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Original scientific paper

Dynamics of fire weather conditions in the mixed forest areas of Belarus and Ukraine under recent climate change

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The study examines spatiotemporal distribution of fire weather conditions during the fire seasons of 1990-2020 in the mixed forests areas of the territory of Belarus and Ukraine using monthly mean Fire Weather Index (FWI) averaged for each administrative area in the study region. It was revealed that the lowest FWI values were observed in the northern and northwestern regions of Belarus, the highest values were in the southeast. On the territory of Ukraine, FWI values increase toward the east regions. In the seasonal distribution, the FWI increases from March to May and in the middle of summer the index reaches a maximum in the all regions. Analysis of the FWI dynamics over the five-year periods showed that the frequency of danger fire weather conditions varied from a "very low" level to "moderate" level most of the study period. In the last pentad 2015–2020, "high" fire danger level began to appear in the south of Belarus and in the northern part of Ukraine. During the study period, in some regions of Ukraine, there was a decrease in the frequency of the FWI values of 'low' danger level and its simultaneous increase at the higher levels, in connection with the observed climate change in the region.

Keywords: fire weather index, fire weather condition, fire danger level, wildfires, mixed forests

1. Introduction

A variety of weather-related emergencies includes fires in forests, fields and peat deposits. Fires annually destroy and damage forests over large areas, which have a negative impact on the social and economic development of countries. Hot weather, strong winds under low air humidity play a significant role in the occurrence of extensive fires. Current climate change in the central regions of Eastern Europe demonstrate an annual increase in air temperature and lengthening the warm season of the year, which potentially increases the period when wildfires can be observed (Danilovich and Geyer, 2021). The temperature increase results in increased moisture evaporation from the soil surface that, in turn, may result in desertification in the forest zone. As noted by Didukh (2009), the temperature increase by 1°C leads to a shift of natural zones by 160 km that in the conditions of Ukraine and Belarus means their further moving to north.

The territories of Belarus and Ukraine belong to the region, in which wildfires occur annually in any type of forest zone. For example, according to the State Statistics Service of Ukraine[1], in the forest areas of the country about 106.8 thousand fires with a total area of 139.2 thousand hectares arose during 1990–2017. An analysis of the long-term dynamics of fires shows that forest fires in Ukraine are a sustainable phenomenon (Zibtsev et al., 2019). Last outstanding cases were in 2020, when under strong drought, 209 forest fires occurred in Ukraine, most significant of them were in the Chernobyl zone in April and in the Lugansk region in July and in October.

In addition, wildfires in the study region may cause the redistribution of radionuclides into different parts of Eastern Europe because many areas in Belarus and northern part of Ukraine were contaminated by the Chernobyl Nuclear Power Plant explosion in 1986 (Ager et al., 2019).

Frequency, intensity of wildfires and amount of burned areas depend on the current weather conditions, therefore warming of climate, generally, will increase the risk of hot and dry weather conducive for the wildfires.

The weather conditions favorable for the occurrence of forest fires are usually estimated and predicted by various indicators or indices. For example, in Ukraine, to assess the fire weather conditions a complex indicator by V. Nesterov for the fire danger is used (Nesterov, 1949). This indicator characterizes a degree of dryness of weather conditions, taking into account the temperature and humidity of the air. As studies have shown, this indicator does not correspond to the state of the forest flammability VS the current weather conditions (Balabukh, 2017), so the topic of choosing the optimal indicator for Ukraine remains open.

Monitoring and forecasting of forest fires on the territory of Belarus are based on the indicator of forest fires by N. A. Dichenkov (STB, 2003). This method allows to determine the period of fire occurrence under the forest canopy and the class of fire hazard according to weather conditions. The calculation of a complex indicator of forest fire hazard is based on observations of air temperature; dew point temperature; the number of dry days, *i.e.* number of days without

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[1] http://www.ukrstat.gov.ua/

precipitation or with daily precipitation less than 2.6 mm. Using this method, the Department of meteorological forecasts compiles brief overviews of the fire hazardous situation over the past day and forecasts of forest fires for 1–3 days.

