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Ecological determinants of the spatiotemporal dynamics of wildfires in the Polissia and forest-steppe zones of Ukraine

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Abstract. This study investigates the ecological factors determining the spatiotemporal dynamics of wildfires in the Polissia and forest-steppe physiographic zones of Ukraine over the period 2001–2023. The relevance of the research stems from the increasing frequency and intensity of forest and steppe fires caused by climate change, particularly rising air temperatures and the growing incidence of extreme weather events. The present study utilised satellite-derived wildfire data from the Fire Information for Resource Management System (NASA MODIS/VIIRS) and climate data from the CRU TS 4.09 dataset in order to evaluate the monthly number of wildfire occurrences within administrative regions across the two physiographic zones. The modelling approach employed utilised generalized linear mixed models (GLMM) with autoregressive (AR(1)) structure, thereby facilitating a quantitative assessment of the effects of temperature, precipitation, and their interaction on fire intensity. The findings indicated a discernible nonlinear effect of temperature, with a notable escalation in fire risk beyond a threshold of approximately 18–20 °C, while fire activity remained minimal under moderate temperatures (10–15 °C). The findings indicated that precipitation had a statistically significant negative effect, particularly during the vegetation season. Seasonal analysis demonstrated that the majority of regions experience a spring peak in wildfire activity (March–April), with a secondary local maximum in August. The spatial variation between Polissia and the Forest-Steppe is indicative of distinct climatic regimes, land use patterns, and landscape structures. The study also examined changes in the fire dynamics after 2011, which may be attributed to both climatic trends and institutional reforms in environmental governance. A marked decline in the fire intensity was observed in several regions after 2014, possibly linked to changes in landscape accessibility, land use patterns, and reduced anthropogenic pressure. The overall ecosystem sensitivity to fire remains high, with an increased frequency and extent of fire outbreaks during drought years. The findings may contribute to the enhancement of wildfire monitoring and forecasting systems, particularly within the context of integrated natural risk management frameworks. The proposed approach to quantifying ecological determinants of fire activity can be applied to other regions of Ukraine and Central and Eastern Europe to support the development of adaptive conservation and land management strategies under climate change.

Keywords: wildfire occurrence; fire seasonality; climatic drivers; temperature threshold; precipitation effect; satellite-based fire monitoring; autoregressive temporal structure; landscape fire risk; environmental gradients.

Introduction

Fires play a significant role in the transformation of terrestrial ecosystems, acting as a powerful ecological disturbance that changes the structure, functioning and species composition of biocenoses (N'dri et al., 2019). Their impact can be short-term, through the destruction of aboveground biomass, damage to soil cover, and changes in the microclimate, or long-term, causing ecosystems to transition to alternative stable states (Vernooij et al., 2021). Fires can cause the loss or significant reduction of populations of individual species, especially those that are sensitive to high temperatures or those that do not have post-fire recovery mechanisms (Adab et al., 2013). This leads to changes in species composition, decline in biodiversity, increase in the dominance of pyrophytic species, or even invasion of alien taxa adapted to the changed conditions (Efthimiou et al., 2020). For many natural ecosystems, fire is a key ecological factor that maintains their dynamic equilibrium. In fire-resistant biomes such as steppes, savannas or boreal forests, regular fires ensure vegetation regeneration, stimulate seed germination and prevent excessive accumulation of organic matter (Esposito et al., 2019). Such adapted ecosystems demonstrate high resilience to pyrogenic impacts and the ability to self-recover (Van der Werf et al., 2003). Fires also have a profound impact on soil properties, altering organic content, temperature, hydrophobicity, and microbiological activity, thereby affecting the biogeochemical cycles, especially carbon and nitrogen (Langenfelds et al., 2002). This can both increase soil fertility in the short term and cause degradation and erosion processes under conditions of intensive or repeated exposure (Shi et al., 2021). Changes in vegetation cover after fires often lead to changes in water balance, surface albedo, and local climate, amplifying or mitigating regional climate shifts. Fires alter local ecosystems and can have cumulative effects at the landscape and biosphere levels (Loiselle et al., 2020).

Global carbon dioxide (CO_2) emissions from fires are a significant contributor to the atmospheric carbon balance and are considered one of the main sources of this naturally occurring gas (Abdollahi et al., 2018). During the combustion of biomass, especially under the conditions of incomplete oxidation, significant amounts of CO are formed, which is an intermediate product between organic carbon and carbon dioxide (Siegmund et al., 2024). Its emission concentration is particularly high during decay, which is typical for undergrowth, peat, and partially wet ecosystems (Amalina et al., 2022). Estimates show that global fires cause tens, and sometimes more than 100 million tonnes of CO emissions annually, depending on regional conditions and the scale of seasonal disturbances (Fan et al., 2024). The largest volumes come from tropical regions, particularly South America, Central Africa, and Southeast Asia, where large-scale fires are common in savannas, tropical forests and degraded peatlands (Bolaño-Díaz et al., 2022). Carbon oxide plays an important role in atmospheric chemistry as it participates in the formation of tropospheric ozone and influences the concentration of hydroxyl radicals (OH), which in turn regulates the lifetime of greenhouse gases, particularly methane. Long-term accumulation of CO in the surface layer of the atmosphere also affects air quality, posing risks to human health, especially in regions with chronic fires or high anthropogenic loads. Fires are an important natural contributor to global CO emissions from ecosystems to the atmosphere, with significant implications for both the climate system and regional air pollution (Volkova et al., 2022).

Fires have a multifaceted impact on agroecosystems, altering their structure, functioning, and productivity (Kooch et al., 2024). In the short term, fires can lead to total or partial crop loss, soil degradation, destruction of agronomic infrastructure (e.g., irrigation systems, protective strips), as well as the destruction of vegetation residues that protect the soil from erosion (Naval et al., 2025). High temperatures contribute to a decrease in organic matter content in the soil, disruption of humus structure and a decrease in microbiological activity, which negatively affects fertility (Datta, 2021). In certain cases, fires can have a short-term positive effect – destroying weeds, pests and disease pathogens, as well as releasing nutrients in an accessible form (Pullaro et al., 2006). However, this effect is unstable and does not compensate for long-term losses, especially in cases of repeated or intense fires in terms of scale and temperature. In the medium and long term, fires can disrupt the ecosystem balance of agrocenoses, reduce the biodiversity of associated flora and fauna, and affect pollinators and biological regulation (Roy et al., 2014). Increased fire frequency exacerbates the risk of aridification, especially in regions with already insufficient moisture, which increases the vulnerability of agrosystems to climate extremes (Fox et al., 2015). Fires also contribute to increased carbon emissions, which have a feedback effect on the climate system and can exacerbate adverse conditions for agriculture (Gajendiran et al., 2024). Fires in agroecosystems should be considered a powerful destructive factor that undermines the sustainability of agricultural production and requires adaptive risk management strategies at the levels of landscape planning, monitoring, and agricultural practices (Idowu et al., 2023).

Climatic factors, primarily air temperature and precipitation, are key determinants of the spatial and temporal dynamics of natural fires, as they directly affect the combustibility of biomass, the rate of its drying, the duration of the fire hazard period, and the probability of ignition (Naawa et al., 2025). Higher temperatures promote accelerated evaporation of moisture from the surface layer of soil and vegetation, increasing their flammability (Eskandari et al., 2020). In regions with a temperate climate, an increase in average daily temperatures by 1–2 °C can significantly alter the seasonal structure of fires, shifting the peak of activity to earlier dates or prolonging the period of high danger (Carrasco-Escaff et al., 2024). Temperature extremes, especially in combination with windy weather, can create critical conditions for large-scale fires (Abatzoglou et al., 2025). Precipitation plays a regulatory role by reducing the likelihood of fires due to the saturation of combustible material with moisture. However, the effect of precipitation is nonlinear and time-dependent (Bolan et al., 2024). Heavy precipitation at the beginning of the growing season can stimulate the development of grassy vegetation, which, when drying out in the second half of summer, creates conditions for intense late-season fires (Richardson et al., 2022). Precipitation deficits, especially in spring or summer, significantly increase the risk of ignition and spread of fire by reducing the water content in living and dead plant residues (Pagadala et al., 2024). The interaction between temperature and precipitation forms complex seasonal and interannual patterns of fire activity. In most regions of the world, there has been an increase in the frequency, area, and intensity of fires due to rising temperatures and a decrease in effective precipitation as a result of climate change (Tang et al., 2021). These trends require a deeper understanding of climate-dependent mechanisms regulating fire dynamics in order to predict risks and develop preventive landscape management measures (Zhao et al., 2022).

The study of the dynamics of natural fires in the Polissia and Forest-Steppe regions of Ukraine is of exceptional scientific and practical importance in the context of contemporary climate change and land use transformation. These natural and climatic zones are characterised by high landscape mosaic diversity and significant areas of forest, agricultural, and wetland ecosystems, which makes them particularly vulnerable to changes in the frequency, seasonality, and intensity of fires (Tkachuk et al., 2024). Polissia, as an area with high forest cover and water-saturated soils, is severely affected by aridification processes that alter moisture regimes and, accordingly, the potential for ignition (Zymaroieva et al., 2021). The forest-steppe, with its predominantly agricultural landscape structure, lies on the border between natural and anthropogenically altered fire dynamics (Zymaroieva et al., 2020). Despite the growing risks, regional features of spatio-temporal trends in fire activity in these areas remain poorly studied. There is an urgent need for a quantitative analysis of the relationships between climate variables (temperature, precipitation) and fire intensity, as well as the identification of possible threshold effects and regional differences. The objective of the study was to analyse the spatial and temporal dynamics of the natural fire intensity in the Polissia and Forest-Steppe regions of Ukraine in 2001–2024, identify the seasonal and annual trends, assess the impact of climatic factors (temperature and precipitation), and identify the characteristics of regional variation in baseline fire activity.

Materials and methods

Within the study, the fire dynamics were analysed in sixteen administrative regions of Ukraine representing the natural zones of Polissia and Forest Steppe. The list of regions studied included: Cherkasy, Chernihiv, Chernivtsi, Ivano-Frankivsk, Kharkiv, Khmelnytskyi, Kyiv, Lviv, Poltava, Rivne, Sumy, Ternopil, Vinnytsia, Volyn, Zakarpattia, and Zhytomyr oblasts. This selection ensured coverage of a variety of climatic, landscape and forest conditions, which made it possible to identify the spatial features and temporal trends in the fire activity against the background of regional differences.

