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ASSESSMENT OF FIRE-INDUCED CO_2 EMISSIONS IN BULGARIAN FOREST ECOSYSTEMS

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ABSTRACT

Forest fires are one of the most significant natural phenomena, significantly affecting the state of the environment and the carbon balance of ecosystems. As a result of the combustion of plant biomass, significant amounts of carbon dioxide are released into the atmosphere, which contributes to the enhancement of the greenhouse effect and climate change. The present study aims to estimate the amount of carbon dioxide released during forest fires in Bulgaria by using data on burned area, heat load and fuel mass for the main types of forests. The study used average values for the calorific value and heat load of deciduous and coniferous forests, typical of the temperate climate zone. Based on these data, the amount of carbon dioxide released was calculated for the period 1980–2025, as well as for individual years for coniferous and deciduous forests. The results obtained show that there is a clear relationship between the number of fires, burned area and the amount of carbon emissions released. The highest values of released CO_2 are observed in years with large and intense fires, especially in coniferous forests, which have a higher heat load. The analysis shows a trend towards increasing fire activity and released carbon emissions in recent decades, which can be related to climate change, rising temperatures and increasing droughts. The results confirm the significant impact of forest fires on the environment and the carbon cycle and emphasize the need for more effective measures for fire prevention and management.

KEYWORDS: Forest Fires, CO_2 Emissions, Biomass Burning, Carbon Cycle.

1. INTRODUCTION

Forest fires are one of the most significant natural and anthropogenic phenomena, significantly affecting the state of the environment. In recent decades, the frequency and scale of fires in forest ecosystems have increased, which is associated with both climate change and the growing human impact on the natural environment. Rising temperatures, prolonged droughts and changes in the precipitation regime create favorable conditions for the occurrence and rapid spread of fires, especially in areas with a large amount of combustible vegetation [1-3].

Forest fires have a complex impact on ecosystems. On the one hand, they lead to the destruction of vegetation cover, loss of biodiversity and soil degradation, and on the other hand, they change the structure and functioning of forest ecosystems. As a result of the combustion of biomass, significant amounts of gases and aerosols are released into the atmosphere, including carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x) and fine dust particles. These emissions affect air quality, and global climate[4-10].

The release of carbon dioxide is particularly important, as it is the main greenhouse gas associated with global warming. In forest fires, carbon that has been stored in plant biomass for decades is released in a short period of time, disrupting the carbon balance between the atmosphere and terrestrial ecosystems. The amount of CO_2 released depends on a number of factors, including the type of forest vegetation, the amount of biomass available, the extent of burning, and the intensity of the fire.

The assessment of emissions from forest fires is a complex process that requires the use of different approaches based on data on the burned area, fuel mass and heat energy released during combustion. In modern research, methods based on determining the heat load and the amount of biomass burned are widely used, which allows for an approximate estimate of the released greenhouse gases. These methods are particularly suitable for analysis at the regional level, when detailed measurements for each individual fire event are lacking[11-13].

In the conditions of the temperate climate zone, which is typical for Bulgaria, forest ecosystems consist of both deciduous and coniferous tree species, which differ in the amount of biomass, fuel characteristics and calorific value. Therefore, different types of forests have different potential for the release of thermal energy and carbon dioxide during a fire. The study of these differences is important for a more accurate assessment of the impact of forest fires on the environment and for the development of effective risk management measures.

The present study aims to estimate the amount of carbon dioxide released during forest fires using data on burned area, heat load and fuel mass for the main forest types in Bulgaria. The results obtained may contribute to a better understanding of the role of forest fires in the carbon cycle and their impact on climate change.

2. FOREST FIRES IN BULGARIA

Forest fires are one of the main factors affecting the state of forest ecosystems in Bulgaria. Due to the diverse relief, climatic features and the different composition of forest vegetation, the country is characterized by varying degrees of fire danger in individual regions. The most affected are the low-mountain and mid-mountain areas, where oak and pine forests predominate, characterized by a larger amount of dry plant mass and higher flammability. The high-mountain coniferous forests, composed mainly of spruce, fir and Scots pine, can also be subjected to intense fires, especially during prolonged droughts and high temperatures.

Figure 1 shows the distribution of natural disasters in Bulgaria. It can be concluded from it that forest fires represent one of the most significant natural disasters in Bulgaria both in terms of frequency and environmental impact. Therefore, their study and assessment of the consequences, including carbon dioxide emissions, are of great importance for the protection of natural resources and for limiting the negative effects on the climate[14].

