"Relationship between economic development, forest resources, and forest fires: European context"

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RELATIONSHIP BETWEEN ECONOMIC DEVELOPMENT, FOREST RESOURCES, AND FOREST FIRES: EUROPEAN CONTEXT

Abstract

Conservation of forest resources is a prerequisite for sustainable development of human society, both in the context of preventing negative climate change and for economic growth. The study aims to establish or refute the co-dependence between the level of forest cover in European countries and the production of gross domestic product. The study object is the socio-economic systems of the national economies of European countries in relation to the totality of forest resources of the continent. Studying the dynamics of forest cover indicators (the share of forests in the total area of the country and forest area per capita), weighted within the internationally recognized regions of Europe, it is confirmed that the level of forest cover of European countries is gradually increasing. The analysis of forest fire area maps identifies three main groups by the level of vulnerability to forest fires: safe (Northern European countries), conditionally safe (Western European countries), and dangerous (Eastern and Southern European countries).

Denmark, Finland, France, Norway, and Finland show a direct correlation between the level of forest cover of a country's territory and gross domestic product. The results of cluster analyses based on the data from 2000, 2010, 2015, and 2020 confirm the existence of a stable cluster of European countries (34 countries) in which there is one type of relationship between the production of gross domestic product and the level of forest cover of the territory.

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INTRODUCTION

Forest resources are now rightly considered one of the most valuable resource endowments for human development. The volume and conservation of forest resources not only determine the supply of certain unique raw materials but also contribute to the conservation of the planet's biota and prevent climate change. Forest resources also contribute to the conservation of soils and surface water quality, act as natural filters in air purification, and ensure the existence of about 1.6 billion people (PEFC, n.d.).

Sustainable forest resources are favorable not only for ensuring the reduction of greenhouse gas emissions but also contribute to the sustainability of economic development. It is no coincidence that forest cover restoration is included in the UN (n.d.) global goal system – global goal 15 "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." All this leads to the transformation of the paradigm of sustainable development and changes the vector of tasks of economic development of human society (Dobrovolska, 2018).

Nowadays, forest resources are constantly decreasing due to a significant number of risks and threats. In addition to deforestation associated with negative climatic changes and natural disasters, the forest area and forest cover density are negatively affected by growing population pressure, invasion of non-natural forest species, diseases, and ineffective forest management (Singh et al., 2022). In contrast to world statistics, forest cover across European countries is steadily increasing (EFI, n.d.). Over the last seven decades, the forest area in Europe has increased by 37%. Europe's terrestrial forest cover is now approximately 40%, compared to approximately 31% globally. Ensuring the growth of sustainable forest cover in Europe is the result of a deliberate overall policy, the implementation of which, however, requires significant financial resources. The question arises as to the feasibility and effectiveness of incurring significant expenditure on forest conservation and restoration.

Forest fires are one of the most significant drivers of forest loss, together with intensive forest management and climate change. The results of a quantitative assessment of forest losses due to fires confirm the increase in their destructive power during the last years (Tyukavina et al., 2022). The increase in forest loss is also consistent with climate anomalies, modeled carbon losses, and economic losses associated with slower economic growth. It becomes obvious that there is a complex set of links between forest area, forest damage (including forest fires), environmental conditions, climate change, and economic development of human society.

1. LITERATURE REVIEW

The relationship between the economic development of the territory/country and the volume of forest resources has been the subject of multidirectional scientific interest in recent years. More recently, the economic importance of forestry was perceived primarily through industrial forest areas, but since the end of the twentieth century, the decisive importance of forests for the preservation of the planet's ecology, and thus maintaining the efficiency of production in other spheres of economy, has been noted (Perry, 1998). Numerous scientific studies state an inverse relationship between the area of forests and the volume of greenhouse gas emissions into the atmosphere (Begum et al., 2020; Yamulki, n.d.; Kwilinski et al., 2024).

The economic development of local territorial communities is sustainable when they directly consume forest resources and use their recreational potential (Tadesse et al., 2022). However, the importance of sustainable forest cover has been emphasized for other aspects of human management (Vărzaru & Bocean, 2023; Hao et al., 2019; Razafindratsima et al., 2021).

Works on the relationship between economic development indicators and the volume of forest resources or/and their structure can be divided into three main groups. The first group of studies determines the economic effect of certain forestry models, for example, the Fautman model in timber management or Monte Carlo simulation to estimate the level of risk in a forestry model (Hanewinkel, 2009). The first forestry models appeared back in the 70s of the twentieth century. Nevertheless, even now, forestry models are widely used to justify forest management (Rivière & Caurla, 2020), becoming the basis for further research.

For example, Cuaresma et al. (2017) used the Smith curve to prove that the marginal effect of forest cover on per capita income growth depends on the stage of economic development. However, Smith's U-shaped curve (Katan et al., 2018) is quite widespread in other economic studies that link environmental conservation and economic development. There are also combinations of forestry models with forest damage characteristics (Posavec et al., 2023), where the economic effect of fires on forestry is established. The use of these models also revealed several significant theoretical aspects that required clarification in each individual case. One needs to clarify the concepts of "forest sector," "forestry," "forest industry," and "forest resources." The impact of the coverage area on the result of the use or economic evaluation of forests should be researched. Estimating losses from forest

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disturbances and deferred losses from the economic use of forests needs to be done. Finally, research focuses on the impact of forests or deforestation on the environment and, thus, derivatively, on the efficiency of the economy in other sectors.

The second group of models determined the relationship between the volume of forest resources and indicators of economic development from the "opposite" – as the determination of the relationship between "forest disturbance" and the productivity of production. In particular, Zhai and Ning (2022) note four models of this type: analysis "with… without," general or partial equilibrium models, intervention model, and social welfare model. Each of these groups has its own purpose and specificity of application. Thus, "with… without" inherently aims to identify the damage caused by forest disturbance, using different techniques to estimate different types of loss or damage. General or partial equilibrium models aim to determine the share of forestry or forestry alone in the formation of the social product directly through operations or indirectly through factors of production. General or partial equilibrium models consider forest disturbance as a factor closely related in their content to forestry models. The social welfare model is based on determining the welfare of owners before and after forest disturbance. The social welfare model establishes a relationship between the amount of forest disturbance and the welfare of different market participants. In any case, all these models link "forest disturbance" to the economic benefits of forest use.