Satellite data on active fires from NASA's global fire monitoring system FIRMS (Fire Information for Resource Management System) were used to analyse the spatial and temporal dynamics of fires in the study area. The source was MODIS Collection 6.1 (MODIS C6.1 Active Fire Data), which provides daily detection of fire hotspots using Terra and Aqua satellites. The data covers the period from November 1, 2000, to July 11, 2025, and was obtained in shapefile (.shp) format for the entire territory of Ukraine through the Fire Archive Download Tool (https://firms.modaps.eosdis.nasa.gov). Each record contains the spatial coordinates of the detected fire, the date of observation (acq_date), brightness (pixel temperature), confidence index, and an estimate of the fire radiative power (FRP), which is an indirect indicator of fire intensity. Further processing was performed in R using the sf and dplyr packages. The geospatial data was linked to the administrative boundaries of Ukraine's regions (in the form of a polygonal layer), after which the number of fires was aggregated by year and month for each region. This made it possible to assess seasonal patterns and identify features of interannual variability in the fire activity.

The source of precipitation and temperature data in this study was the CRU TS v4.09 (Climatic Research Unit Time-Series) climate archive developed by the University of East Anglia. This dataset covers global climate variables with a spatial resolution of 0.5° × 0.5° and provides monthly values for key meteorological indicators, including air temperature and precipitation, since 1901. Data for the period 2001–2024 were used for the analysis, which were previously aggregated within the administrative regions of Ukraine with subsequent construction of annual and monthly average series, as well as assessment of long-term trends.

The trend in temperature and precipitation changes over time was assessed separately for each region using linear regression, in which the annual average values of climatic indicators (temperature or total precipitation) were considered as the dependent variable and the year as the independent variable. For each region, a model of the following form was constructed:

$$Y = \beta_0 + \beta_1 \times Year + \varepsilon,$$

where Y is the average annual temperature or precipitation, β_1 is the slope coefficient reflecting the annual rate of change in the indicator, and ε is the residual error. The estimated coefficient β_1 was interpreted as the average increase or decrease in the climate indicator per year. The regression was performed separately for each region for the period 2001–2024, after which the obtained coefficients were visualised in the form of spatial maps showing the intensity of climate change at the regional level. All calculations were performed in the R environment using the lm() and tidy() functions from the broom package.

The regression model was constructed as a generalised linear mixed model with gamma distribution and a logarithmic link function, which is an appropriate choice for modelling positive continuous variables, such as fire density per unit area:

$$\log(\mu_{i,t}) = \beta_0 + \beta_1 \cdot \mathrm{MonthF_i} + \beta_2 \cdot \mathrm{Year_i} + \beta_3 \cdot \mathrm{Year_i^2} + \beta_4 \cdot \mathrm{Temp_i} + \beta_5 \cdot \mathrm{Temp_i^2} + \beta_6 \cdot \mathrm{Precip_i} + u_{\mathrm{Region}[i]} + \phi \cdot \log(\mu_{i-1}),$$

where: μi,tis the fire density in region i in month t (fires/km^2), β_0 is the total intercept, MonthF(i) is a factor predictor that takes into account the seasonal component (the model includes 11 dummy variables for months), Year(i), Year(i) (2) are polynomial time terms reflecting the overall linear and quadratic trends, Temp(i), Temp(i) ^{2}are the average temperature and its quadratic term, Precip(i) is the amount of precipitation (mm), uRegion([i]) is a random intercept for region i, which takes into account spatial heterogeneity, φ•– is the autoregressive component

AR(1), which models the dependence on the value in the previous month in the same region.

The model takes into account both fixed and random effects, as well as temporal autocorrelation. Fixed effects include the following variables: the month factor (MonthF), which reflects seasonal patterns of fire occurrence; second-degree polynomial terms for the variable "year" (poly(Year, 2)), which allow for the estimation of both linear and quadratic trends over time; the polynomial effect of the average annual temperature (poly(Temp_C, 2)), which takes into account the possible nonlinearity of the temperature effect; and the linear effect of annual precipitation (Precip_mm). Spatial heterogeneity was taken into account by including a random intercept for each region (Region), which allows the model estimates to be adjusted for regional differences in the average level of fire activity. The temporal structure of the data is represented by the variable t_ind, which is calculated as the product of the year multiplied by 12 plus the ordinal number of the month (t_ind = Year * 12 + Month). This provides a continuous time scale for modelling autocorrelation. For each region, first-order autoregressive dependence (AR(1)) was taken into account for the observation time, which allows modelling a sequential dependence in fire density between months. The model was implemented in R using the glmmTMB() function from the package of the same name, which provides flexible specification of random effects and time structures. The optimisation parameters of the model were increased to achieve stable convergence under complex data structures.

To verify the adequacy of the generalized linear mixed model constructed using the log-link Gamma distribution, diagnostic procedures were applied using the DHARMa package (Hartig, 2024). In particular, the residuals were simulated using the simulateResiduals() function, which generates simulated residuals that are independent of the distribution assumptions and can be used for further visualisation and testing. To detect potential overdispersion (i.e., a situation where the variance significantly exceeds that expected by the model specification), the testDispersion() function was used. Overdispersion may indicate that the model does not account for hidden variability in the data or that some important structural factors have been left out of the model. If the test result is significant, either the functional form of the model should be revised or more flexible approaches should be used (e.g., inclusion of permission variables, higher-order polynomials, or selection of a different distribution family). All tests were performed in R using the DHARMa package version 0.4.6. The test results did not reveal any statistically significant signs of overdispersion or an excessive number of zero values, which indicates that the model is consistent with the selected specification and can be considered suitable for further interpretation of the results.

To select the most appropriate probability distribution for the response variable Fires_per_km2 (fire density per square kilometre), which is a positive continuous variable, a comparative analysis of several candidate distributions was performed using the fitdistrplus package in R. Preliminarily, the descdist() function revealed asymmetry in the empirical distribution and deviation from normality, which is typical for environmental data. Next, four distributions were fitted: gamma, log-normal, Weibull, and normal. For each of them, the maximum likelihood method was applied using the fitdist() function. The quality of the approximation was assessed using the gofstat() function, which includes the calculation of Akaike (AIC) and Bayesian (BIC) information criteria, as well as Kolmogorov–Smirnov, Cramer–Mieses, and Anderson–Darling tests. The results show that the gamma distribution demonstrated the best fit to the empirical data according to all statistical criteria: it had the lowest AIC and BIC values, as well as the best goodness-of-fit test values. This confirms the applicability of the gamma distribution for modelling the variable Fires_per_km2 in the construction of a regression model.

Results

The analysis revealed a significant spatial and temporal variability in the fire intensity within the Forest-Steppe Zone and Polissia in 2001–2024 (Fig. 1). The highest total number of fires was recorded in Kharkiv Oblast (over 45,000 cases), which also has the highest interannual variability ($\sigma \approx 352$). The most intense fires occurred in 2006–2007, when over 4,000 cases were recorded annually. In 2022, there was an increase, but it did not exceed the previous highs. Chernihiv (36,401 fires), Poltava (34,886), and Kyiv (29,354) oblasts are also characterised by significant intensity. In the western regions (Zakarpattia, Ivano-Frankivsk, Lviv), fires were recorded with less regularity, reduced frequency, and less pronounced peaks. Most often, the peaks of fire intensity in the regions occurred in the period 2007–2012. It was during this time that most oblasts recorded the highest number of fires (for example, Kharkiv – 2007, Zakarpattia – 2011, Ivano-Frankivsk – 2009, Sumy – 2008, etc.). This period may reflect the accumulation of several factors: changes in the climatic conditions (droughts), land use patterns, and increased observability in the first years of full-scale satellite monitoring. After 2013, most regions saw a decrease in peaks or a shift in dynamics towards less intense but more frequent events. In regions that experienced direct military aggression from Russia, a local increase in the fire intensity was recorded after 2022. In Sumy, Chernihiv, Kyiv, Kharkiv, and Poltava oblasts, there has been a local increase in the number of fires compared with previous years. These values do not exceed the peak levels of the 2000s, but their context deserves special attention. This increase may be related to combat operations, the destruction of ecosystems and infrastructure, as well as deliberate arson or the uncontrolled spread of fire as a result of explosions. For the rest of the regions, no upward trend in the number of fires has been recorded after 2020.

An analysis of fire dynamics throughout the year within the administrative regions of Ukraine shows a clear seasonal pattern in their intensity (Fig. 2). The highest number of fires is usually recorded in spring (March–April) and in late summer–early autumn. In the Chernihiv, Kyiv, Poltava, and Sumy oblasts, the maximum number of fires was observed in April. In Chernihiv Oblast, there is a clearly pronounced spring peak in fires, with a maximum in April, when more than 9,000 cases were recorded. March is also marked by high activity, second only to April. After May, the frequency of fires drops sharply, with the lowest values in June. In the second half of the year, there is a second, less intense rise: fires become more frequent again in August and September, reaching about half of the spring level. November and the winter months are characterised by extremely low numbers of fires. This double-humped seasonal profile with a pronounced spring peak indicates the dominance of spring landscape fires, probably caused by the burning of dry vegetation. Kyiv Oblast also experiences a pronounced spring peak in the fire activity, with a peak in April, when the number of recorded fires exceeds 7,000. A similar level is observed in March, indicating a characteristic spring wave of dry vegetation fires. In June and July, the number of fires decreases significantly, but in August there is a second peak, although less pronounced than in spring. September shows a moderate decrease in the activity, and in autumn and winter the number of fires drops sharply. This two-phase structure, with a dominant spring peak, is typical for the northern forest-steppe and indicates the significant role of deliberate arson at the beginning of the fire season.

Poltava Oblast also has a spring peak in the fire activity, with a peak in April – over 8,500 recorded cases. High values are also observed in March, which together with April forms a powerful spring wave of fires characteristic of this region. The summer months show a second, less intense but clearly pronounced peak: July and August are particularly active, followed by a decline in September and October. This seasonal pattern reflects the typical two-phase dynamics of fires in the forest-steppe, with deliberate arson in spring against a backdrop of dry vegetation and an increase in summer and autumn due to climatic factors. In Sumy Oblast, the fire activity peaks in April, with over 7,000 cases, which is the highest figure for any month. High levels are also recorded in March, forming a typical spring peak. In the summer-autumn period, there is a noticeable second wave of fires, peaking in July, with significant levels in August and September. At the same time, fires in May, June, and October have significantly lower rates, and in other months they are almost absent. This double-humped seasonal pattern indicates a combination of anthropogenic spring fires and summer fire hazards caused by high temperatures and dryness.

