, albeit with a cyclical rather than modal spatial pattern.

Principal Components 4-6 account for a decreasing proportion of the variability in precipitation; yet, they reflect more spatially detailed patterns of variability that do not align with the patterns of geographic zonation. These components are significantly correlated with both soil properties and vegetation cover. To gain a deeper understanding of the correlation between vegetation cover and precipitation variability, it is essential to distinguish between areas covered by crops and those covered by natural or distinct vegetation types. It can be posited that the natural variability of precipitation is related to the organisation of landscape cover, which, in turn, determines the distribution of suitable and unsuitable areas for agricultural production. Furthermore, it can be postulated that anthropogenic alterations to the landscape may influence precipitation patterns and contribute to the emergence of significant spatial and temporal patterns.

A more comprehensive examination of the hypothesis that anthropogenic transformation influences the trajectory of climate processes could potentially yield insights that inform strategies for climate change adaptation. W. Lahmer *et al*. (2001) emphasise that the impact of global changes on the regional water cycle, caused by either climate change or land-use changes, represents a significant scientific issue. C. Stephens & A. Ngari (2024) note that the most important sources and drivers of global climate change are known to be at the regional level. N.W. Arnell *et al*. (2019) highlight that temperature and precipitation show significant regional variability in the context of global climate change. According to P.S. Roy *et al*. (2022), transformations in land use or land cover represent a human-induced systemic disturbance that exerts an influence, either direct or indirect, on a multitude of hydrological processes. P.A. Dirmeyer *et al*. (2010) also point out that the climatic features of the region exert a pivotal influence on the consequences of land-use modification. Thus, the results allow for a reasonable assumption that a significant oscillatory component of precipitation variability in the studied region can be induced by both natural landscape heterogeneity and anthropogenic landscape transformation, primarily through agricultural activities.

The oscillatory regularity observed in precipitation rhythms allows for two practical considerations to be made. This enables the forecasting of future precipitation dynamics based on data from previous years, as well as the consideration of fluctuating precipitation dynamics to recommend optimal crop rotations and select the most suitable range of crop varieties for cultivation. The established regularities provide a basis for formulating empirical rules for the selection of crops in crop rotation. It is well documented that the cultivation of soybeans as a predecessor to winter wheat in the sub-zone of sufficient moisture in Forest-Steppe is an inherently risky venture. The crop is highly susceptible to fluctuations in temperature and moisture levels throughout the growing season. However, the awareness of crop characteristics is of limited practical value in the absence of a forecast of the probable amount of precipitation in the subsequent year. Spatial and temporal patterns with different time lags have been established, which can serve as a foundation for climate forecasts and the development of optimal crop rotations. The cultivation of sugar beet is adversely affected by the overlap of crops in the crop rotation, which can also be attributed to a discrepancy between the rhythm of climatic processes and the requirements of the crop.

CONCLUSIONS

The distribution of total precipitation in the study area results from a superposition of processes that reflect the patterns of geographical and altitudinal zonation, as well as geographical sectorality (meridional zonation). The mean precipitation level within the study area for the period between 1960 and 2023 was 625 ± 68 mm, with a range spanning from 535 to 1,160 mm. During the study period, there was a discernible trend towards both increasing and decreasing precipitation. The southeastern region exhibited a declining precipitation trend, whereas the northwest and north demonstrated an increasing precipitation trend over time. A global principal component analysis identified six statistically significant principal components, which collectively explained 84.8% of the variation in the detrended precipitation data. The principal components exhibited particular spatial patterns of variability and spectral features of time variation. The established spatial and temporal patterns of precipitation are formed as a result of the influence of various factors. Principal Components 1-3 result from geographical factors that are regular in both space and time. Principal Component 1 is indicative of the meridional sectoral variability of precipitation rhythms. Principal Components 2 and 3 exhibit a spatial organisation that closely corresponds to geographic zonation, albeit with a cyclical rather than modal spatial pattern. Principal Components 4-6 are the result of local ecological and landscape factors. The anthropogenic transformation of the landscape can also impact precipitation rhythms and contribute to the formation of relevant spatial and temporal patterns. For future research, it is essential to determine the impact of spatial and temporal dynamics of precipitation on the yield of key agricultural crops in the region.

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CONFLICT OF INTEREST

None.

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Коливальна просторово-часова мінливість опадів в Поліссі та Лісостепу та вплив аграрного перетворення ландшафтів

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Анотація. Території Полісся та Лісостепу мають велике значення для України, пропонуючи значний потенціал для розвитку сільського та лісового господарства. У світлі нагальної проблеми глобальної зміни клімату вкрай важливо, щоб активне господарське використання цих територій відбувалося з урахуванням зобов'язань щодо збереження екологічних систем та підтримання екосистемних функцій. Метою цієї статті було з'ясувати закономірності просторової та часової мінливості опадів і встановити вплив антропогенної трансформації земель внаслідок сільськогосподарського виробництва. На досліджуваній території середній рівень опадів становив 625 ± 68 мм і коливався від 535 до 1160 мм. Протягом досліджуваного періоду (1960-2023 рр.) спостерігалася тенденція як до збільшення, так і до зменшення кількості опадів. Південний схід регіону характеризувався тенденцією до зменшення кількості опадів, тоді як на північному заході та півночі часовий тренд показував збільшення кількості опадів. Кількість опадів у Карпатському регіоні значно вища, ніж в інших частинах території. Наявність коливальної закономірності в ритмі опадів дозволяє розглядати два практичні аспекти: можливість прогнозування майбутньої динаміки опадів на основі наявної інформації за попередні роки та врахування коливальної динаміки опадів при рекомендаціях оптимальних сівозмін і підборі найбільш придатного асортименту сортів сільськогосподарських культур для вирощування

Ключові слова: клімат; просторова структура; часова динаміка; ландшафтне різноманіття; рослинний покрив