The third group of models defines the relationship between the forest resources of a country (groups of countries) and their economic development indicators. For example, Vărzaru and Bocean (2023), using hierarchical methods of cluster analysis, prove the existence of such a relationship. The relationship between forest resource consumption and economic growth has been proven in some countries. Hao et al. (2019) confirm the limited nature of economic growth through enhanced consumption of forest resources. Caravaggio (2020), using the environmental Kuznets curve (EKCd), confirms the existence of a certain "turning point" of deforestation of the territory, beyond which economic growth stops. In contrast, Razafindratsima et al. (2021) prove that a decrease in forest area leads to an increase in poverty. At the same time, the opposite effect of economic growth on forest cover is confirmed.

Ewers (2006) showed that rich countries are more characterized by an increase in forest area, while less rich countries are more characterized by deforestation. Siregar et al. (2024) proved that the level of forest cover in Indonesia is not related to the indicators of socio-economic development of the country; there is only a relationship between the area of forests and the area of active economic use. Meier et al. (2023), using data on the volume of forest fires in the countries of Southern Europe, prove that the GDP growth rate in the regions of the countries of Southern Europe decreases by 0.11-0.18% if there is at least one forest fire in the region.

However, the situation is more complex than just the dependence of economic growth on the level of forest cover. When determining the relationship between the volume of forest resources and indicators of economic development, there is an indirect and non-linear relationship, all the effects of which are realized over a long period. It may have a recurrent nature and be realized on a wider scale than within a single national economy. In order to better account for the possible effects of such a relationship, it is necessary to conduct research on the world region over a long time horizon. At a minimum, such a time interval should be the period necessary for the full recovery of forest resources after their complete destruction as a result of consumption and man-made or natural disasters. In some cases, it is impossible to establish a link between the parameters of socio-economic development and the volume of forest resources or/and their damage. The impact of the volume of forest resources on the parameters of economic or socio-economic development is complex, realized through indirect or direct links, and often leads to synergetic effects. At the same time, the determination of such impact is necessary and relevant, given the importance of forest resources not only to ensure economic development but also to preserve environmental parameters.

The aim of this paper is to establish the relationship between the level of forest cover of European countries and/or their damage and economic development. The object of the study is the complex of socio-economic systems of national economies of European countries in interrelation with the totality of forest resources of the continent. The study seeks to determine the current trends in the forest cover of European countries and regions and analyze the existence of interrelationships between the level of forest cover and indicators of economic development. Thus, the findings may result in typical regularities of the influence of forest cover in countries on economic development.

The hypotheses are formulated as follows:

H1: *There is a relationship between the level of forest cover of territories and indicators of economic development.*

H2: *One can group European countries according to typical patterns of influence of forest cover on economic development.*

2. METHODS

The study employs grouping and processing of statistical information, quantitative and qualitative comparison, analysis and synthesis, construction of dynamic series (including Fourier series), regression analysis, variance analysis, cluster analysis, satellite monitoring, artificial intelligence, and deep learning. The following steps were performed:

- data on the area of European countries (km^2), forest area (% of total area), forest area (ha per person of population), GDP production (USD per person of population in 2010 comparable prices), agricultural production growth index by European countries, forest damage due to fires by European countries (% of forest area) were collected and grouped. The source of this statistical information was the UNECE Statistical Database (2015, n.d.);

- stable clusters of European countries according to the indicators of GDP production (USD per 1 person of population in comparable prices of 2010) and forest area (ha per 1 person of population) were determined using the k-means method (using a variant of the "trout" method);

- the co-dependence between the level of forest cover of European countries (forest area (ha per one person of population) and the production of gross domestic product (USD per 1 person of population in comparable prices of 2010) was established;

- an algorithm for monitoring forest fires and assessing their damage was developed.

The sequence of the study is shown in Figure 1.