In the Cherkasy, Kharkiv, Khmelnytskyi, Rivne, Ternopil, and Vinnytsia oblasts, the maximum number of fires was observed in August. In Cherkasy Oblast, unlike most other regions, the highest number of fires was observed not in April, but in August. This indicates a slightly different seasonal distribution of the fire activity, probably due to the specific climatic or landscape conditions of the region, as well as a potentially later start to the dry season or more intensive economic activity in summer. In Kharkiv Oblast, the highest fire activity is observed in August. This month stands out significantly from the others in terms of the number of fires, although noticeably high values are also recorded in April, July and September. This distribution indicates an extended fire hazard period covering the spring-summer and early autumn seasons. The peak in August may be associated with a combination of high temperatures, dry conditions and anthropogenic factors, in particular field work or military operations. In Khmelnytskyi Oblast, the maximum number of fires occurs in

August, indicating a pronounced summer peak in the fire activity. There are also noticeable increases in April and September, but they are much less intense than in August. This distribution is typical for agricultural landscapes with seasonal agricultural activity and dry summer conditions. The temporal dynamics of fires in Rivne Oblast has a distinct bimodal structure with two main peaks – in spring and summer. The largest share of fires occurs in August (25.17%), indicating a high fire hazard during this period, probably due to a combination of high temperatures, droughts, and active economic activity. The second peak is observed in April (18.99%), which is typical for spring burning of vegetation residues. High values are also recorded in July (22.81%) and March (18.99%), confirming a significant seasonal concentration of fires during the transition periods between seasons. By contrast, in the winter months, as well as in May and November, the frequency of fires is minimal. This profile indicates a predominantly anthropogenic nature of ignition combined with the influence of climatic factors. Thus, in Ternopil Oblast, the highest number of fires occurs in August. According to the graph, the August peak stands out sharply against the background of other months, indicating the predominantly summer nature of the fire-hazardous period. This is confirmed by the tabular data: in August, 44.28% of all the fires for the year were recorded. This is one of the highest indicators among all the regions, indicating a strong seasonal concentration of fires, probably caused by the simultaneous action of natural and anthropogenic factors in the summer period. In Vinnytsia Oblast, as in a number of other western and central regions of Ukraine, there is a clearly pronounced seasonal pattern of fire activity. The highest number of fires occurs in August, indicating the highest fire hazard in the second half of summer. High values are also recorded in September, while the spring peak is less pronounced: the share of fires in April is less than 12% of the annual figure. This pattern of fire activity indicates a predominance of summer-autumn seasonality, probably due to a combination of high temperatures, low rainfall and agricultural factors (e.g. stubble burning).

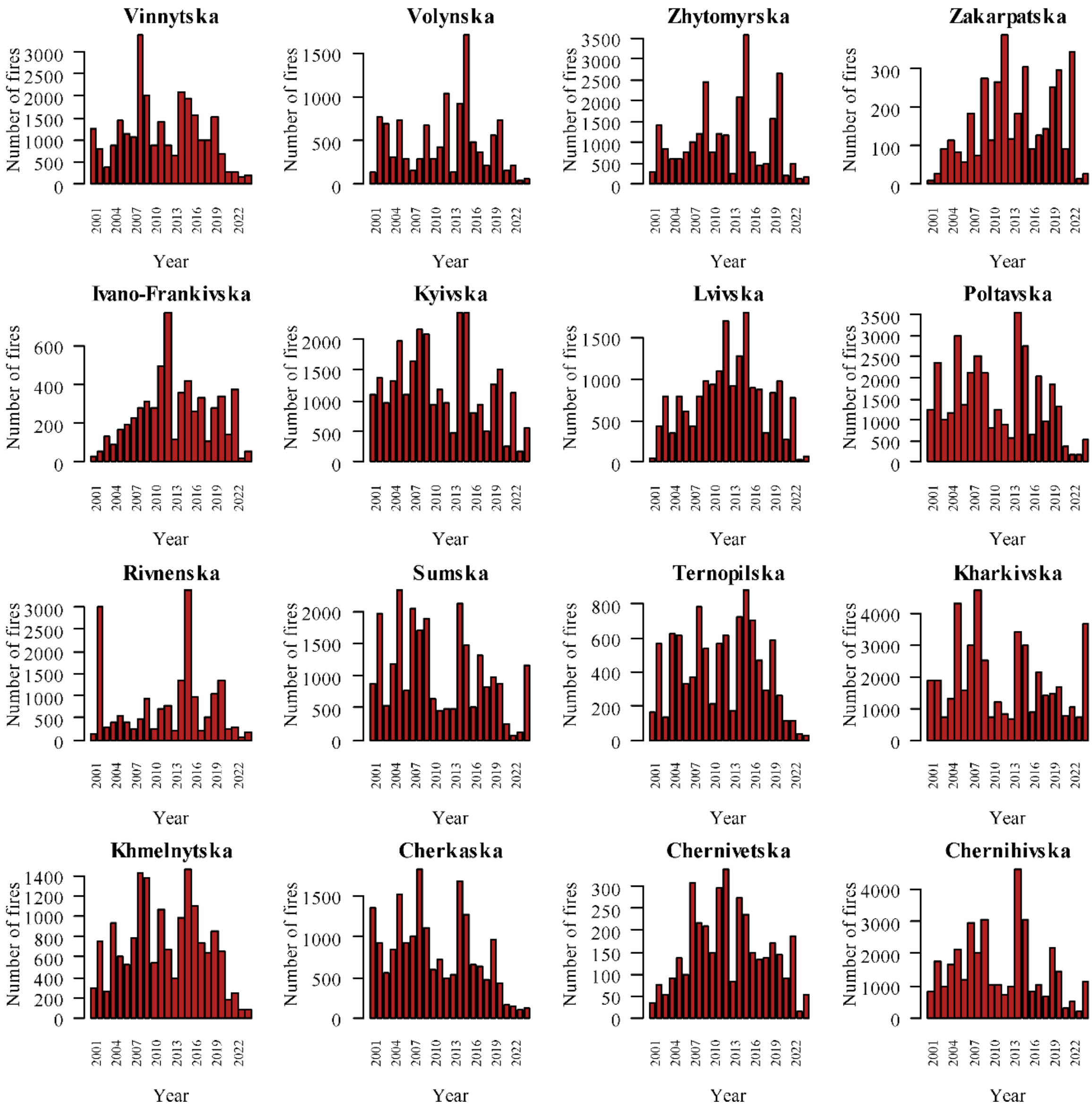

Fig. 1. Temporal dynamics of the number of fires in forest areas of 20 oblasts of Northern and Central Ukraine in 2001–2024: each panel shows the annual number of fires in a particular region, demonstrating spatial and interannual variability

In the Chernivtsi, Ivano-Frankivsk, Lviv, Volyn, Zakarpattia, and Zhytomyr oblasts, the maximum number of fires was observed in March. In Chernivtsi Oblast, the spring type of fire seasonality prevails, with a clearly pronounced maximum in March – over 43% of all the recorded cases occur in this month. April is the second most frequent month for fires, while in the summer (especially in July and August) the number of fires is significantly lower. This distribution indicates the predominance of fires caused by the burning of dry vegetation in spring, which is typical for regions with fewer dry summer days. Ivano-Frankivsk Oblast also has a pronounced spring seasonality of fires, with an absolute maximum in March – about 43% of the total number of cases. April ranks second in terms of frequency, while in the summer months, the fire activity is significantly lower. This distribution indicates the predominance of anthropogenic spring fires of dry grass, typical of the Carpathian region with sufficient moisture and a lower probability of natural summer fires. In Lviv Oblast, the vast majority of fires occur in the spring, with a clear peak in March – over 43% of the total number. April ranks second, with significantly fewer cases recorded in the summer months. This pattern indicates the predominance of spring fires of dry vegetation, probably related to agricultural practices, which is typical for regions with high humidity and a lower frequency of natural fires in summer. In Volyn Oblast, the fire activity is highest in March, accounting for over a third of all the recorded cases (almost 34%). A significant proportion of fires are also observed in April. Starting in May, the intensity decreases significantly, although a second, less pronounced peak is observed in July–September. This seasonal pattern indicates a predominance of spring fires, probably related to economic activities, primarily the burning of plant residues. In Zakarpattia Oblast, the highest frequency of fires occurs in March, when almost 45% of all cases are recorded. April is also relatively active, although with significantly lower rates. In the summer months, there is a second, less pronounced peak with a gradual decline in September and October. This distribution of the fire activity indicates a typical spring wave, probably associated with the burning of dry vegetation, as well as a limited summer-autumn activity, characteristic of western regions with a more humid climate. In Zhytomyr Oblast, the highest number of fires occurs in March and April, with each of these months accounting for more than 30% of the annual fire frequency. This indicates a pronounced spring wave, probably caused by the mass burning of dry vegetation. A second, less intense wave is observed in August–September, which is typical for many northern and central regions with a continental climate.