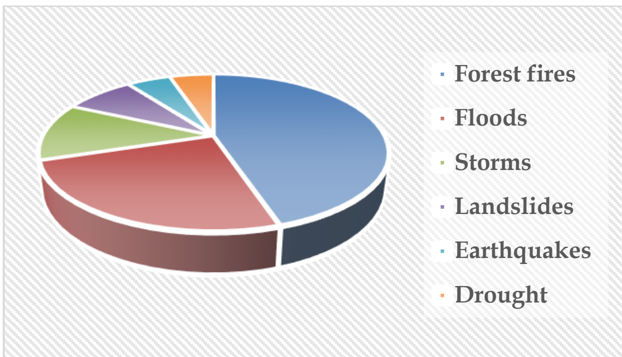

Fig. 1 Distribution of natural disaster in Bulgaria

In Bulgaria, forest fires are mainly divided into lowland (surface), peak and underground, with lowland and peak fires being the most common. Lowland fires spread along the surface of the soil and cover grasses, leaves, needles, shrubs and dry litter, while peak fires cover the crowns of trees and are characterized by much greater intensity and faster spread. (Fig. 2).

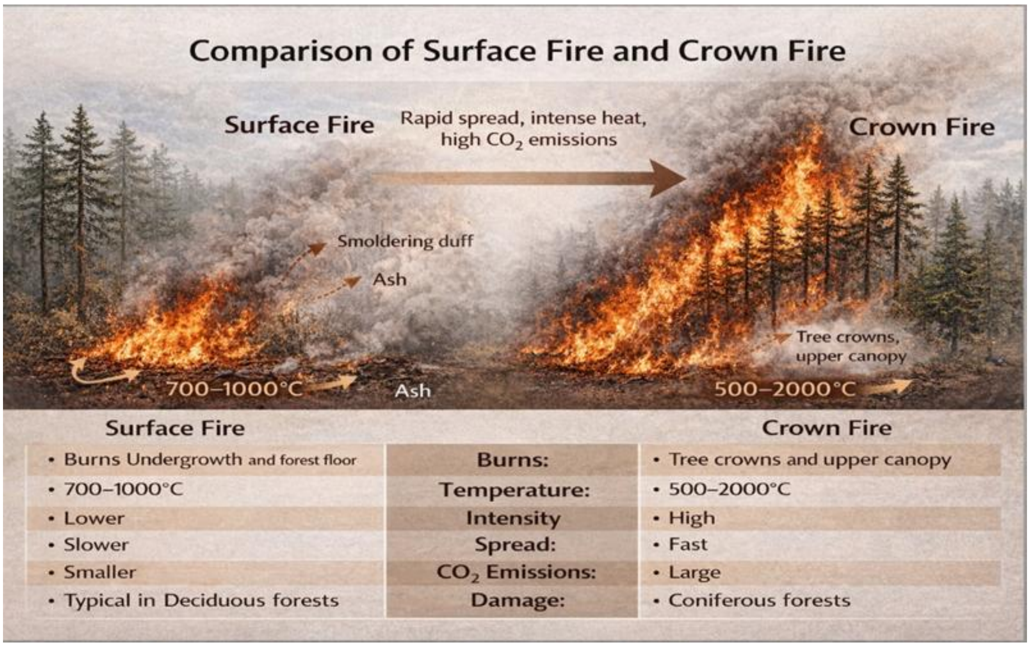

Figure 2 Scheme of surface and crown fire

Statistical data show that in most forest ecosystems, lowland fires are significantly more frequent than peak fires. In the temperate climate zone, including Bulgaria, approximately 70–80% of all forest fires are lowland fires, while 20–30% turn into peak fires. Although peak fires are rarer, they cause the greatest damage, as they burn all above-ground biomass and lead to significant release of heat energy and carbon dioxide. (Fig. 3).