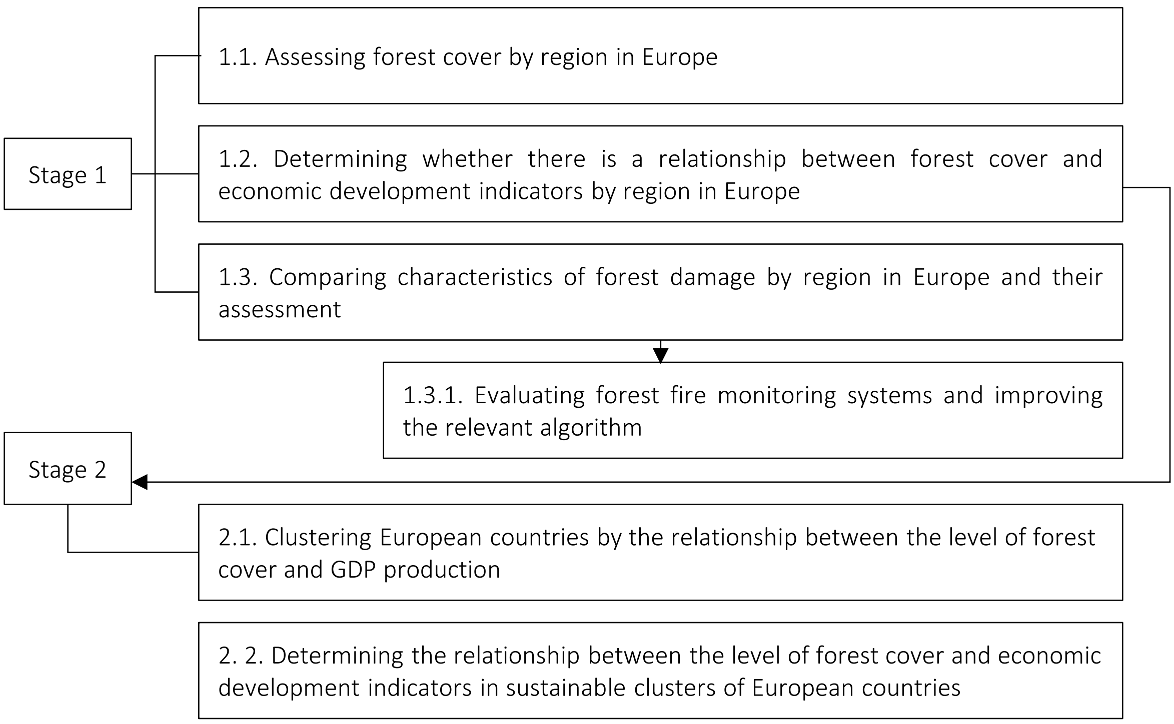

Figure 1. Sequence of research

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3. RESULTS

In the first stage of the study, the data on the level of forest cover in European countries were grouped by region (according to the UN). These countries include Northern Europe (Denmark, Estonia, Iceland, Latvia, Lithuania, Norway, Sweden, Finland, the UK, and Ireland), Southern Europe (Portugal, Spain, Andorra, Italy, Greece, Malta, Cyprus, Albania, Croatia, Slovenia, Bosnia and Herzegovina, Montenegro, Serbia, and Northern Macedonia), Western Europe (France, Belgium, the Netherlands, Luxembourg, Germany, Austria, Liechtenstein, and Switzerland), and Eastern Europe (Ukraine, Belarus, Moldova, Romania, Bulgaria, Hungary, the Czech Republic, Slovakia, and Poland). The level of forest cover was estimated according to two indicators: the share of forests in the total land area of the country (Figure 2) and the forest area per inhabitant of the country. For European regions, the calculations were made as weighted averages. For the indicator of the share of forests in the total land area of the country, the weighting was based on the total land area of the countries, for the indicator of forest area per capita – on the number of inhabitants of the country.

The description of trends is based on incomplete data, with the numbering of periods starting with t_{1990} = 1. The highest level of forest cover is, of course, in Northern Europe. At the same time, Northern Europe has the smallest increase in forest cover – 0.03 percent annually or –0.003 ha per person, while in Southern Europe, the increase is 0.20 percent or 0.001 ha per person, in Western Europe – 0.10 percent or ha per 0.0003 person, in Eastern Europe – 0.07 percent or 0.002 ha per person. The pronounced upward trend in the level of forest cover as a proportion of forests in the total land area is not at all the case if the criterion is the area of forests per person in a country.

Table 1 summarizes the trends in forest cover in European regions for the period 1990–2020.

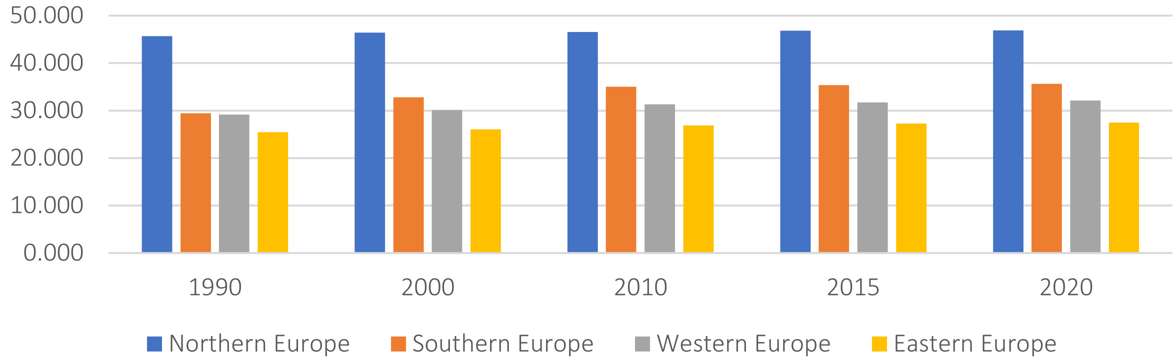

Figure 2. Dynamics of the level of forest cover of European regions according to the share of forests in the total land area of the country (λ_{SF}), %

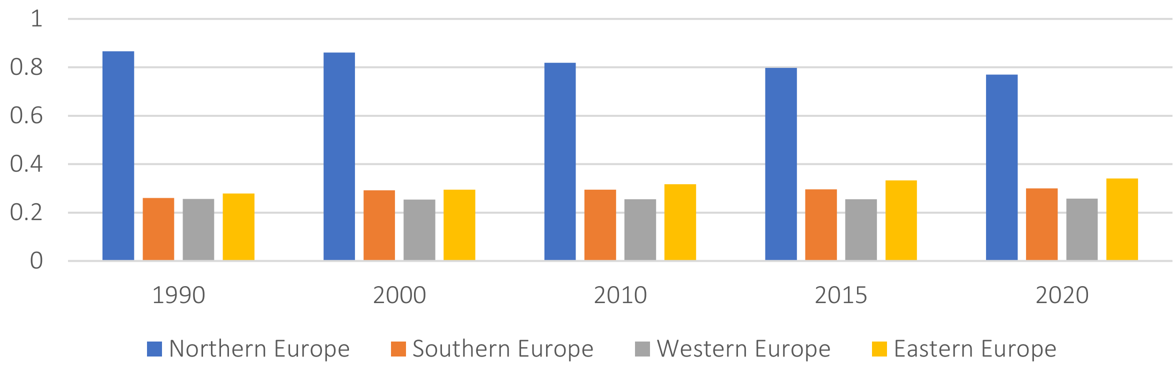

Figure 3. Evolution of forest cover in European regions in terms of forest area per 1 person (SF_i), hectare (ha)