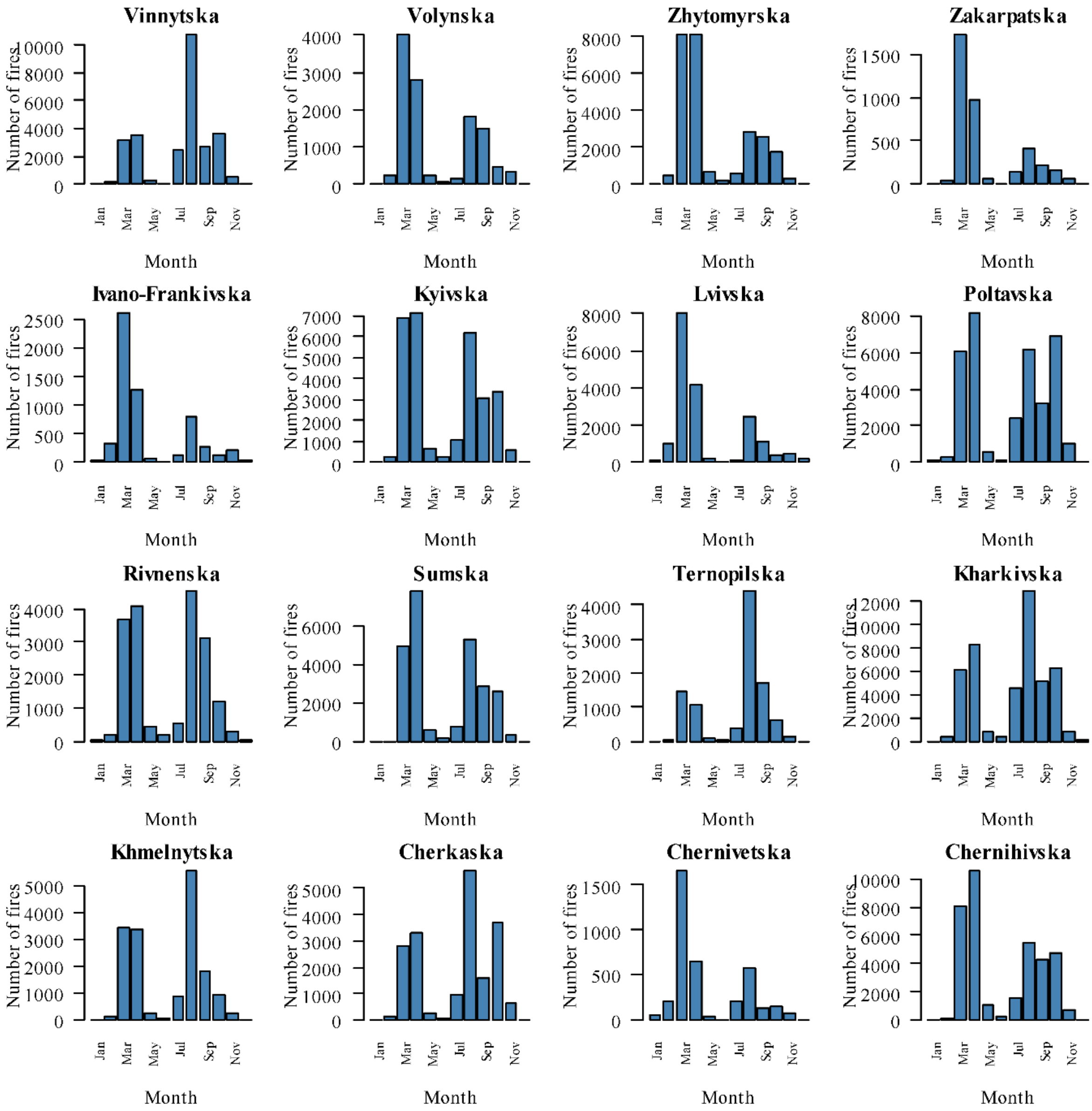

Fig. 2. Monthly dynamics of the number of fires in 2001–2022 by oblast of Ukraine

The analysis of the spatial distribution of average annual precipitation for the period 2001–2024 revealed a clear regional differentiation in the moisture content across the Ukraine's territory. The total range of annual precipitation varies from 506 mm in Poltava Oblast to 779 mm in Zakarpattia Oblast. The lowest precipitation values are recorded mainly in the central and eastern regions (Poltava, Cherkasy, and Kharkiv oblasts), while the highest values are recorded in the western regions (Zakarpattia, Ivano-Frankivsk, and Lviv oblasts), which is due to both orographic features and the influence of the western transfer of moist air. Most regions show characteristic seasonality: the majority of precipitation falls in the summer months, with a maximum in June–July. Zakarpattia Oblast has the most intense precipitation growth in the summer, with a peak of over 110 mm in July. By contrast, precipitation is consistently low in almost all regions during the winter months, especially in December and January (mainly up to 30 mm in the central and northern regions). In most western oblasts, particularly in Chernivtsi and Lviv, precipitation in the spring (April–May) also exceeds 60–70 mm, which can be significant for the spring development of agricultural crops. The results obtained indicate the presence of both climatic and orographic factors that determine the spatial and temporal structure of the moisture supply. These patterns are critical for agricultural planning, water balance assessment, and forecasting the response of landscapes to climate change.

The average precipitation trend throughout the year in the study area shows a clear seasonality. The lowest average monthly precipitation values are observed in the winter months – December, January and February, when the average moisture level does not exceed 30–40 mm. Starting in March, precipitation gradually increases, exceeding 60 mm in May. The peak precipitation occurs in June (≈72.7 mm) and July (≈75.8 mm), which are the wettest months of the year in all the regions without exception. In August, precipitation begins to decline but remains relatively high, followed by a gradual decrease throughout the autumn (September–November). December, like January, is characterised by the lowest values. The trend obtained is typical for a continental climate in the temperate zone, where precipitation is highest in summer and lowest in the cold season. This precipitation pattern is important for agronomic planning, in particular for choosing sowing dates, assessing water stress in crops and developing agronomic measures.

The western regions of Ukraine – Chernivtsi, Ivano-Frankivsk, Lviv, Ternopil, and Zakarpattia – are characterised by higher levels of moisture throughout the year compared with the national average (Fig. 3). The most pronounced difference is observed in the summer, especially in June and July, when precipitation in these regions consistently exceeds 80 mm, while the average for other areas is significantly lower.

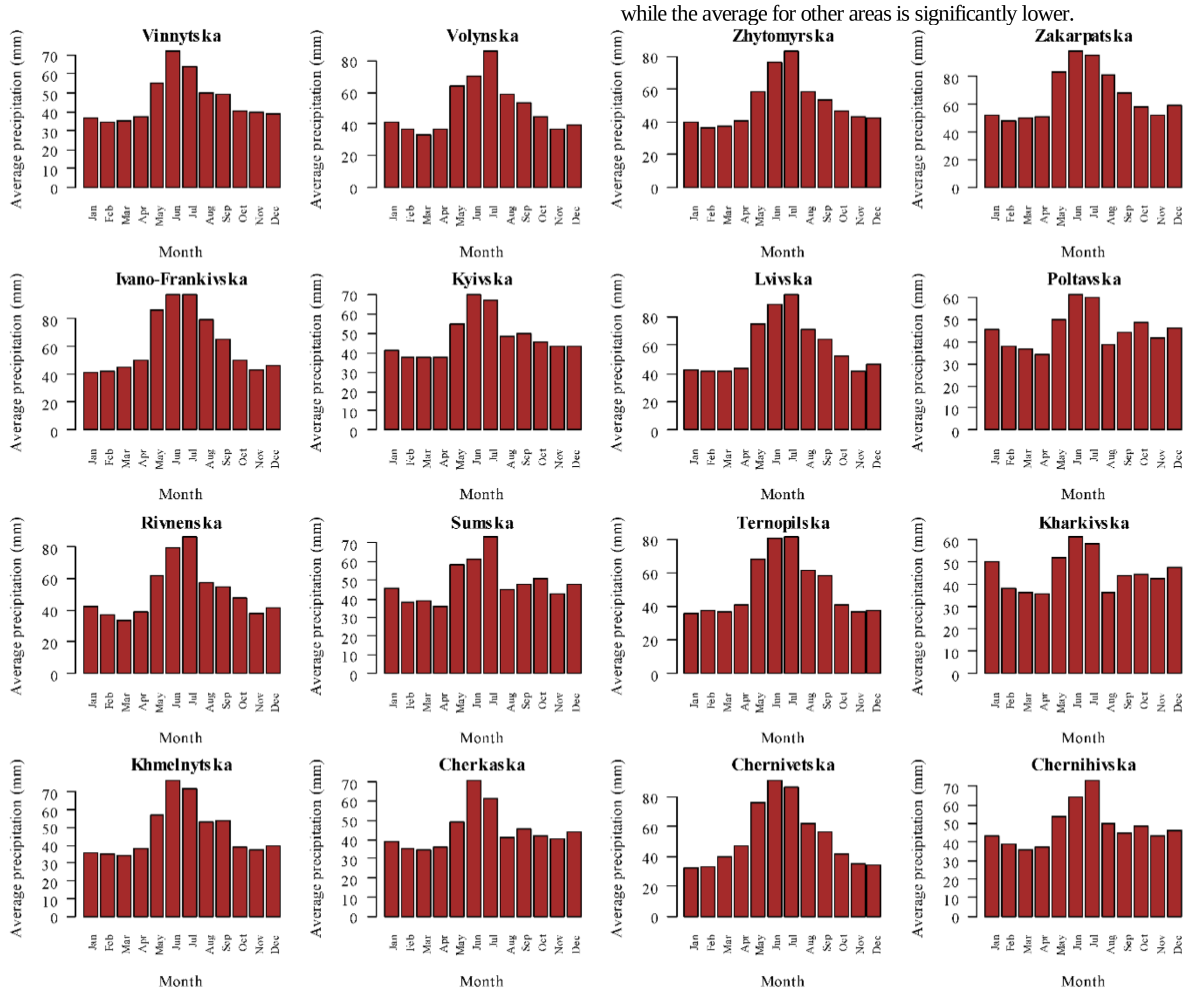

Fig. 3. Average monthly precipitation (mm) for the period 2001–2024 in the regions of Ukraine within the Polissia and forest-steppe zones: data are presented separately for each region, with vertical bars representing monthly averages

In these regions, the annual precipitation pattern is prolonged and smoothed, without sharp declines immediately after the summer maximum, unlike in the eastern and central regions, where the seasonal peak is limited to a short interval. The climatic features of this part of Ukraine are determined by the combination of the Carpathian orographic barrier and the dominance of western air masses from the Atlantic. The rising air above the mountain ranges causes it to cool and moisture to condense, resulting in increased precipitation, especially in the Zakarpattia, Ivano-Frankivsk and Chernivtsi regions. In addition, these regions receive significantly more precipitation in winter than most other regions, which mitigates the effects of winter drought. Such climatic conditions create favourable conditions for soil moisture conservation, surface runoff formation, maintenance of natural vegetation, and high agricultural potential. At the same time, increased moisture can increase the risk of erosion processes and requires appropriate adaptive agronomic solutions.

The Cherkasy, Kyiv, and Vinnytsia oblasts are characterised by relatively lower precipitation throughout the year compared with the average for Ukraine and other clusters. The seasonal dynamics in these regions follow a typical annual pattern for a temperate climate, with a peak in June–July, but maximum values in these months do not exceed 70–75 mm, while in other clusters these values reach 80–85 mm and above. The spring period (March–May) in these regions is characterised by a slow increase in precipitation, with particularly moderate values in April and May, which may indicate limited moisture supply in the early stages of crop vegetation. The autumn decline in moisture is less pronounced, but in September–October, precipitation is also lower than in more humid clusters. In winter, especially in December and February, precipitation is the lowest among all groups (about 23–30 mm), indicating a pronounced seasonal aridity. These regions in central Ukraine are characterised by a temperate continental climate with unstable moisture supply, sensitive to interannual variation. They have the lowest average annual precipitation (522 mm) among all the clusters, which creates increased vulnerability to summer droughts and water shortages in agrosystems, especially under climate change conditions.