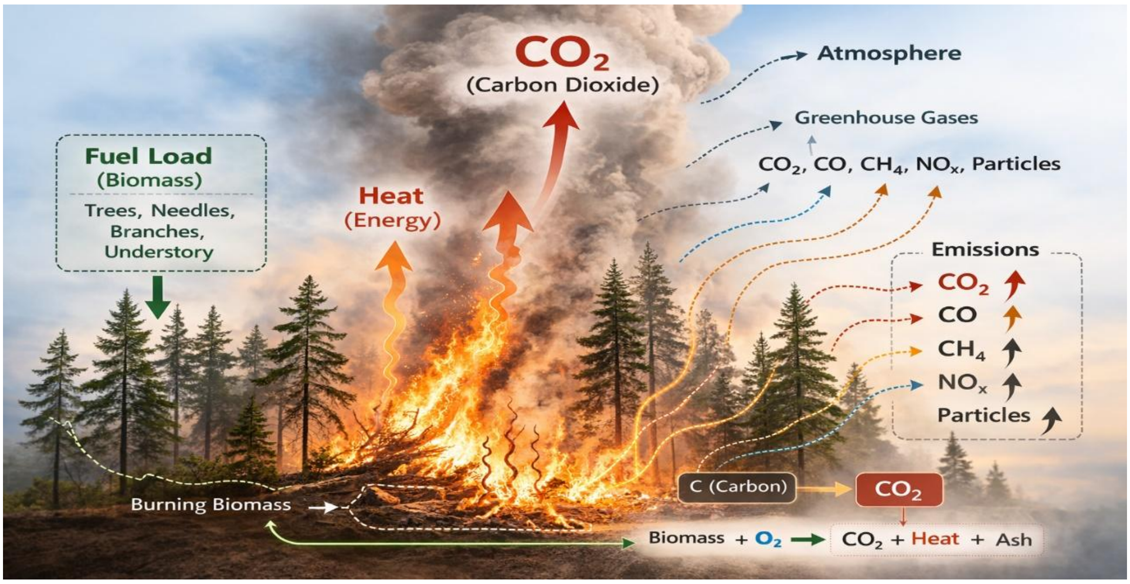

Figure 3 – Scheme of emissions from forest fires

3. METHODOLOGY OF THE STUDY

The study was conducted for the territory of the Republic of Bulgaria, which is characterized by a diverse relief, climate and forest vegetation. Forest ecosystems include both deciduous and coniferous species, located in different altitudinal zones. In the low mountain regions, oak forests predominate, in the mid-mountain regions - beech, and in the high mountain regions - coniferous forests, consisting mainly of Scots pine (Pinus sylvestris), black pine (Pinus nigra), spruce (Picea abies), white fir (Abies alba) and mugo

(Pinus mugo). Different types of forests are distinguished by different amounts of available biomass and different combustion characteristics, which determines different potential for the release of thermal energy and carbon dioxide in the event of a fire. (Fig. 4).

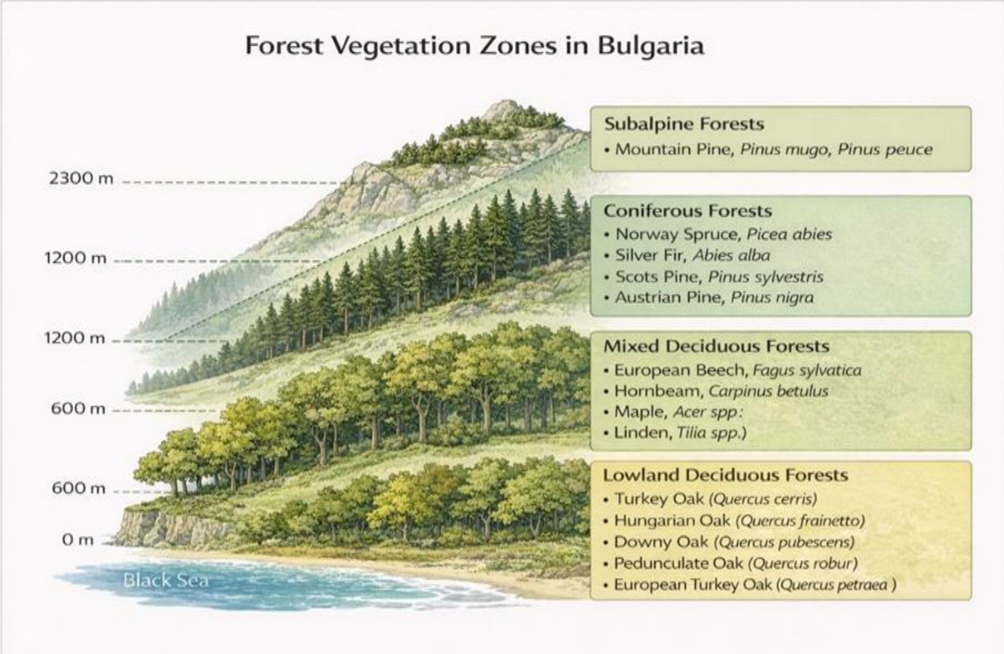

Figure 4 Forest zones in Bulgaria

The following data were used to estimate carbon dioxide emissions:

- burned area in forest fires (ha);
- type of forest vegetation;
- average values of heat load for different forest formations;
- calorific value of wood biomass;
- carbon fraction of dry biomass;
- combustion efficiency.