One of the most developed fire risk assessment systems is the Canadian Forest Fire Danger Rating System[2] (CFFDRS), which is a national system for rating the risk of forest fires in Canada. This system based on two subsystems – the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System (Stocks et al.,1989), both of which produce sets of indices of fire potential used in fire management activities. The Canadian Forest Fire Weather Index System (Van Wagner, 1987) consists of six components that account complex of weather conditions, and one of which is the Fire Weather Index (FWI) as a general index of fire danger in the forested areas. The FWI is a meteorological index, based on various components that take into account the influence of fuel moisture and wind in fire behavior and spread. Such parameters as temperature, relative humidity, wind speed and 24 h accumulated precipitation are recorded at noon local standard time and used for the calculation of conditions at the site in late afternoon that is in the peak of fire danger. Currently, the FWI is widely used worldwide to assess wildfire risks, and the index criteria can be adapted to specific geographic conditions (*e.g.* Ullah et al., 2013; de Jong et al., 2016).

The European Forest Fire Information System[3] (EFFIS) was adapted from the Canadian Forest Fire Weather Index System as the method for assessing the fire danger level in Europe (San-Miguel-Ayanz et al., 2012). The FWI was classifying in six classes (levels of fire danger): Very Low, Low, Moderate, High, Very High, Extreme and Very Extreme (Tab. 1). The fire danger classes are the same for all countries and apply in regions Europe, Middle East and North Af-

Table 1. The Fire danger classes according to EFFIS and CFFDRS.

Hazard Rating	FWI CFFDRS	Hazard Rating	FWI EFFIS
Low	0–4	Very low	FWI < 5.2
Moderate	5–10	Low	5.2 ≥ FWI < 11.2
High	11–18	Moderate	11.2 ≥ FWI < 21.3
Very High	19–29	High	21.3 ≥ FWI < 38.0
Extreme	30+	Very High	38.0 ≥ FWI < 50.0
		Extreme	FWI ≥ 50.0
		Very Extreme	FWI > 70.0

[2] https://cwfis.cfs.nrcan.gc.ca/background/summary/fdr

[3] https://effis.jrc.ec.europa.eu/

rica. For comparison, in the Tab. 1 the classes also shown in accordance with CFFDRS (for the province of Alberta[4]).

The Fire Weather Index is applied in most countries in Europe for fire management purposes (San-Miguel-Ayanz et al., 2018). For example, in Italy, for the Piedmont region, which is situated in north-western part of the country and covered by large area of forests (Cane et al., 2008). At the beginning of 2021, a new system for forecasting forest fire danger up to two days ahead was introduced in Poland. It is also based on the Canadian Fire Weather Index, but the fire risk is determined using the hazard classes from EFFIS (Figurski et al., 2021). Daily forecasts are calculated using the numerical model WRF METEOPG on the horizontal resolution of 2.5 km. The analysis showed a high correlation between the predicted fire risk and actual fires.

As the Fire Weather Index is calculated from weather measurements and consists of basic meteorological characteristics, the index can be expected to respond to climate change (*e.g.* Hubnerova et al., 2020). The purpose of this study is to define the spatial and temporal changes in the fire weather conditions over the territory of Belarus and Ukraine (in the area of mixed forests) during the *fire season* (March–October) of the period 1990–2020 using the Fire Weather Index. The months of the start (March) and the end (October) of fire season were chosen according to practice of the National Hydrometeorological services of Belarus and Ukraine, in which first date and last date for determining of fire weather vary depending on the time, when snow melts in spring and when snow cover appears in autumn respectively.

2. Materials and methods

The Republic of Belarus has extensive forest lands (Fig. 1). The total area of tree plantations was 9.43 million hectares as of 2010, which is about 46% of the total area of the country (Lysenko and Loginov, 2020). The most wooded regions were Vitebsk and Gomel regions (forest cover is 52 and 50% respectively) and the least forests were in the Grodno region (40%). Since 2016–2018, the area of tree cover in the country decreased by an average of 2.7% due to the consequences of severe drought in 2014–2015.

The total area of forests on the territory of Ukraine in 2010 amounted to 9.7 million hectares, which is about 16% of the total area of the country (Lopatin et al., 2011). The largest forest territories are concentrated in the northern and western parts of the country: in the Polesie zone (mixed forests) and in the Carpathians. The most wooded are Transcarpathian and Ivano-Frankivsk regions, where forest occupy from 37 to 51% of the territory. In the Crimea and steppe regions less than 8% territory is a forest. In the Volyn', Rivne, Kyiv, Chernihiv

[4] https://wildfire.alberta.ca/wildfire-status/fire-weather/default.aspx

Figure 1. Forest areas in Europe (according to de Rigo et al., 2017). Schematically indicated regions of Belarus (1) and Ukraine (2) belonged to the study area.

and Zhytomyr regions, which are considered in this study, forests occupy from 22 to 36% of the total area (see Fig. 1).