The group of regions that includes Kharkiv, Poltava, and Sumy has the lowest annual precipitation among the regions studied – about 520 mm. Their annual precipitation pattern is characterised by a moderate seasonality with a less pronounced summer maximum. In June–July, there is an increase in moisture, but peak values remain lower than the Ukrainian average and amount to only about 60–65 mm. At the same time, precipitation decreases significantly in August and drops to 45 mm or less by September–October. The spring period in this group is also characterised by modest indicators, with average values of less than 40 mm in March and April. In winter, precipitation remains consistently low, with minimums in December (about 28 mm) and February (≈35 mm), forming an overall picture of an arid climate with a short period of moisture. Such precipitation dynamics significantly limit the soil moisture during critical phases of crop development, particularly in spring and the second half of summer. These areas are located in the central-eastern part of Ukraine, where a temperate continental climate prevails with frequent atmospheric blockages in summer, which prevent the formation of rain fronts. As a result, this region has an increased risk of droughts and unstable water supply, which requires the adaptation of agricultural technologies to limited water resources.

The group of regions that includes the Chernihiv, Khmelnytskyi, Rivne, Volyn and Zhytomyr oblasts, has a precipitation distribution close to the average for the studied regions of Ukraine, with some characteristic features. The annual precipitation in this region is about 570 mm, which exceeds the figures for the central-eastern territories but is lower than the more humid western oblasts with orographic influence. The highest values occur in June and July – over 69–80 mm, with a clearly pronounced maximum in July. The spring moisture growth begins in April and reaches a significant level in May (approximately 58 mm), creating favourable conditions for early crop development. In August and September, precipitation gradually decreases but remains at a level sufficient for the completion of vegetation. The winter period, as in most regions, is characterised by the lowest amount of precipitation – about 30–35 mm. The climatic conditions of this region are characterised by moderate humidity and relatively uniform moisture distribution throughout the year, which creates a stable water supply for agricultural production. With effective soil moisture conservation and adaptation of technologies to seasonal characteristics, these areas have the potential for high productivity even under changing climate conditions.

In the vast majority of regions, there is a negative trend in precipitation over time, indicating a gradual decrease in annual moisture (Fig. 4). The largest decrease in precipitation has been recorded in the central-eastern oblasts – Cherkasy, Kyiv, Poltava, Sumy, and especially Kharkiv, where the trend is approaching –2.5...–3 mm/year. This indicates a noticeable depletion of the water balance over the last two decades. Similar trends are observed in some southern parts of the Zhytomyr, Vinnytsia, and Khmelnytskyi oblasts. A moderate decrease (from –1 to –2 mm/year) is characteristic of the northern and north-western oblasts, in particular Chernihiv, Rivne, Volyn, and central parts of Zhytomyr. In contrast, a positive or almost zero trend is observed only in some areas of the western oblasts – Zakarpattia, Ivano-Frankivsk, and partly Lviv, where annual precipitation remains stable or increases (yellow-orange areas). During the period 2001–2024, a spatial differentiation of the moisture changes was observed, with increasing climatic aridification in the east and south of the study area and more stable conditions in the west. This is crucial for assessing climate risks and developing regional adaptation strategies in the agricultural sector and natural resource management.

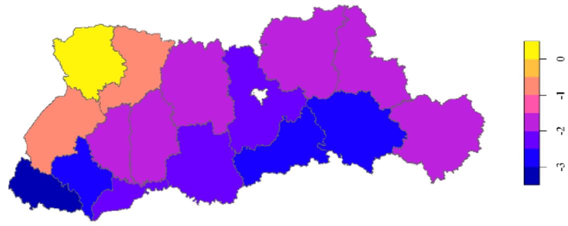

Fig. 4. Spatial distribution of the trend in annual precipitation in 2001–2024 (mm/year) in the studied regions of Ukraine: negative values (blue) indicate a downward trend in precipitation, while yellow-orange shades indicate no change or an increase in precipitation

According to the data presented, a steady trend towards rising temperatures can be observed in all the oblasts, although the rate and amplitude of change vary slightly depending on the oblast and the specific year (Fig. 5). In the first half of the period under review (2001–2010), temperatures ranged between 9 and 13 °C, with some cool years, in particular 2005, 2008, and 2011, which stand out as having the lowest average annual temperatures in most oblasts (e.g., Ivano-Frankivsk – only 6.75 °C in 2011).

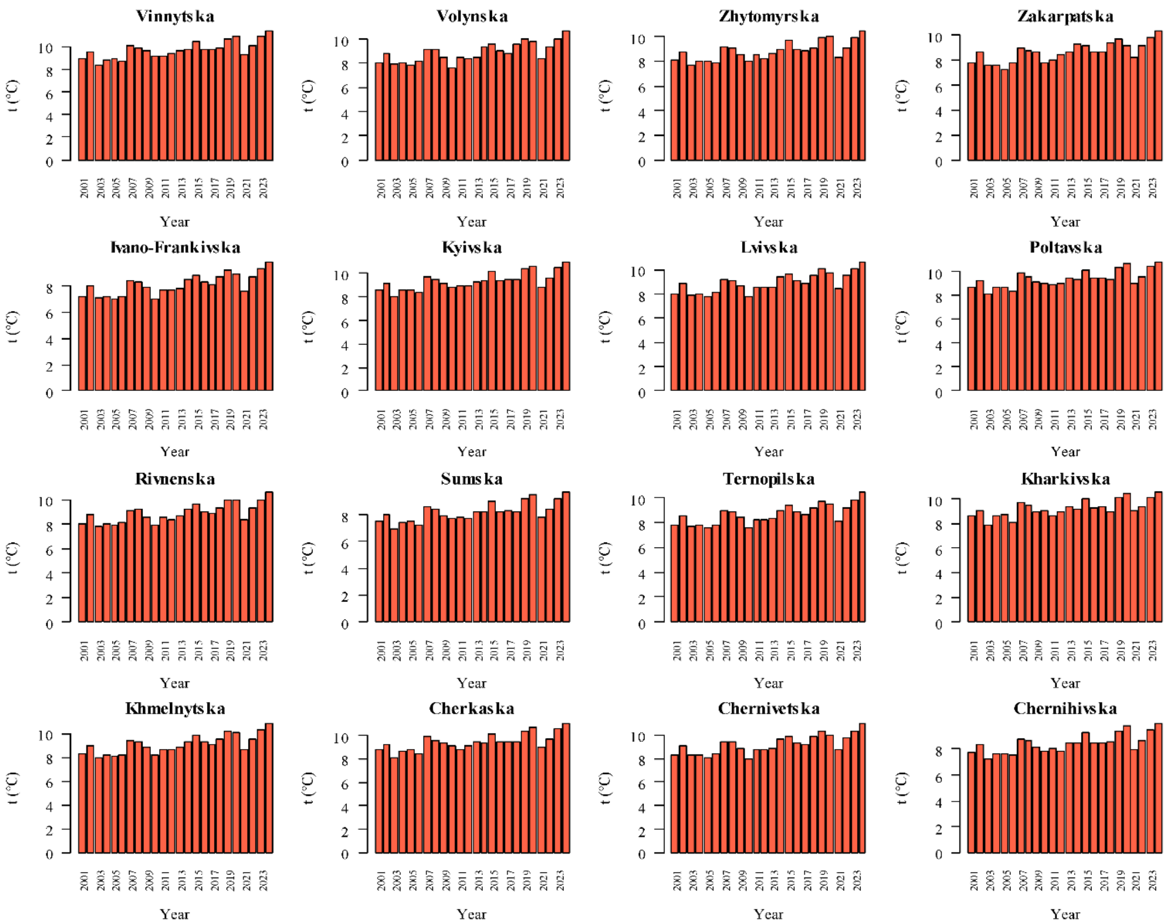

Fig. 5. Dynamics of average annual air temperature in 2001–2024 in the studied oblasts of Ukraine: the bar charts show the annual temperature values (°C) for each region separately, demonstrating a general warming trend

Since 2012, there has been a clear transition to a warmer climate with higher minimum temperatures and an increase in the amplitude of seasonal fluctuations. The warming is particularly pronounced in 2012, 2018, 2023, and 2024, when the average temperatures reach 13–15 °C in many oblasts. The average values for 2023 and 2024 significantly exceed the initial level of 2001–2005, indicating an increase of almost 2 °C in the average annual air temperature over most of the territory. The most dynamic changes are observed in the Kyiv, Cherkasy, Ternopil, Vinnytsia, Lviv, and Khmelnytskyi oblats, where the increase is most pronounced. The results indicate the high climate sensitivity of the oblasts to global warming and confirm the systemic trend towards higher temperatures over the last two decades. These changes have significant implications for the agricultural sector, water balance, and adaptation planning in the context of climate change.

The average monthly air temperature in the Chernihiv, Kharkiv, and Sumy oblasts shows seasonal dynamics characteristic of north-eastern Ukraine, with a marked contrast between cold winters and warm summers (Fig. 6). In this group of regions, the average January temperatures are around –4.6 °C, which is significantly lower than the average for all oblasts studied (–1.8 °C), while in July they are around 21.5 °C, which is almost the same as the regional average. In these regions, the temperature rises more slowly in spring than in the rest of the territory: only in May do average monthly temperatures exceed 15 °C. The most intense warming occurs between April and June, followed by a period of consistently high temperatures in July and August.