The heat load of forest vegetation is determined based on the available fuel mass and the calorific value of the biomass[13]:

$$H_L = M.H \quad (1)$$

Where

H_L – heat load (MJ m^{-2} or GJ ha^{-1});

M- fuel mass (kg m^{-2} or t ha^{-1});

H – calorific value (MJ kg^{-1}).(it is assumed for coniferous forests- $H = 19 MJkg^{-1}$ and for deciduous forest - $H = 18,5 MJkg^{-1}$).

The total energy released in a fire is determined by:

$$Q = A.H_L \quad (2)$$

where

Q – total amount of heat energy (MJ),

A – burned area (m^2),

H_L – heat load (MJ m^{-2}).

The burned biomass is calculated by:

$$B = \frac{Q}{H} \quad (3)$$

where

B – burned dry biomass (kg),

H – calorific value (MJ kg^{-1}).

The amount of carbon in the burned biomass is determined by:

$$C = B.C_F \quad (4)$$

where

- C – released carbon (kg),
- C_F – carbon fraction of the biomass.

The calculation assumes a value of

C_F=0.47, which is widely used in forest fire research and in the IPCC methodology.

To account for incomplete combustion of the fuel, a combustion coefficient η is used:

$$CO_2 = A.H_L.\eta.\frac{C_F.3,67}{H} \quad (5)$$

where

- η – combustion coefficient (0.3 – 0.7).

The following values were used in this study

$H_L = 40 MJ/m^2$ - for deciduous trees

$H_L = 50 MJ/m^2$ - for coniferous trees

$\eta = 0,5$

4. NUMERICAL RESULTS

At Fig. 5 are shown the number of fires in Bulgaria for the period 1980-2025.