Table 1. Trends in the level of forest cover in European regions

Region of Europe	Forest cover assessment indicator	Formal description of trends	
		Formula	Approximation probability
Northern Europe	share of forests in the total area of the country, %, λ_{SF}	$\lambda_{SF}(t) = 45.74 + 0.03 \cdot t$	1.00
	forest area per person in the country, ha, SF_i	$SF_i(t) = 0.882 - 0.003 \cdot t$	0.99
Southern Europe	share of forests in the total area of the country, %, λ_{SF}	$\lambda_{SF}(t) = 29.89 + 0.20 \cdot t$	1.00
	forest area per inhabitant of the country, ha, SF_i	$SF_i(t) = 0.267 + 0.001 \cdot t$	1.00
Western Europe	share of forests in the total area of the country, %, λ_{SF}	$\lambda_{SF}(t) = 29.08 + 0.10 \cdot t$	0.99
	forest area per inhabitant, ha, SF_i	$SF_i(t) = 0.255 + 0.00003 \cdot t$	0.99
Eastern Europe	share of forests in the total area of the country, %, λ_{SF}	$\lambda_{SF}(t) = 25.36 + 0.07 \cdot t$	1.00
	forest area per inhabitant, ha, SF_i	$SF_i(t) = 0.274 + 0.002 \cdot t$	0.98

Although the studied interval has a wide horizon (30 years), the study cannot claim that the sample is representative, as the data are incomplete. In general, the level of forest cover in Europe is gradually increasing; the main factors determining its dynamics are natural and climatic conditions. It can also be hypothesized that the level of forest cover is influenced by demographic pressure and financing of forest conservation and distribution as a result of the implementation of joint agricultural policies or other measures. This requires a separate study of demographic processes and a study of the effectiveness of additional financing of forest conservation from the SAP or national governments.

The next stage of the study was to establish or refute the relationship between forest cover and gross domestic product per capita (in internationally comparable 2010 prices). The study was conducted in Denmark, Finland, France, and Norway, as there were insufficient statistical data to conduct studies in other countries. The results are summarized in Table 2.

Table 2. Formal description of the relationship between forest cover and gross domestic product per capita (in international comparable prices 2010, USD) for selected European countries

Country	Indicator of the level of forest cover	Approximation description			Forest area, km²	GDP, USD/person
		Formula	Probability, P	extreme		
Denmark	λ_{SF}, %	$GGP(\lambda_{SF}) = -4.4 \cdot 10^5 + 6.4 \cdot 10^4 \cdot \lambda_{SF} - 2.14 \cdot 10^3 \cdot \lambda_{SF}^2$	0.998	15.10	6509	45892
	GDP, ha/person	$GGP(SF_i) = -4.1 \cdot 10^6 + 7.5 \cdot 10^7 \cdot SF_i - 3.3 \cdot 10^8 \cdot SF_i^2$	0.930	0.11	6553	46336
Norway	λ_{SF}, %	not determined with a sufficient level of certainty				
	SF_i, ha/person	$GGP(SF_i) = 3.7 \cdot 10^4 + 1.0 \cdot 10^4 \cdot SF_i - 1.2 \cdot 10^3 \cdot SF_i^2$	0.863	4.11	221764	57747
Finland	λ_{SF}, %	$GGP(\lambda_{SF}) = -4.25 \cdot 10^7 + 1.16 \cdot 10^6 \cdot \lambda_{SF} - 7.9 \cdot 10^3 \cdot \lambda_{SF}^2$	0.65	73.2	247549	39825
	SF_i, ha/person	$GGP(SF_i) = -2.2 \cdot 10^6 + 9.87 \cdot 10^5 \cdot SF_i - 1.08 \cdot 10^5 \cdot SF_i^2$	0.99	4.57	252648	39509
France	λ_{SF}, %	$GGP(\lambda_{SF}) = -3.99 \cdot 10^5 + 2.86 \cdot 10^4 \cdot \lambda_{SF} - 4.71 \cdot 10^2 \cdot \lambda_{SF}^2$	0.99	30.4	167665	36504
	SF_i, ha/person	$GGP(SF_i) = 7.08 \cdot 10^6 - 5.48 \cdot 10^7 \cdot SF_i + 1.06 \cdot 10^8 \cdot SF_i^2$	0.99	0.25	173419	33796

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For Denmark, the actual forest cover in 2020 is close to optimal ($\lambda_{SF,2020}$ = 14.97 at $\lambda_{SF,opt}$ = 15.1 and $SF_{i,2020}$ = 0.1106 at SF_i = 0.112) and the actual GDP in 2020 has a deviation of 1.9 % and 0.9 %, respectively, which is quite acceptable for establishing dependence on incomplete data. For Finland also, the forest cover in 2020 is close to optimal ($\lambda_{SF,2020}$ = 73.2 at $\lambda_{SF,opt}$ = 73.4 and $SF_{i,2020}$ = 4.56 at SF_i = 4.51) and the actual level of GDP in 2020 has a deviation of 0.99% and 1.79%, respectively. For France and Norway, the level of forest cover is far from optimal. However, four confirmed cases are not enough to confirm the hypothesis that the level of forest cover is one of the determining factors affecting the efficiency of social production.

One of the objectives of the study was also to determine the proportion of the European forest area damaged by fire. Table 3 summarizes the level of fire damage to forests by European countries.

Table 3. Proportion of forest area damaged by fire in European region, % of total forest area

Region of Europe	2000	2010	2015	2020
Northern Europe	0.0017	0.0055	0.0018	0.0005
Southern Europe	0.5526	0.1868	0.2714	1.3049
Western Europe	0.1196	0.0277	0.0898	0.0343
Eastern Europe	0.0036	0.0238	0.0194	0.0168

Observations state the dependence between the level of forest damage, natural and climatic features of the region, and the area of forests on the territory of the region. Natural and climatic features of the territory and biological and social factors affect the performance of economic activity not only in forestry but also in agricultural production (Dobrovolska et al., 2023). However, they are determinant in the creation of "fire weather." For example, the countries of Northern Europe are characterized by relatively low summer temperatures, high climate humidity, and high levels of forest cover. Therefore, the percentage of forest area damaged by fires is also the smallest. In contrast to Northern Europe, Southern Europe has higher summer and mean annual temperatures, an arid climate, and less forest cover. Therefore, Southern European countries have a high level of fire danger and high losses from forest fires.