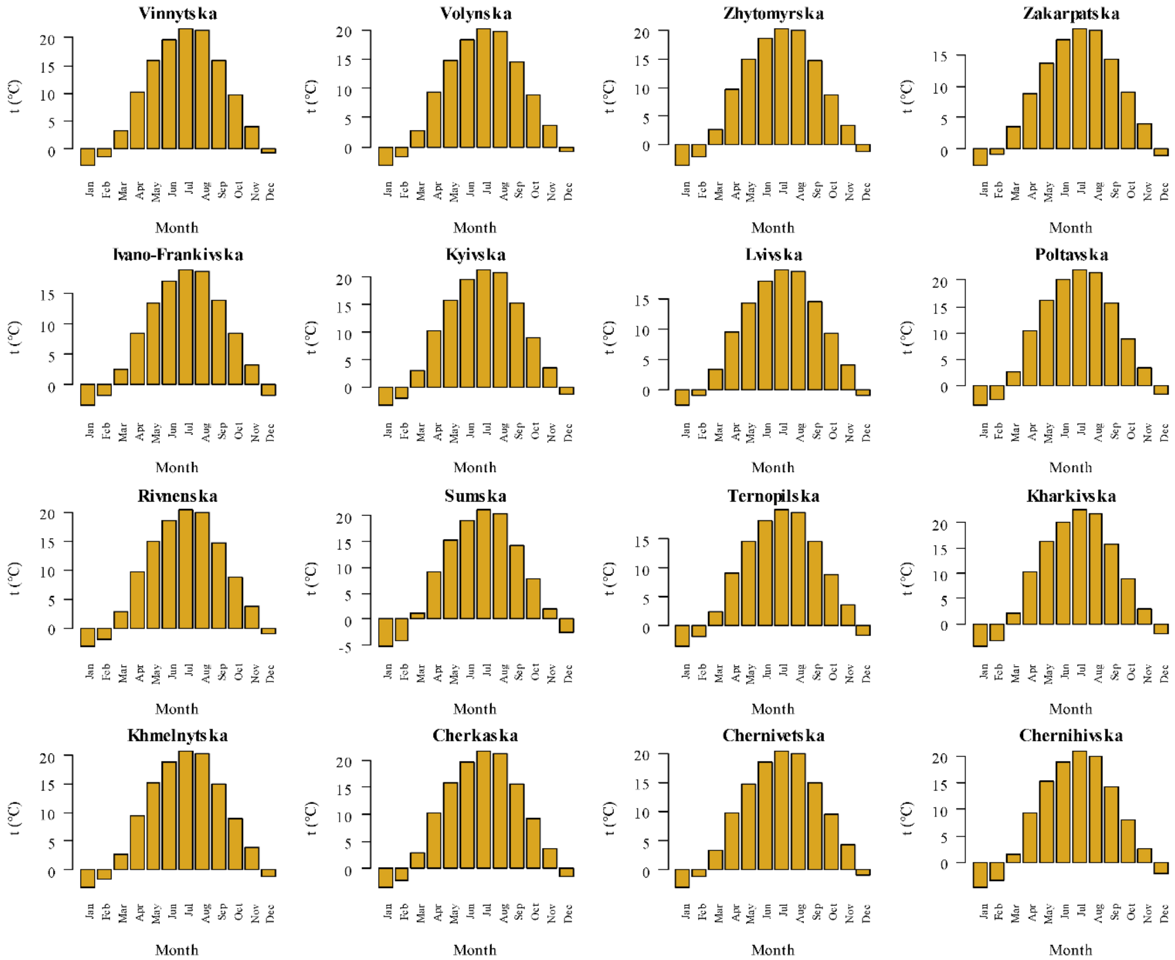

Fig. 6. Average monthly air temperature (°C) for the period 2001–2024 in the studied oblasts of Ukraine: the bar charts show seasonal temperature dynamics, with a clearly pronounced summer maximum (July) and winter minimum (January)

The autumn temperature drop is quite sharp: in October, the average temperature is only about 8.1 °C, and in November it is 2.7 °C, with a further drop to –3.5 °C in December. This group of regions is characterised by a continental climate with the lowest winter temperatures among all the oblasts studied, moderately warm summers, and short transitional seasons. This limits the length of the frost-free period, affects sowing and harvesting dates, and requires increased adaptation of crops to temperature stress. The average annual temperature is 8.84 °C, which is the lowest among all groups of oblasts.

The group that includes the Chernivtsi, Khmelnytskyi, Rivne, and Zhytomyr oblasts is characterised by a typical western and north-western Ukrainian annual temperature pattern with mild winters and moderately warm summers. In January, the average temperature is around –1.5 °C, which is higher than in the eastern or northern regions, and therefore winters are less severe in this area. The summer maximum is reached in July with an average of around 20.5 °C, which is slightly lower than in the warmest regions of Ukraine, but indicates consistently favourable conditions for agricultural activities. Spring warming begins in March, and in April–May, the temperature rises to 9–15 °C, providing good conditions for early vegetation growth. The summer period lasts from June to August with slight temperature fluctuations, followed by a gradual but not sharp autumn decline. In October, the average temperature remains around 9.2 °C, and in November, it is above 3.9 °C. December in this group is characterised by a transition to slightly positive or slightly negative values (on average +0.4 °C), indicating an unstable start to winter. The region has an average annual temperature of about 9.6 °C, which is slightly higher than the overall average for all the areas studied. The moderate climate with relatively mild winters and no excessive summer heat creates stable conditions for agriculture, reducing the risks of winter frosts and summer overheating.

The group comprising the Ivano-Frankivsk, Lviv, Ternopil, Volyn, and Zakarpattia oblasts is characterised by a moderate western Ukrainian climate with mild winters, long spring and summer warming and a slow decline in temperatures in autumn. The average January temperature is around –1.1 °C, indicating relatively warm winters. The highest temperatures occur in July, when the average temperature approaches 19.7 °C, which is slightly lower than in the central and southern regions, due to the influence of the Carpathians and the general humidity of the region. Spring arrives gradually, with a sharp rise in temperatures in April–May, which are approximately 9.1 °C and 14.3 °C, respectively. In summer, comfortable temperatures prevail without extreme heat, and the transition to autumn cooling is smooth: the average values remain around 14.5 °C in September, and around 8.9 °C in October. Even in November, the average temperature remains above 3.8 °C, indicating a late start to winter. The average annual air temperature in this group of regions is 9.17 °C, which is only slightly below the overall average for the regions studied. This temperature regime, combined with abundant precipitation, forms a stable agroclimatic potential favourable for growing a wide range of crops, but also requires the adaptation of technologies to increased humidity and late start of vegetation in the foothill areas.

A group including the Cherkasy, Kyiv, Poltava, and Vinnytsia oblasts is characterised by a moderately continental climate with fairly warm summers and cool winters. The average January temperature is around –1.1 °C, which corresponds to the general level for central Ukraine. In July, the average temperature reaches 21.7 °C, which is the highest summer indicator among all the oblasts studied. Spring warming begins quickly: the temperature rises to 3.2 °C already in March, and exceeds 10 °C in April. In May, the average temperature is over 16 °C, which ensures a quick start to the growing season and favourable conditions for early field work. Temperatures in June–August are consistently high (from 19.9 to 21.2 °C), with the smallest amplitude between months. Starting in September, there is a gradual cooling, with comfortable conditions in October (≈9.2 °C) and a mild transition to winter. December temperatures average –0.2 °C, remaining among the highest winter values in all regions. The average annual temperature for this group is 9.94 °C, which is the highest among all the regions studied. This temperature regime indicates favourable conditions for agricultural production, with a sufficiently long warm period and relatively mild winters. However, it may also mean increased sensitivity to summer droughts, which highlights the need for effective water management and adaptive farming technologies.

During the period 2001–2024, a general increase in the average annual air temperature was observed in the studied regions of Ukraine, but the rates of this warming vary significantly within the region (Fig. 7). The most intense positive temperature trends were recorded in the western part of the country, primarily in the Zakarpattia, Lviv, Volyn, and partly Ivano-Frankivsk oblasts, where the average annual temperature increase exceeds 0.085 °C/year. Such rapid growth is probably due to the influence of Atlantic air masses, less pronounced continental climate, and local geographical factors, in particular the orography of the Carpathians.

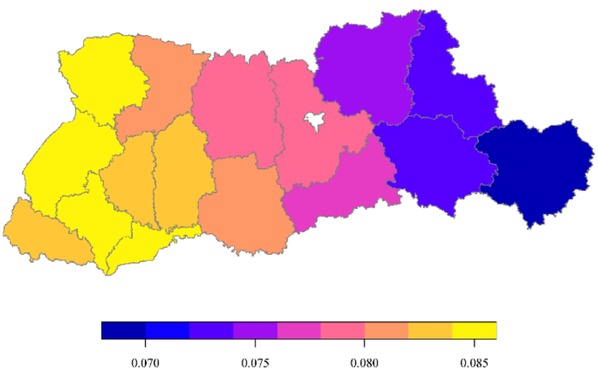

Fig. 7. Spatial distribution of trends in average annual air temperature in 2001–2024 (°C/year) in the studied regions of Ukraine: the colour scale reflects the rate of warming: from the slowest (dark blue) to the fastest (yellow)

In the central oblasts – Kyiv, Vinnytsia, Cherkasy, and Poltava – the rate of temperature increase is moderate and varies between 0.078–0.082 °C/year. These regions form a transition zone between the western maximum temperature changes and the eastern zone with a relatively more stable regime. While the absolute values of the trend are lower, the warming trend remains consistent and stable. The slowest temperature increase is observed in the east and northeast, particularly in the Kharkiv, Sumy, and Chernihiv oblasts, where the annual temperature increase does not exceed 0.075 °C. These areas are characterised by a more continental climate and less influence from Atlantic air masses, which explains the relative stability of the temperature regime. At the same time, even in these regions, a gradual warming trend can be observed, which, although less intense, is still consistent with the general trend of global climate change. In general, it can be said that the average annual air temperature is increasing throughout the study area, but this warming is most intense in western Ukraine, while the east remains relatively more stable. Spatial differentiation of climate change needs to be taken into account in regional planning, especially in the context of agricultural development, water resource management, and adaptation to climate risks.

In the analysis of fire density distribution (number of fires per km²), the Cullen–Freeman graph was used to assess the characteristics of asymmetry and excess of empirical data and compare them with theoretical distributions. The empirical point (red dot) is located on the right side of the graph with high values of the asymmetry square (about 20) and excess (more than 30), indicating strong positive asymmetry and excessive steepness of the distribution. Such characteristics are typical for gamma and lognormal distributions. The results of the graphical analysis are supplemented by a numerical assessment of the goodness of fit of various theoretical distributions, according to which the gamma distribution showed the best fit (according to the AIC, BIC, and Kolmogorov–Smirnov statistics). To construct a regression model using the variable Fires_per_km² as a response, the choice of a gamma distribution with a logarithmic link function was justified. The QQ plot on the left shows good agreement between the empirical residuals and the expected theoretical distribution. The P-value according to the Kolmogorov–Smirnov test is 0.16, indicating no significant deviations. No significant overdispersion (P = 0.08) or outlier effects (P = 0.28) were found. The graph on the right shows the residuals as a function of the predicted values (ranked). The residuals are distributed symmetrically around the zero axis, with no significant systematic deviations or heteroscedasticity. This pattern indicates the correctness of the model specification, the good choice of the link function, and the adequacy of the distribution used (gamma with a logarithmic link). Taken together, these results confirm the statistical acceptability of the model for further interpretative analysis. The value of first-order autocorrelation (AR(1)) in the model is ρ = 0.41, with a confidence interval of 95% CI [0.34; 0.47] (Table 1). This indicates a moderate positive autocorrelation in the dynamics of the number of fires by month within each region, i.e., current values depend on previous ones in time. This effect is expected for time series of natural phenomena, in particular seasonal processes, and was taken into account in the model to improve its accuracy and statistical adequacy.