The fire weather conditions in all administrative areas of the study region (see Fig. 1) were estimated using the monthly mean area-averaged data of Fire Weather Index obtained from daily values of gridded FWI (0.25o×0.25o) historical data from the Copernicus Emergency Management Service, available through Copernicus Climate Data Store (CDS, 2021). To interpret the results of analysis of obtained the FWI time series the EFFIS criteria were used (given in Tab. 1).

3. Results and discussions

On the territory of Belarus, the lowest seasonal average (March-October) values of the FWI index were observed in the northern and northwestern regions of the country – Vitebsk and Grodno regions (3.7–3.9); the highest values were in the south-east of the republic (Gomel region), where the index values reached 5.8, which corresponds to a low level of the FWI (Tab. 2). In the northern regions of Ukraine, these values respectively reached 4.4–4.7 in the Volyn' and Rivne regions and 7.1–8.0 in the Chernihiv and Sumy regions.

The seasonal time course of the FWI is characterized by increasing the monthly mean values of the index from March to May (from the very low to the low level), but in June, a decrease of FWI values was observed in all regions of Belarus and Ukraine. The decrease in FWI values in June can be explain by the features of the atmospheric circulation in the study region, which is characterized by increase in the number of cyclones in June, when their maximum frequency is observed over Ukraine in the warm season (*e.g.*, Balabukh, 2004). At the same time, southern cyclones, which move to the north through the territory of Ukraine toward Belarus, are most frequent (Sumak and Semenova, 2017). Intensification of cyclonic activity leads to some increase in the number of days with general and low cloudiness compared to May in both areas (Climate Cadaster of Ukraine, 2006; Liudchik and Umreika, 2017), although the monthly precipitation sum reaches an annual maximum in July due to convective processes.

In July, the index values increase and reach a maximum throughout the study area: in Belarus from 6 in the north (Vitebsk region) to 8–9 in the south (Brest and Gomel regions) that corresponds to a "low" level of fire danger weather; in the Chernihiv and Sumy regions of Ukraine the average monthly FWI

Table 2. Monthly mean (mn., numerator) and standard deviation (s.d., denominator) of the FWI for the regions of Belarus and Ukraine averaged for the period 1990–2020.

Region	Month							
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	mn. *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*	*mn.* *s.d.*
Vitebsk	3.1 2.1	5.6 3.3	5.6 3.5	4.7 3.6	5.6 3.5	3.4 2.2	1.4 1.2	0.6 0.8
Grodno	3.2 2.3	5.3 3.4	5.6 3.7	5.0 4.1	6.0 4.0	3.8 2.3	1.8 1.5	0.9 1.4
Minsk	4.1 3.4	6.0 3.6	6.6 4.0	5.6 4.1	7.0 4.0	4.9 2.9	2.3 1.6	1.2 1.6
Mogilev	4.0 2.4	6.0 3.3	6.8 4.1	5.7 4.1	7.3 4.2	4.9 2.7	2.2 1.7	1.1 1.5
Brest	4.0 2.7	6.1 4.1	6.4 3.4	5.9 4.1	7.5 4.5	5.1 3.1	2.6 1.9	1.5 2.4
Gomel	4.7 3.4	7.2 3.5	8.3 5.0	6.7 4.3	8.5 4.4	6.5 3.9	2.9 2.0	1.5 1.9
Volyn'	3.9 3.0	5.7 3.7	5.4 2.8	4.9 3.6	6.6 4.1	4.8 3.1	2.7 2.0	1.6 2.7
Rovno	4.1 3.3	6.1 3.7	5.8 3.2	5.0 3.5	6.8 4.2	5.3 3.8	2.8 2.0	1.5 2.3
Zhytomyr	4.5 4.1	7.2 3.7	7.6 5.0	6.3 3.6	8.3 4.5	6.6 4.8	3.1 2.1	1.5 2.0
Kyiv	4.7 3.6	8.5 4.3	9.2 5.5	8.1 3.6	11.0 5.5	8.1 5.4	3.7 2.1	1.7 1.9
Chernihiv	4.9 3.4	9.0 4.5	9.9 5.7	8.1 3.8	11.3 5.7	8.4 5.2	3.7 2.4	1.8 2.1
Sumy	5.1 3.1	9.4 4.4	10.7 6.0	9.1 4.2	13.4 6.9	10.3 6.6	4.5 2.9	2.0 2.4

values are at the level of “moderate” fire danger weather, with 11.3 and 13.4 respectively.