Based on the above, the assessment of sources and types of forest damage is extremely important. Forest damage caused by human activities is one of the most topical issues of forest management and is not the subject of this study. However, the issue of so-called "natural forest damage," especially as a result of fires, is becoming more and more urgent, given the deterioration of "fire weather" in the world.

Satellite-based forest fire monitoring systems are based on special thermal sensors: SEVIRI (Spinning Enhanced Visible and InfraRed Imager) for active fire monitoring products; AVHRR (Advanced Very High-Resolution Radiometer) installed on NOAA satellites; MODIS (Moderate Resolution Imaging Spectroradiometer) installed on TERRA and AQUA satellites (Wooster et al., 2021); and VIIRS (Visible Infrared Radiometer Suite).

However, detecting and analyzing forest fires from special sensors without the use of automation is an expensive and complex process. For this reason, work is now underway worldwide to create automated systems for detecting and assessing forest fires (Barmpoutis et al., 2020). At the same time, the main direction of creating such systems is the development of methods for the automated processing of satellite data (Seydi et al., 2022). The use of the latter significantly simplifies the process of assessment of fires and, in some cases (swamps, protected areas), exceeds the accuracy of assessment on the ground.

Modern approaches to forest fire risk assessment considering the influence of natural and anthropogenic environmental factors differ significantly between countries. For example, Australia uses the MacArthur Forest Fire Danger Index (FFDI) and the Forest Fire Behaviour Tables (FFBT). Canada, several US states, Europe, Mexico, New Zealand, and Southeast Asian countries use the Canadian Wildfire Weather Index (FWI). The United States has developed and operates the National Fire Danger Rating System (NFDRS). In addition, as Mahmoud et al. (2018) indicated, wildland-urban interface (WUI) maps in the United States span more than two decades. However, they have not investigated its influence on the effectiveness of early fire detection from space. Moreover, given the variety of factors that influence the potential for wildfire occurrence, an integrated approach that incorporates both natural and anthropogenic factors is needed. Recently, convolutional neural networks have been successfully used for image recognition and have achieved higher accuracy than traditional methods of object recognition (V. Hnatushenko & Vik. Hnatushenko, 2020), detection, and semantic segmentation (Hnatushenko et al., 2023). Due to its multi-layer structure, the neural network can perform approximation of complex functions and represent the distribution characteristics of input data.

The proposed forest fire monitoring algorithm based on artificial intelligence and deep machine learning consists of the following steps:

- a space image of any size in the form of satellite images is fed to the input of the forest fire recognition system;
- filtering, radiometric and geometric correction of the data with spectral correction, as well as the transformation of features and attributes of the observed objects (Hnatushenko & Kashtan, 2021);
- CNN training and classification (Figure 4);
- construction of fire center polygons (Figure 5). Thus, one can obtain contour polygons of the corresponding regions with different attributes: position, size, etc.

The study of the existing systems of automated detection, identification, and analysis of forest fires has shown that the source of operational detection of fires is satellite imagery information. The analysis of maps of the areas covered by fire in dynamics shows a rather strict differentiation by countries/regions of Europe.

A comparative analysis of European countries by the level of forest damage caused by fires clustered three main groups:

- Safe – countries where forest fires do not occur or occur occasionally. These countries are characterized by favorable natural and cli-