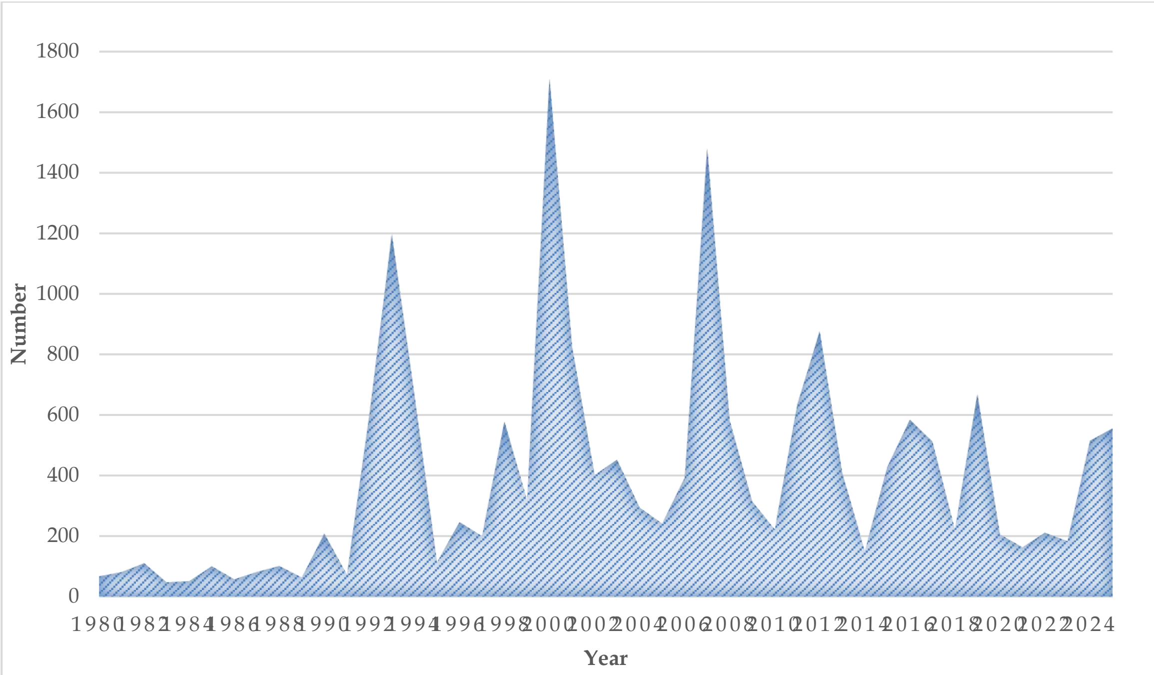

Figure 5 Number of forest fire for period 1980-2025

Fig. 6 presents the amount of carbon dioxide released calculated using the formulas presented in section 3, with average values for typical Bulgarian trees used for the heat load and thermal conductivity.

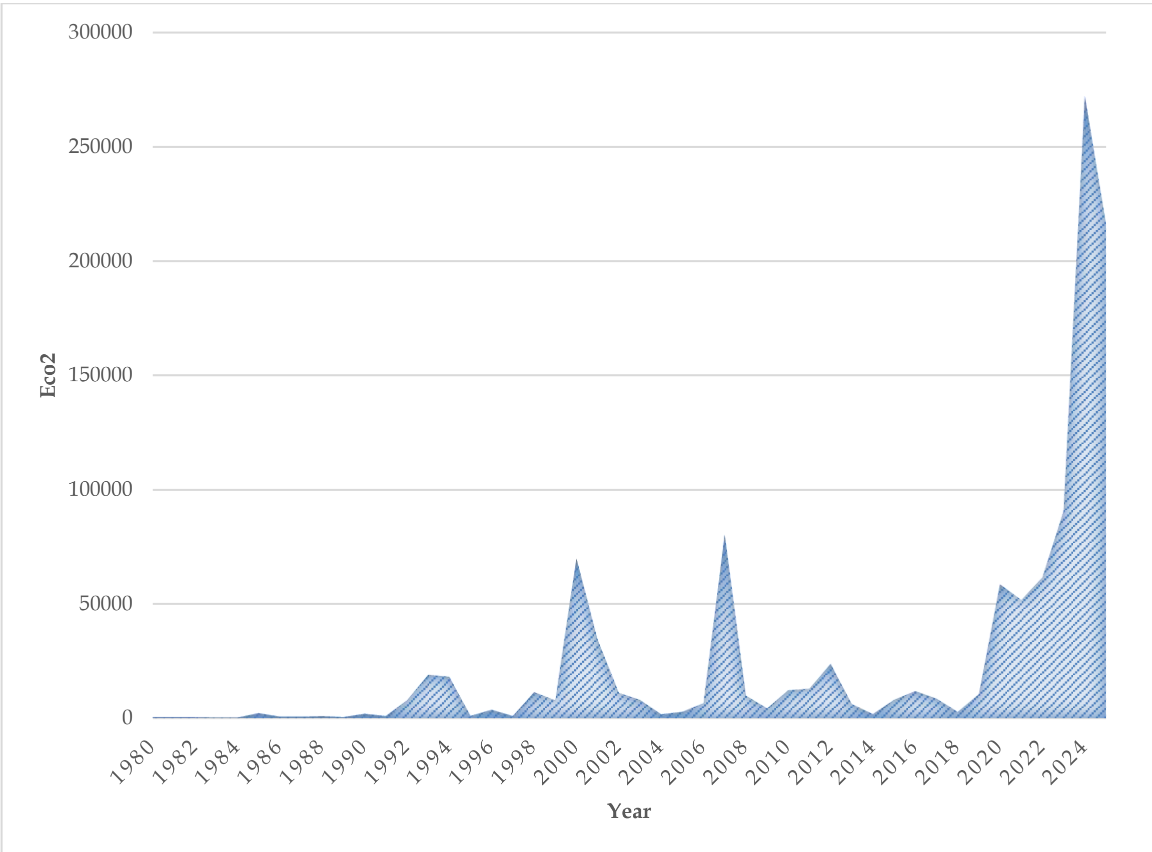

Figure 6 Amount of carbon dioxide released from forest fire

Figures 7 and 8 present the specific carbon dioxide emissions for the period 2019-2025. The calculations were made separately for the burned areas of coniferous and deciduous forests.