An analysis of standard deviation (*s.d.*) shows that the greatest variability of the FWI is typical for spring (April–May) and the first half of summer (June–July) in both countries. The lowest interannual fluctuations of the FWI are in autumn. In general, highest variability of this index in the fire season is observed in Ukrainian areas (except for the northwestern part, Rivne and Volyn’) and in the southern half of Belarus (Gomel, Brest).

The study period was characterized by changing the frequency of different danger levels of the fire weather in separate time intervals in all regions (Figs.

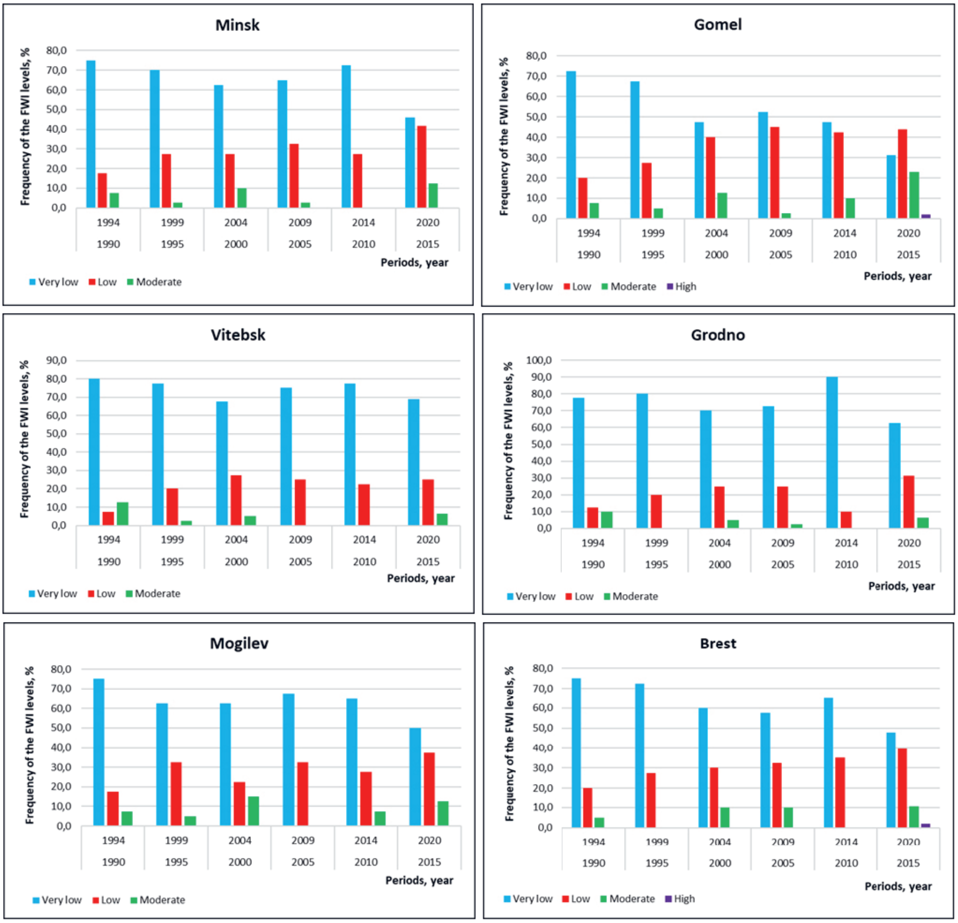

Figure 2. Dynamics of frequency of the FWI levels (%) in five-year periods during fire season of 1990–2020 in Belarus regions.

2 and 3). At the beginning of the period, in 1990–1994 the “very low” level of the FWI prevailed from 80% of cases in the Vitebsk region to 73% in Gomel region in Belarus, and from 85% in the Volyn’ and Rivne regions to 62% in Chernihiv and Sumy regions of Ukraine. In the next five-year period, the frequency of the FWI in a “low” class increased from 20 to 40% in most regions.