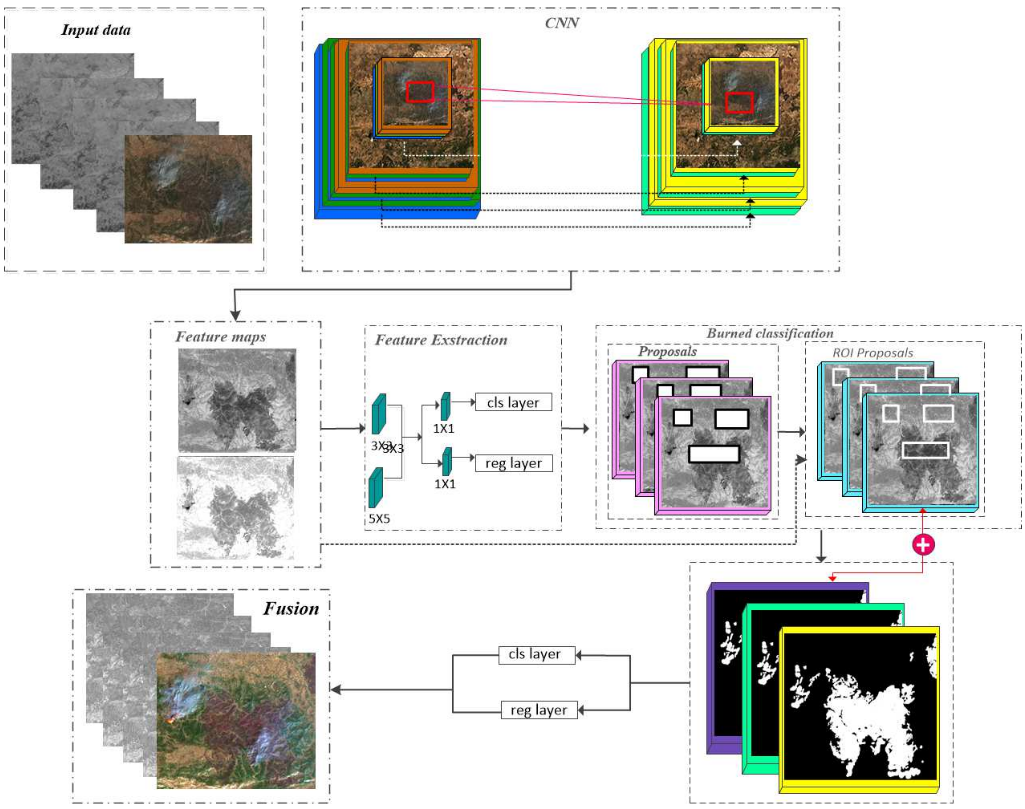

Figure 4. Training and classification of CNNs in forest fire detection

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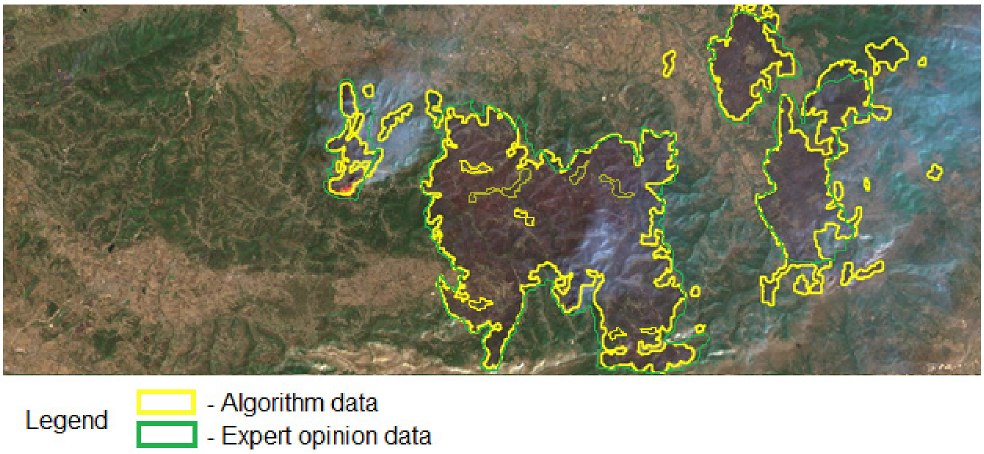

Figure 5. Map of areas covered by forest fires in forest damage assessment

matic features and a high level of effectiveness of state services for monitoring and preventing forest fires. This group includes Andorra, Austria, Belgium, Denmark, Estonia, Finland, Iceland, Luxembourg, Liechtenstein, Norway, Sweden, and Switzerland.

Conditionally safe – countries in which forest fires occur and are quickly extinguished or occur extremely rarely. This group includes Albania, the Great Britain, Latvia, Lithuania, the Netherlands, Germany, France, and Montenegro.

Dangerous – countries in which forest fires occur systematically and the national service for preventing and fighting forest fires is relatively ineffective. This group of countries includes Belarus, Bosnia and Herzegovina, Bulgaria, Cyprus, the Czech Republic, Croatia, Greece, Ireland, Italy, Malta, Moldova, North Macedonia, Poland, Portugal, Romania, Serbia, Slovenia, Slovakia, Spain, Hungary, Ukraine, and the Czech Republic.

The first group includes predominantly Nordic countries, the second group includes predominantly Western European countries, and the third group includes Eastern and Southern Europe. The results also confirm that the level of forest damage is primarily influenced by climatic factors. The results also correlate with Cuaresma et al. (2017) since the countries of the first and second groups are predominantly countries with a high standard of living. In developed economies, of course, more funds are allocated for forest protection, including from fires. Therefore, the economic efficiency of the use of forests should be lower.

The second stage of the study was the grouping of European countries according to typical patterns of influence of forest cover on economic development. Vărzaru and Bocean (2023) also carried out a similar grouping of European countries. They used cluster analysis (hierarchical methods) to group countries with similar profiles in terms of forest resources and economic and environmental indicators. Clustering was used primarily to group countries according to the proportion of areas covered by forests, GDP production per person, and the Sustainable Development Goals index. The list of sustainable development goals is quite broad and includes both economic development indicators and environmental and social indicators. At the same time, researchers have proposed the existence of sustainable groups of countries in which these characteristics coincide. Without dwelling on the content of the initial indicators used for the study, it would be desirable to confirm the sustainability of clusters for more than one year of observation. However, the very hypothesis of the existence of stable clusters of countries formed by indicators of forest cover and economic development (*H2*) is used by Vărzaru and Bocean (2023) to confirm the existence of a relationship between them.

In the same study, hypothesis 1 (*H1*), which states that economic and environmental indicators and forest resources have a significant positive relationship, is put forward and confirmed. The partial least squares method was used to estimate the specific derivative and total effects of the relationships between the level of forest cover, greenhouse gas emission intensity, GDP production per person, and the Sustainable Development Goals index. This relationship was confirmed not for sustainable clusters of countries but for the EU countries as a whole.

This current study sought to determine regression relationships between the level of forest cover of the countries' territory and indicators of socio-economic development. The same characteristics were chosen – forest area (ha per capita, SF_i) and production of gross domestic product (USD per capita in comparable prices in 2010). Individual countries are considered as points in n-dimensional space, two dimensions of which are known (forest cover and GDP). On the plane with coordinates from these two dimensions, they are placed with a certain grouping in order to determine the regularity of their mutual location. However, the statistical sample for these indicators is also incomplete, as regression analysis and the formation of dependence on dynamic series for individual countries did not have a sufficient level of reliability. Therefore, the grouping of European countries by indicators and using k-means clustering was carried out. The logic of using clustering was as follows: if stable clusters of countries are formed in different years, it is likely that there are similar dependencies within each stable cluster. Clustering was performed for the years 2000, 2010, 2015, and 2020. The clustering resulted in one sustainable base cluster, which included Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Liechtenstein, Lithuania, Luxembourg, Malta, the Netherlands, North Macedonia, Poland, Portugal, Moldova, Romania, Serbia, Slovakia, Slovenia, Spain, Switzerland, Ukraine, and the United Kingdom. The composition of this cluster was constant for each of the periods studied, which demonstrates its sustainable nature. Also constant were the clusters:

- 2 – Belarus, Estonia, Latvia, Montenegro, Estonia;
- 3 – Finland;
- 4 – Norway;
- 5 – Sweden.