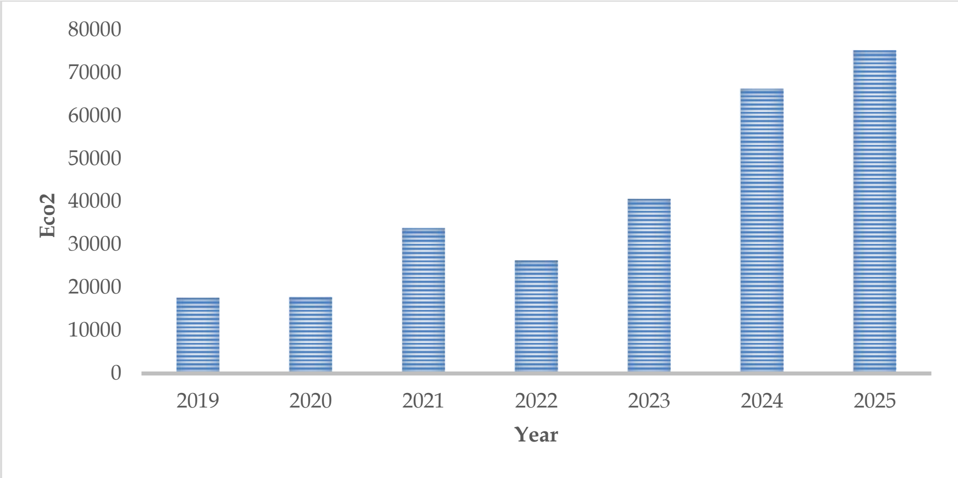

Figure 7 The amount of carbon dioxide released by coniferous forests

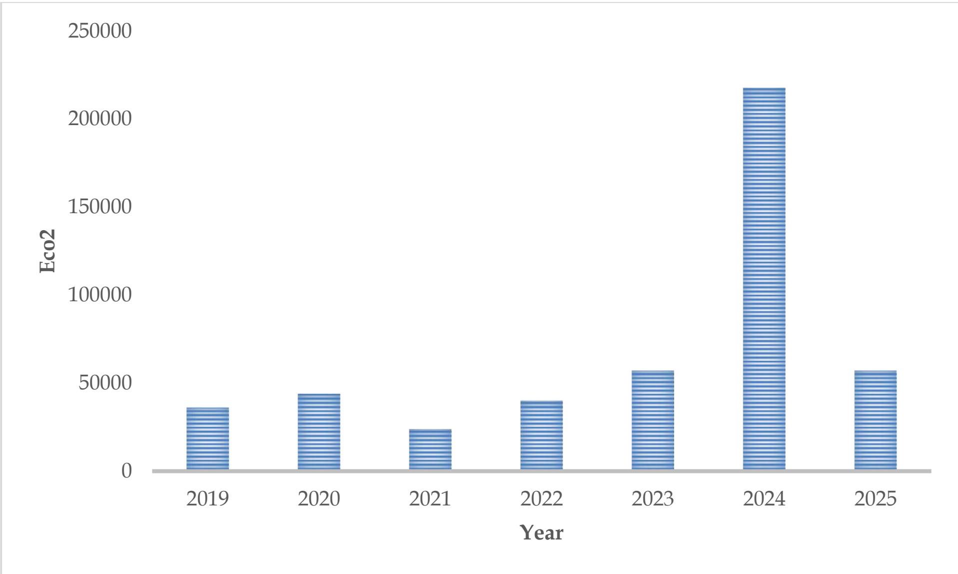

Figure 8 The amount of carbon dioxide released by deciduous forests

5. DISCUSSION OF THE RESULTS

Figures 5 and 6 present the change in the number of fires and the amount of carbon dioxide released for the period 1980–2025. Comparing the two indicators allows us to trace the relationship between the frequency of fires and the released carbon emissions, as well as the influence of various factors such as climatic conditions, type of forest vegetation and the scale of the fires. At the beginning of the period under consideration, from 1980 to the early 1990s, both the number of fires and the amount of CO_2 released were relatively low. This shows that during this period the fires were less frequent and of smaller area, which led to less biomass burning and, accordingly, lower carbon dioxide emissions.

After the beginning of the 1990s, a sharp increase in the number of fires was observed, which was also accompanied by an increase in the released CO_2. Around 1993–1994, the first significant peak was recorded in both graphs. This shows that the greater number of fires leads to a greater amount of burned vegetation mass and, accordingly, to higher carbon emissions.