In the period 2000–2009, this class was a predominant (45%) in the Kyiv region of Ukraine. In the last decade, the frequency of appearance of the “moderate” level of the FWI increased to 10–23% in Belarus and to 33–42% in the northern regions of Ukraine. Only in Vitebsk and Grodno regions of Belarus, as well as in Volyn’, Rivne and Zhytomyr regions of Ukraine prevailed the “very low” and “low” levels of the FWI in this period. The “high” level of the FWI was

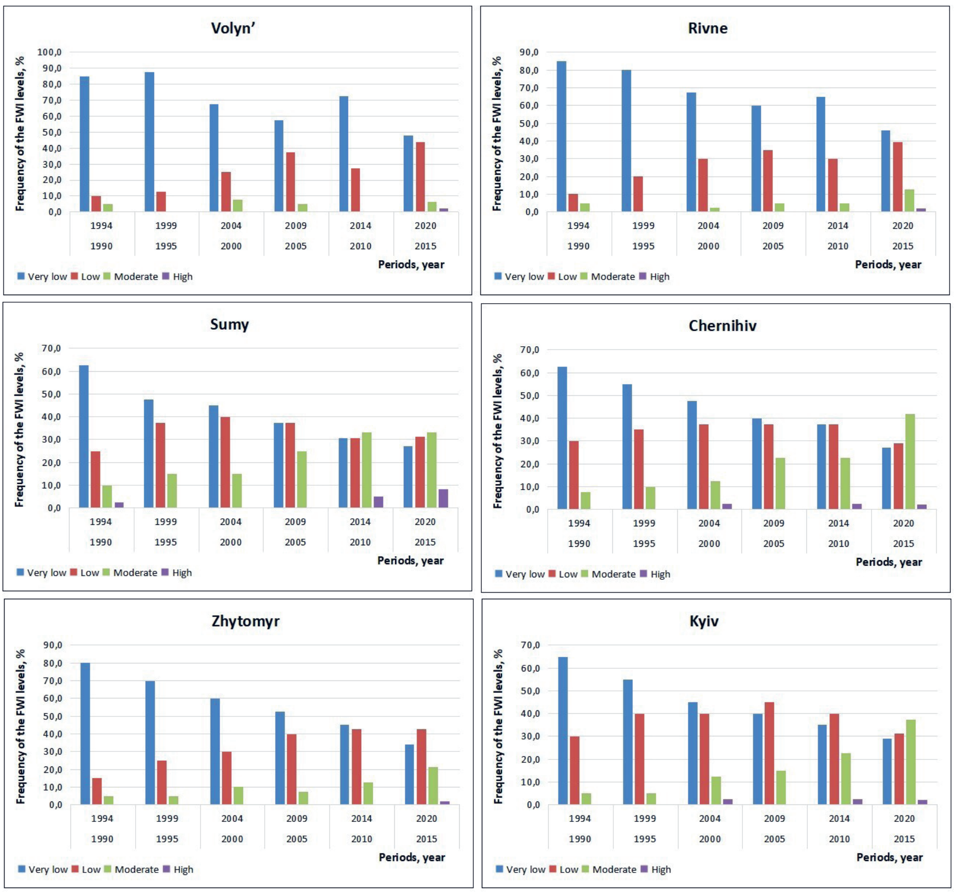

Figure 3. Dynamics of frequency of the FWI danger levels (%) in five- year periods during fire season 1990–2020 in Ukrainian regions.

observed only in the period 2015–2020 in the south of Belarus and in the northern regions of Ukraine with a low frequency of 2%, but in the Sumy region, it increased up to 8.3%.

Thus, the greatest temporal changes in the distribution of the frequency of the FWI occurred in three regions of Ukraine: Sumy, Chernihiv and Kyiv. Similar changes were noted in the neighboring Gomel region on the territory of Belarus; however, the "low" level of the FWI index had the greatest frequency here, while the "moderate" level of fire weather hazard became the predominant in the mentioned Ukrainian regions. That is, in these areas of Ukraine and Belarus, the most pronounced climatic changes were observed over the past 30 years, which led to more dry and warm weather conditions that generally increase the level of fire danger during the warm period of the year.