The centers of the clusters changed from period to period, but their composition remained unchanged.

Further, regression analysis was performed to identify the dependence $GDP(SF_i)$ within the base cluster. The initial hypotheses concerning the linear, polynomial (from the second to the sixth order), and exponential nature of the dependence were refuted. However, it was possible to confirm the linear-periodic character of the dependence GDP from SF_i for each observed period. In order to form a linear-periodic dependence, the indicator of forest cover SF_i (i – count of the country within the cluster) was transformed into SF_r (r – radian measure of the level of forest cover for individual countries within the cluster), and dependencies were formed $GDP(SF_i, SF_r)$ for each of the studied periods. The dependencies $GDP(SF_i, SF_r)$ have the form

$$\begin{aligned} GDP\left(SF_i, SF_r\right) &= a_0 + a_1 \cdot SF_i \\ &+ a_2 \cos(SF_r) + a_3 \cdot \sin(SF_r) \\ &+ a_4 \cdot \cos(2 \cdot SF_r) + a_5 \cdot \sin(2 \cdot SF_r), \end{aligned} \tag{1}$$

where a_0, a_1 is obtained as a result of regression analysis for linear dependence, a a_2, a_3, a_4, a_5 – are the result $GDP(SF_r)$ of Fourier series decomposition of the second order. Together the dependencies $GDP(SF_i, SF_r)$ can be visualized as curves existing in space with coordinates GDP, SF_i, SF_r. For each of the periods under study the range of SF_r equal turned out 2π to be different.

Thus, according to the data of 2000, the form of dependence T $GDP(SF_i, SF_r)$ was as follows:

$$\begin{aligned} GDP\left(SF_i, SF_r\right) &= 37,360 - 37,010.4 \cdot SF_i \\ &-1,111.8 \cdot \cos(SF_r) + 33,239.3 \cdot \sin(SF_r) \\ &-16,205.4 \cdot \cos(2 \cdot SF_r) \\ &+6,071.7 \cdot \sin(2 \cdot SF_r), \end{aligned} \tag{2}$$

with the reliability of approximation by one-factor analysis of variance of 0.906, the range for SF_r in $2\pi \in [0.000928; 0.81353]$.

In 2010, the dependence $GDP(SF_i, SF_r)$ had the following form

$$\begin{aligned} GDP\left(SF_i, SF_r\right) &= 42,960.78 \\ &-39,020.1 \cdot SF_i - 24,248.5 \cdot \cos(SF_r) \\ &+7,183.2 \cdot \sin(SF_r) - 15,490.77 \cdot \cos(2 \cdot SF_r) \\ &+10,024.71 \cdot \sin(2 \cdot SF_r), \end{aligned} \tag{3}$$

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with approximation reliability of 0.9398, range for SF_r in $2\pi \in [0.000883; 0.62428]$.

In 2015 –

$$GDP(SF_i, SF_r) = 46,051.5 - 43,405.9 \cdot SF_i - 26,042.6 \cdot \cos(SF_r) + 4,851.18 \cdot \sin(SF_r) + 118,520.83 \cdot \cos(2 \cdot SF_r) + 6,283.45 \cdot \sin(2 \cdot SF_r), \tag{4}$$

range for SF_r in $2\pi \in [0.000774; 0.811413]$, reliability of approximation 0.90555.

In 2020, the confidence of approximation decreases significantly (0.8009) with the range for SF_r in $2\pi \in [0.000831; 0.762311]$ for the function

$$GDP(SF_i, SF_r) = 41,340.22 - 31,709.2 \cdot SF_i - 18,765.1 \cdot \cos(SF_r) + 14,331.2 \cdot \sin(SF_r) + 14876 \cdot \cos(2 \cdot SF_r) - 4,518.53 \cdot \sin(2 \cdot SF_r). \tag{5}$$

The analysis of the above dependences $GDP(SF_i, SF_r)$ suggests that their parameters are related to the range boundaries SF_r for 2π, to the characteristics of the space $\{SF_i, SF_r, GDP\}$. In particular, the change of slope angles for the second order of Fourier series was observed for the minimum value of the lower range boundary SF_r for 2π and the maximum value of the upper range boundary. It can be assumed that transforming the space $\{SF_i, SF_r, GDP\}$ in such a way that range alignment is observed SF_r will yield one form of the pattern $GDP(SF_i, SF_r)$.

Such studies are only possible if more detailed statistics exist. In any case, within a homogeneous basic cluster of European countries, typical patterns of relationships between the level of forest cover and the production of gross domestic product were observed. Taking into account the form of dependencies, such regularities have a recurrent character; if more detailed data are obtained over a wider period of time, it is possible to reveal the fractal-like nature of the relationship. The hypothesis of fractal-like relationship also follows from the results of Ewers (2006), who notes the influence of economic growth on the level of forest cover. Together, the results of this study and the study by Ewers (2006) can characterize the relationship between GDP as cyclical, recurrent, and fractal-like.

One of the results of the study by Ewers (2006) is the relationship between a country's level of economic development and deforestation or afforestation rates. Poor countries are more likely to be deforested because the economic use of forests is a significant source of GDP growth. Agro-industrial production also has limited growth potential, depending on the level of national economic development (Dobrovolska, 2023). It is possible to ensure the progressive development of agricultural production through the use of innovative methods of farming. The same applies to forest management.

The dynamics of Ukraine's forest cover, in combination with the dynamics of gross domestic product production, confirms the above thesis. Ukraine is a typical representative of Eastern European countries and, simultaneously, a unique object of study. According to Timber Trade Portal (n.d.), Ukraine has about 9.7 million ha of forested land, which is 16.7% of the total land area. Only 60 thousand ha (0.6%) are primary forests, 4.7 (49%) million ha of naturally regenerated forests, and more than 50%, 4.9 million ha are planted forests (Dobrovolska, 2023). Forest resources of Ukraine territorially have a high level of specificity; their quality (parameters of wood density and bark density) depends on species composition and biometrics, which also determines the level of fire danger (Sytnyk et al., 2018).