The strongest increase was observed around 2000–2001, when both the number of fires and the amount of released carbon dioxide reached high values. This shows a direct relationship between the frequency of fires and the released emissions. A similar maximum was also observed around 2007, which is probably related to unfavorable climatic conditions, such as high temperatures and prolonged droughts, which create prerequisites for the occurrence of large fires.

Significant fluctuations were observed in the period after 2010. There are years with a smaller number of fires, but with relatively high CO_2 emissions. This shows that the amount of carbon dioxide released depends not only on the number of fires, but also on their intensity, area and type of vegetation burned. Large fires in coniferous forests, which have a higher heat load, can lead to significantly higher emissions even with a smaller number of fires.

The strongest increase in CO_2 emissions was observed in the last years of the period, when the values reached maximums significantly higher than in previous years. This increase was more pronounced in emissions than in the number of fires, which indicates that modern fires are larger and more intense. A likely reason for this is climate change, which leads to more frequent droughts, higher temperatures and the accumulation of a larger amount of fuel mass. In summary, it can be concluded that there is a clear relationship between the number of fires and the amount of carbon dioxide released, but it is not completely linear. In addition to the frequency of fires, their area, intensity and the type of forest vegetation are of significant importance. The results obtained show that in recent decades there has been a trend towards increasing fire activity and greater release of carbon dioxide, which is of great importance for the carbon balance of forest ecosystems and for climate change processes.

At fig. 7, which shows emissions from coniferous forests, a gradual increase in the amount of CO_2 released is observed over the period under consideration. At the beginning, the values are relatively low, but after 2021, a clear upward trend is observed, with the highest values being recorded in 2024 and 2025. This can be explained by a larger burned area, higher heat load and a larger amount of fuel mass in coniferous forests. Coniferous vegetation contains more resins and dry litter, which leads to more intense combustion and the release of a larger amount of heat energy and carbon dioxide.

Fig. 8 shows the amount of CO_2 released from deciduous forests. They also show an increase over the years, but the values are more uneven. The largest increase is observed in 2024, when the amount of carbon dioxide released is significantly higher compared to previous years. This shows that although broadleaf forests generally have a lower heat load, in large fires they can lead to significant carbon dioxide emissions due to the larger area burned.

A comparison between the two figures shows that coniferous forests generally emit a larger amount of CO_2 during a fire, which is due to the higher calorific value and the larger amount of fuel mass. At the same time, broadleaf forests show greater fluctuations, meaning that the amount of emissions depends more on the area of the fire.

Particularly indicative is the year 2024, when both types of forests experienced a sharp increase in carbon dioxide emissions. This may be related to adverse climatic conditions, such as high temperatures and prolonged drought, which increase the risk of large and intense fires.

In summary, it can be concluded that the amount of carbon dioxide released during forest fires depends on both the number and area of fires and the type of forest vegetation. Coniferous forests have a greater potential for carbon dioxide emissions, while deciduous forests can lead to high emissions during large fires. The results obtained show a trend towards increasing carbon emissions in recent years, which confirms the growing impact of forest fires on the environment and on the carbon balance.

6. CONCLUSION

The conducted study shows that forest fires are one of the main factors influencing the state of forest ecosystems and the carbon balance of the environment. Analysis of data for the period 1980–2025 shows a clear relationship between the number of fires, the burned area and the amount of carbon dioxide released. It was found that in years with a greater number of fires and a larger burned area, significantly larger amounts of CO_2 are released, which has an impact on climate processes.

The results show that coniferous forests have a greater potential for releasing carbon dioxide compared to deciduous forests, due to the larger amount of fuel mass and the higher heat load. At the same time, high emissions can also be observed in large fires in deciduous forests, especially with a large burned area.

There has been a trend towards increasing emissions in recent years, which is probably related to climate change, more frequent droughts and an increase in the amount of dry plant mass. This confirms that forest fires are of significant importance for the carbon balance of ecosystems and can contribute to the enhancement of the greenhouse effect.

The results obtained show that the use of a method based on heat load and burned area allows a realistic assessment of the released emissions in the absence of detailed measurements. Such studies are important for assessing the impact of forest fires on the environment and for developing measures to reduce the risk and limit the negative consequences.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, R.V. and P.K.; methodology, R.V. and I.S; validation, R.V. and E.G.; formal analysis, P.K.; investigation, R.V.; resources, E.G.; writing—original draft preparation, R.V.; writing—review and editing, I.S..; visualization, E.G. All authors have read and agreed to the published version of the manuscript.”.

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