The regression model indicates a clearly pronounced seasonal dynamics of changes in fire intensity throughout the year. Statistically significant coefficients for most months indicate a significant deviation from the baseline (probably January or the average value). The largest increase in the intensity is observed in March (estimate = 2.44, P < 0.001) and April (1.88, P < 0.001), reflecting the spring peak in the fire activity, primarily associated with the burning of dry vegetation. Other noticeable spikes occur in August (1.67, P < 0.001), September (0.97, P < 0.001), and October (0.96, P < 0.001), indicating a summer-autumn maximum, probably caused by dry conditions, high temperatures, and economic activities, in particular post-harvest burning. By contrast, in June (–1.30, P < 0.001) and December (–0.57, P = 0.001), a statistically significant decrease in the fire intensity was observed. The model confirms the existence of two main seasonal maxima – in spring and late summer – reflecting both natural climatic patterns and the influence of anthropogenic factors.

In the regression model, both linear (b= 32.36) and quadratic (a = –0.00805) predictors of the time variable (year of observation) were statistically significant. These estimates were calculated for a nonorthogonal polynomial representation. The negative coefficient of the quadratic term indicates the presence of a maximum, i.e., an increase in the values of the response variable in the first years of the study, followed by a decline. The abscissa of the extreme point (the year of maximum fire intensity) can be found using the standard formula:

$$x_{\text{ext}} = -\frac{b}{2a} = -\frac{32.36}{2\cdot(-0.00805)} = \frac{32.36}{0.0161} \approx 2010.8$$

The peak of the average fire intensity was observed around 2011, followed by a gradual decline. This is consistent with the graphical visualisation and other modelling results, confirming the nonlinear annual trend and the end of the period of increased fire activity in the study area.

Based on the obtained regression coefficients for temperature, a similar analysis of the quadratic dependence can be performed and the abscissa coordinate of the extreme point of the temperature response (i.e., the value of the average monthly temperature at which the fire intensity reaches its maximum) can be calculated. The coefficient for the linear term is b = 0.1525, and the coefficient for the quadratic term is a = −0.004113. The coefficients were calculated for a nonorthogonal polynomial representation.

General form of the quadratic equation:

$$y = a\cdot x^2 + b\cdot x + c$$

Coordinate of the vertex (extremum):

$$x_{\text{ext}} = -\frac{b}{2a}$$

Substituting the values:

$$x_{\text{ext}} = \frac{-0.1525}{2\cdot(-0.004113)} = \frac{0.1525}{0.008226} \approx 18.54$$

Therefore, the maximum fire intensity (under fixed conditions) is observed at an average monthly temperature of approximately 18.5 °C, after which a decline begins. This indicates the presence of a nonlinear temperature threshold, after which a further increase in the temperature is associated with a decrease in the frequency of fires or the area affected by them, possibly due to a reduction in the available biomass as a result of aridification.

Table 1

Fixed effects of Gamma-GLMM (log link) with AR(1) (ρ = 0.41, 95% CI [0.34; 0.47]), dispersion φ = 0.723; N = 3349 monthly observed in 16 regions; AIC = 10848.3, BIC = 10976.8; DHARMa: overdispersion P = 0.08

Category	Level	E_{st} ± SE	z–value	P–value	CI lower	CI upper	Signif
Intercept	–	0.34	1.47	0.14	–	0	–
Month	Feb	0.41 ± 0.17	2.51	0	0	0	*
	Mar	2.44	14.2	<0.001	2.1	2.7	***
	Apr	1.88	8.46	<0.001	1.45	2.3	***
	May	–0.40	–	0.14	–	0	–
	Jun	–1.30 ± 0.32	–	<0.001	–	–	***
	Jul	0.48	1	0.16	–	1	–
	Aug	1.67	5.0	<0.001	1.02	2.3	***
	Sep	0.97 ± 0.27	3.6	<0.001	0.44	1.5	***
	Oct	0.96 ± 0.22	4.4	<0.001	0.53	1.39	***
	Nov	0.03 ± 0.18	0	0.85	–	0	–
	Dec	–0.57 ± 0.19	–	0	–	–	**
Time	Year	–13.98 ± 1.53	–	<0.001	–	–10.98	***
	$Year^2$	–19.69	–	<0.001	–	–	***
Temperature	Temp	27.2	4.62	<0.001	15.6	38.7	***
	$Temp^2$	–12.04 ± 2.35	–	<0.001	–	–7.45	***
Precip_mm		–0.02 ± 0.01	–19.24	<0.001	–	–	***

The analysis of the results of the regression model indicates a statistically significant negative effect of precipitation on fire intensity. The coefficient for the Precip_mm variable is –0.02 ± 0.01, which is significant at a significance level of $P < 0.001$. This means that as precipitation increases, the average fire intensity per unit area decreases. This relationship is logical from an environmental point of view, as wetter conditions reduce the risk of ignition and spread of fire. In the context of the gamma regression with a logarithmic relationship used here, this means that each additional increase in precipitation of 1 mm is associated with an exponential decrease in the expected fire intensity, emphasising the role of precipitation as a key mitigating factor in the occurrence of forest and landscape fires.

Figure 8 illustrates the spatial variation of the baseline fire intensity within the 16 administrative regions of the study area, estimated using random intercepts in a Gamma-GLMM model with AR(1). These intercepts reflect the average fire intensity per unit area in each oblast, adjusted for the general climatic conditions, seasonality, and annual dynamics.

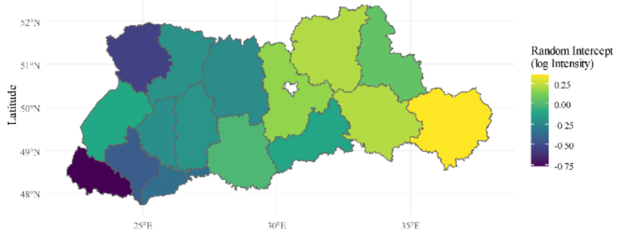

Fig. 8. Spatial distribution of baseline fire intensity by administrative regions: the map shows random intercepts from a Gamma-GLMM regression model with an AR(1) autoregressive structure, characterising the baseline fire intensity (on a logarithmic scale) in each region, assuming fixed values of climate predictors and time

There is a clear spatial gradient: the lowest values of baseline intensity are recorded in the western oblasts (in particular in Zakarpattia and Chernivtsi), where random intercepts have negative values (dark purple colouring). This may indicate a lower probability or intensity of fires, probably due to the higher moisture content and specific land use (e.g. predominance of forests or less pressure from agricultural burning). By contrast, the highest intercept values (yellow colour) are characteristic of eastern and central-eastern oblasts, particularly Dnipropetrovsk, Poltava, and Kharkiv. This indicates an increased baseline fire intensity even under identical climate and time conditions, which may be related to local land management practices, vegetation types or the intensity of anthropogenic pressure. The spatial pattern is consistent with the hypothesis of regional differences in landscape structure and socioeconomic factors that influence fire activity beyond climatic determinants. As one moves from the Carpathian region to the eastern regions, the influence of Western European moist air masses decreases, the annual temperature range increases, the average annual precipitation decreases, and the duration of the dry season increases – all of which are manifestations of increasing continentality. Such conditions create a more favourable environment for the emergence and spread of fire, especially in steppe and forest-steppe landscapes, where, given the availability of combustible biomass, the fire hazard increases. In more continental eastern regions, agricultural practices involving the burning of stubble or vegetation residues are widespread, which can also increase the baseline fire activity regardless of the weather conditions of a particular year. The geographical gradient of continentality is one of the potential climatic and geographical factors contributing to higher baseline fire intensity in the east of the country compared with the more humid western regions.

Discussion

The results of your study, according to the regression model, indicate that the average fire intensity per unit area had a clear peak around 2010–2011, followed by a downward trend. This pattern corresponds to the presence of a quadratic trend described by a second-degree polynomial, with a maximum within the study period (2001–2024). This result indicates the presence of nonlinear dynamics, which may be due to a combination of climatic, anthropogenic or organisational and administrative factors. The maximum average fire intensity per unit area, observed around 2011, may be the result of a combination of several environmental and anthropogenic factors. During this period, Ukraine experienced abnormal weather conditions, including warm springs and dry summers, which created a favourable environment for the occurrence and spread of fires. According to the climate monitoring data, the summer of 2010 was extremely hot and dry in most regions, and such extreme events can have a prolonged effect, accumulating dry biomass, which subsequently acts as fuel. In addition, during this period, there may have been disruptions in the fire risk management system due to political and administrative instability, which contributed to an increase in the number of uncontrolled arson attacks. It is also important to consider factors related to land use practices: an increase in the area of neglected agricultural land or the degradation of forest ecosystems, combined with favourable weather conditions, could have significantly increased the vulnerability of landscapes to fire. The peak fire activity in 2011 was probably caused by a complex interaction of climatic anomalies, the accumulation of combustible biomass, inadequate fire prevention measures, and changes in land use. Our findings are consistent with the data on the peak increase in the number of fires in forest ecosystems in Ukraine in 2010–2012 (Zibtsev, Soshenskyi, et al., 2019). In this study, the main causes of the peak were identified as exceptionally dry weather conditions in certain years (especially 2010), poor organisation of monitoring and response to local fires, and the lack of a coordinated forest fire prevention strategy in the post-crisis period. Our results confirm the conclusions drawn from forest monitoring, but extend them by considering a larger area (not just forests) and refine the statistical nature of the dynamics by establishing a form of dependence and taking into account spatial and seasonal components.