As known, cloudless dry and warm weather conditions, contributing to an increase in the level of fire hazard, are formed under extensive and prolonged droughts. Analysis of long-term trends in the drought regime in Eastern Europe showed (Jaagus et al., 2021) that in the study areas there was an increase in the intensity and frequency of droughts in late summer (especially in August). At the same time, the number of dry warm seasons in Ukrainian Polesie has especially increased since the beginning of the 21st century, and the most severe droughts were more often observed in late summer and early autumn (Semenova, 2017).

Thus, obtained dynamics of frequency of the FWI levels corresponds to drought regime, which makes it possible to use an integrated approach to seasonal forecasting of fire weather hazards using information on drought (*e.g.* drought indices) as a background process. As studies show, the SPEI (the Standardized Precipitation Evapotranspiration Index) drought index can indicate the risk of fires at the beginning of summer, and averaged seasonal fire weather indices correlate well with the drought indices on an annual time scale (*e.g.* Riley et al., 2013; McEvoy et al., 2019). These relations can be used in the warning system for drought and fire weather.

As climate modeling showed (Balabukh and Malytska, 2017; Shvidenko et al., 2017), in the study area, the predicted temperature increase will be accompanied by a decrease in the number of days with rain and a decrease of relative air humidity and significant increase in the potential evapotranspiration, especially in summer, which will lead to increase of water stress on vegetation and to rise the degree of flammability of forests.

The number of dry warm seasons will also increase in the northern regions of Ukraine, and by the middle of this century, six to ten seasonal droughts per 10 years can be expected (Semenova and Polevoy, 2020). Thus, the expected climate changes in the study area in the current century will lead to a further increase in the level of fire hazard and expansion of the duration of fire hazardous season.

4. Conclusions

Most climate studies show that from the mid-XX century there are global and regional trends in the growth of air temperature, which will be observed in the future (IPCC, 2018), and, in turn, will lead to an increase in cases of heat waves, droughts and raising the risk of wildfires.

This study showed that the dynamics of the fire weather index is correspond to observed climate changes in the continental part of Europe, where climate becoming warmer and drier (Shevchenko and Snizhko, 2019). The increase in the frequency of higher levels of fire hazardous weather occurs primarily in the southern areas of Belarus and northern areas of Ukraine, which indicates climatic shifts towards a dry and hot climate in the zone of mixed forests, as a result of which is possible to change the type of natural zone into the forest-steppe.

On the other hand, due to good compliance of the Fire Weather Index to the observed changes in the weather conditions and by high level of physical content of this parameter, the FWI can be recommended for use in the national hydro meteorological services of Belarus and Ukraine in methods for assessment and forecasting of fire weather hazards.

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SAŽETAK

Dinamika vremenskih uvjeta tijekom požara u mješovitim šumskim područjima Bjelorusije i Ukrajine pod utjecajem trenutnih klimatskih promjena

Inna Semenova i Katsiaryna Sumak

Studija ispituje prostorno-vremensku raspodjelu vremenskih uvjeta tijekom požara tijekom požarne sezone u razdoblju 1990.–2020. u područjima mješovitih šuma na području Bjelorusije i Ukrajine koristeći prosječni mjesečni vremenski indeks za pojavu požara (Fire Weather Index - FWI) za svako administrativno područje u istraživanoj regiji. Utvrđeno je da su najniže vrijednosti FWI zabilježene u sjevernim i sjeverozapadnim područjima Bjelorusije, a najviše na jugoistoku. Na području Ukrajine vrijednosti FWI rastu prema istočnim regijama. Gledano po sezonama, FWI raste od ožujka do svibnja, a sredinom ljeta indeks doseže maksimalne vrijednosti u svim regijama. Analiza dinamike FWI-a u petogodišnjim razdobljima pokazala je da je učestalost vremenskih uvjeta opasnosti od požara varirala od “vrlo niske” do “umjerene” razine veći dio razdoblja istraživanja. U posljednjih pet godina (2015.–2020.) “visoka” razina opasnosti od požara počela se pojavljivati na jugu Bjelorusije i u sjevernom dijelu Ukrajine. Tijekom razdoblja istraživanja u pojedinim regijama Ukrajine došlo je do smanjenja učestalosti FWI vrijednosti ‘niske’ razine opasnosti i istodobnog povećanja više razine opasnosti, a u skladu s uočenim klimatskim promjenama u regiji.

Ključne riječi: vremenski indeks za pojavu požara, vremenski uvjeti tijekom požara, stupanj opasnosti od požara, šumski požari, mješovite šume

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