The presence of two peaks in the fire intensity – in early spring (mainly in March–April) and late summer (mainly in August) – reflects the bimodal seasonal pattern of fire activity characteristic of Ukraine's temperate climate, caused by a combination of climatic conditions, plant phenology, and land use patterns. The spring peak is explained by the rapid drying of last year's dry grass vegetation after snow melt, when the vegetation cover has not yet been restored. During this period, relatively low air humidity and high wind speeds are usually observed, which contribute to the rapid spread of fire. At the same time, in early spring, there is an increase in the burning of dry vegetation on household plots, agricultural land, pastures, and wasteland, which is traditionally associated with preparing the land for field work, although it is officially prohibited. The summer peak in August is primarily due to high temperatures accompanied by prolonged periods without precipitation, leading to extreme drying of plant biomass. In addition, after harvesting, a significant amount of flammable plant residues remain in the fields, including stubble, which is often deliberately or accidentally set on fire. The growth of recreational pressure also plays an important role: in summer, the number of visitors to natural areas increases, raising the risk of fires due to careless handling. The spring peak is mainly anthropogenic, while the summer peak is the result of a combination of climatic, agricultural and social factors. The bimodal seasonality of fires is a typical feature of Ukraine's agricultural landscapes and, in the context of climate aridification, may persist or intensify, especially in the absence of an effective fire monitoring and prevention system.

The findings regarding the two-peak seasonal dynamics of fires – with peaks in spring (March–April) and late summer (August) – are consistent with the results of other studies (Zibtsev, Myroniuk, et al., 2019). It has been proven that the vast majority of natural fires occur during periods when favourable thermal conditions are combined with low fuel moisture – in early spring, when last year's dry vegetation has not yet decomposed, and in summer during dry winds and prolonged periods without precipitation. The research indicates that up to 50% of natural fires occur in spring, especially in the forest-steppe zone, which was also noted in the results of the analysis as a typical spring peak. According to the same article, the summer peak in fire activity is due to high temperatures and a lack of precipitation, which leads to critical drying of the surface layer of soil and vegetation, especially in agricultural landscapes and forests in northern and central Ukraine. This summer peak in August was also clearly identified in our regression model based on FIRMS data. Independent sources confirm the two-phase structure of the seasonal fire activity in Ukraine, caused by a combination of climatic factors (temperature, precipitation) and seasonal dynamics of combustible biomass (Zibtsev, Myroniuk, et al., 2019). This indicates the reliability of the identified pattern and its potential for further forecasting fire risks in the context of climate change.

The presence of an autocorrelation component in the regression model indicates that fire intensity is not independent in time: the value of this indicator in a given month or year is partly determined by its values in previous periods. Such a time-dependent structure, in particular first-order autoregression (AR(1)), is included in the model for each region separately. This allows for the inertial nature of changes inherent in natural and socioecological systems to be taken into account. The presence of autocorrelation itself can be caused by a number of reasons. Biophysical factors, such as the accumulation of dry biomass, provide the basis for maintaining the sequence of fires: in regions where fires have not occurred for a certain period of time, combustible material can accumulate, increasing the likelihood of subsequent fires. Climatic regimes (especially periods of prolonged drought or consistently high temperatures) are often persistent and contribute to the formation of fire series in adjacent seasons or years. The human factor – in particular the practice of spring burning of dry vegetation and changes in the prevention and response system – also tends to recur over time. All these factors create the conditions for statistical relationships among adjacent observations. Therefore, including an AR(1) component in the model allows for a more accurate account of the internal time structure of the data, reduces residual autocorrelation, improves the quality of the approximation, and avoids overestimating the significance of other predictors.

The identified trend of monotonous growth in the number of fires until 2011, which persists even after taking into account temperature and precipitation in the regression model, indicates the influence of additional nonclimatic factors. Since climate warming was directly included in the model as a separate temperature predictor, the polynomial component by year, which describes the annual dynamics, reflects other processes, primarily of socioecological nature. The increase in fire intensity is likely linked to the spread of dry vegetation burning, particularly in spring, against the backdrop of insufficient control by environmental and administrative authorities. In regions with a high proportion of rural population and large areas of open agricultural land, favourable conditions for uncontrolled burning, not restricted by legal sanctions, could have developed. In addition, in a number of regions, combustible plant matter may have accumulated as a result of previous wet seasons or structural changes in land use, including an increase in the area of low-yield or abandoned land. The recorded increase in the number of fires until 2011 should not be seen as a direct consequence of climate change, but rather as a reflection of the complex interaction between social practices, the institutional environment, and environmental conditions. The decrease in the number of fires after 2011, recorded in the regression model analysis, may have several possible explanations combining environmental, social, and administrative factors. This trend may reflect a gradual change in climatic conditions towards increased aridification, i.e. a decrease in humidity and available biomass. In many regions of Ukraine, since 2010, there has been an increase in air temperature combined with a decrease in effective precipitation, leading to the degradation of vegetation cover, especially in low-productive or degraded lands. Under such conditions, the frequency and intensity of fires may decrease due to the lack of sufficient dry combustible material necessary for the spread of fire. After 2011, Ukraine began to implement individual regional measures to combat spring burning, including information campaigns, increased fines, and more active work by the State Emergency Service and environmental inspection authorities. Systematic control over fire safety compliance is still lacking, but even partial administrative intervention could have a cumulative effect in reducing the number of fires. Socioeconomic changes after 2014 – in particular, a decline in the rural population, migration, and the decline of certain agricultural areas – may also have led to a reduction in anthropogenic pressure and changes in land use practices, including a decrease in the frequency of arson. Together, these factors provide a plausible explanation for the downward trend observed after 2011, which accompanies a change in the peak maximum in the regression curve.

The nonlinear effect of temperature on the fire intensity, identified in the regression model, can be interpreted as a manifestation of a temperature threshold, after which a further increase in temperature does not contribute to an increase in the number of fires, but rather is associated with their decrease. This pattern is ecologically sound and indicates that the relationship between temperature and fire is not monotonous. At the initial stage, rising temperatures create favourable conditions for combustion: plant material dries faster, air humidity decreases, and the fire-hazardous period lengthens. Under these conditions, especially in ecosystems with sufficient biomass reserves (meadows, agricultural landscapes, forest edges), the risk of fires occurring and spreading increases significantly. With further temperature increases, especially in combination with precipitation deficits, an aridification effect occurs. This results in a reduction in phytomass, a decrease in vegetation cover density, and a decline in the productivity of grass and shrub formations. Biomass, which usually acts as fuel, becomes less accessible or is interrupted by fragments of noncombustible areas, which prevents the spread of fire. In warmer and drier regions or in years with extremely high temperatures, the fire activity may even decrease. The curvilinear nature of the effect of temperature on the fire dynamics therefore reflects the balance between two opposing factors: on the one hand, temperature as an enhancer of ignition and combustion, and on the other, as a factor in the depletion of plant fuel. This indicates the existence of an optimal temperature range in which fires are most frequent, and outside of which their intensity decreases due to ecological or biophysical constraints.

The negative impact of precipitation on fire intensity is ecologically significant and consistent with the mechanisms of fire hazard formation in natural and agricultural landscapes. Precipitation directly affects the moisture content of plant biomass, soil and air, which are critical parameters for the likelihood of ignition and fire spread. Higher precipitation increases the moisture content of both living and dead plant residues, reducing their ability to ignite and sustain combustion. Even a slight increase in the moisture content of combustible material (e.g., dry grass or brushwood) significantly reduces the likelihood of a fire starting. Precipitation adds moisture to the topsoil and contributes to microclimatic conditions (air humidity, temperature reduction), which reduces the potential for the development of fire outbreaks, especially in conditions where the sources of ignition are predominantly anthropogenic. In regions with sufficient moisture, even at high temperatures, denser and greener vegetation prevails, which is less fire-prone than dry, degraded land. Such ecosystems recover more quickly after fires, and their ability to self-moisten (through transpiration) further limits the development of fires. The negative regression relationship between precipitation and fire intensity indicates the key role of moisture as a limiting factor in the formation of favourable burning conditions. This effect is particularly pronounced in spring and summer, when precipitation can prevent the accumulation of dry biomass and reduce the risk of fires spreading over large areas.

The practical significance of the study lies in the possibility of using the results obtained to improve the effectiveness of monitoring, forecasting, and managing the risks of natural fires in the Polissia and forest-steppe zones of Ukraine. Establishing quantitative relationships among temperature, precipitation, and fire intensity allows climate factors to be taken into account when assessing the vulnerability of areas to fires, particularly in the context of global warming and aridification. The identification of seasonal and interannual patterns of fire activity can be used to adjust fire prevention calendars, optimise the allocation of resources for emergency response, and plan preventive measures (clearing deadwood, restricting agricultural burning). The results have practical significance for environmental protection activities: regional assessment of baseline fire activity allows the identification of areas with an increased risk of forest and wetland ecosystem degradation. The models obtained can be integrated into decision support systems for natural resource management, climate adaptation, and environmental protection.

Prospects for further research lie in expanding the spatial coverage and detail of natural fire analysis, taking into account land cover types, landscape structure, land use, and anthropogenic impacts. Special attention should be paid to the integration of satellite products with high spatial and temporal resolution (e.g., VIIRS, Sentinel-2), which will allow for more accurate estimates of fire areas, duration, and intensity. Further research may also focus on the interaction between fires and ecosystem services, in particular their impact on the carbon balance, biodiversity and the regenerative potential of natural communities. A separate area is the consideration of socioeconomic factors such as population density, land use structure, and the availability of firefighting infrastructure, which will allow for a better explanation of the spatial variability of fire activity. In addition, it is advisable to conduct scenario modelling of fire dynamics in the context of projected climate change (based on SSP or RCP scenarios), which will contribute to the development of adaptation strategies for natural resource management in vulnerable regions.

Conclusions

This study analysed the spatial and temporal patterns of natural fires in the Polissia and Forest-Steppe regions of Ukraine based on the FIRMS satellite data (MODIS, 2000–2024) and the climate indicators of temperature and precipitation. A distinct seasonal double-peak structure of the fire activity was established, with peaks in early spring and late summer. The regression modelling (GLMM with AR(1) autocorrelation structure) revealed nonlinear annual trends: an increase in the fire intensity until 2011, followed by a steady decline. The analysis also showed a positive but nonlinear effect of temperature on the fire intensity, with a possible temperature threshold beyond which activity decreases, which may be a consequence of aridification. Precipitation showed a consistent negative effect on the fire frequency, confirming the role of moisture as a key limiting factor. The results obtained indicate a complex interaction between the climate factors and fire dynamics, which is important for adaptive ecosystem management under climate change. The study also provides a basis for further monitoring and forecasting of wildfire risks at the regional level.

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