The test of hypotheses (linear, polynomial – up to the sixth order, exponential, indicative, linear-periodic) of the relationship between the volume of GDP production (both in the economy as a whole and in particular in forestry) taking into account the time lag of up to six years demonstrated its absence. The maximum reliability of the approximation was 0.36. The period under study was 23 years – 2000–2023. Since the level of GDP production in Ukraine is one of the lowest in Europe, the obtained result is quite consistent with the results of Ewers (2006).

Since 2014, there have been war actions on the territory of the country, which has led to a significant increase in forest damage. For the period 2000–2013, the average annual forest area damaged by fire was 3,902.42 ha. For the period 2014–2021, the average annual volume of damaged forest areas due to fires increased by 263% to 14,193 ha. Full-scale military operations in 2022–2023 resulted in an even greater loss of Ukraine's forests, with the average annual volume of damaged areas totaling 33,400 ha. Almost all forests of Donetsk and Luhansk regions, a significant part of forests of Kharkiv, Zaporizhzhia, and Sumy regions, a significant amount of forest areas of Chernihiv, Kyiv, and Zhytomyr regions were destroyed (Derzhstat, n.d.). The level of forest cover in the country's territory has significantly decreased. However, the lack of correlation between the forest area and the production of gross domestic product, determined for previous periods, does not allow one to fully assess the losses of the economy from the reduction of the country's forest areas as a result of the destructive effects of the war. In addition, there is a need to accurately assess the damage and losses of forests due to warfare.

4. DISCUSSION

Forest resources, as a kind of biological resource, are extremely variable. In addition to economic utilization, their volume is influenced by various natural and climatic factors, as well as damage caused by man-made or natural destruction. Unfortunately, no studies separately determine the influence of individual factors (or groups of factors) on the area and level of forest cover of territories. Such studies are extremely difficult to carry out due to the lack of detailed data on the level of forest cover of territories. For the absolute majority of countries in the world, statistics on the level of forest cover have been provided since 2000 (22 data points); generalized climate indicators are not detailed or are not provided for all countries. The scientific literature also notes insufficient statistical data on the volume of forest resources, their damageability, the resulting economic effect of utilization, the relationship with economic parameters, etc. (Hao et al., 2019; Caravaggio, 2020).

Thus, the influence of natural and climatic factors on the level of forest cover in countries is rather difficult to isolate. Forest damage due to economic utilization is also not separately identified. Forest damage due to the impact of man-made or natural destructions can only be assessed by determining the area of fires. However, even here, three problematic aspects arise:

- accurate estimation of the area of forest fires, which can only be achieved by means of aerial photography;
- estimation of economic losses from forest damage caused by man-made or natural destructions;
- escalation of losses from forest fires.

Vishnu and Katti (2023) note escalation of wildfire losses, although it does not have a cumulative character. However, the identified trend is quite threatening.

The assessment of damage from forest damage due to the action of man-made or natural destruction should include the following aspects: assessment of the loss of national wealth; assessment of the loss of economic benefit from the deterioration of the effect of the influence of forest resources on the production of GDP; assessment of the costs of forest resource restoration in fire-damaged areas. Using the sequence of this study, it is possible to determine only the loss of economic benefit from the worsening effect of forest resources on GDP production. Two more significant tasks arise – to create methodological approaches to determining the loss of national wealth due to forest resource damage with possible consideration of natural and climatic features of countries and methodological approaches to estimating the costs of restoration of damaged forest resources. Again, in fulfilling these tasks, there is an urgent need to accurately determine the area of damaged forests. Thus, a prerequisite for the economic assessment of any losses from forest fires is the accurate determination of their area.

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CONCLUSION

Modern research on the use of forest resources and their impact on social production has a different orientation. A significant part of them uses the forestry approach, linking the structure of forest resources, their volume, approaches in utilization with the efficiency of forestry, the efficiency of the national economy of countries as a whole, changes in ecological parameters of the environment, etc. Usually, within individual national economies or national territories, a certain direct correlation between the volume of forest resources and positive indicators of socio-economic development is determined. Or otherwise – an inverse relationship between forest damage and indicators of socio-economic development. This study focused on identifying/refuting such a relationship for supranational entities – Europe as a whole and its individual regions. The increase in the usual scale of the study is due to the fact that specific relationships between the level of forest cover or/and forest damage and the efficiency of social production are formed on a larger scale of territories than the territory of a single country.

The results indicate that Europe as a whole is characterized by an increasing level of forest cover. The current trends in the share of forests in the total area of a country and in the area of forests per inhabitant are determined with a high level of confidence for all regions of Europe and are predominantly positive. The exception is the Nordic countries, for which the potential for growth of forest cover is limited. The formal description of the relationship between the indicators of the level of forest cover and the production of gross domestic product per capita for some European countries (Denmark, Norway, Finland, and France) confirmed its parabolic nature. In the vast majority of cases, it was possible to determine the optimal level of forest cover at which the production of GDP will be maximized. However, the established dependencies are not functional because time lags were not used in their determination, and the causal character could not be confirmed.

The comparative analysis of forest damage caused by wildfires in European countries showed three groups of forests according to their vulnerability: safe, conditionally safe, and dangerous. The main factors determining the level of safety of the country's territory were natural-climatic factors and a high standard of living. This gave grounds to conclude that there may be an inverse relationship between the indicators of economic development and the level of forest cover of the territory.

The application of cluster analysis and further formalization of the relationship between the forest area per capita and GDP production per capita for European countries confirmed the existence of the repeatability of the relationship over limited intervals of the forest cover indicator. The general direction of the pattern of GDP production depending on the forest cover indicator is negative, and the range of periodic fluctuations in the studied time interval (2000–2020) increases. This suggests that the relationship between the level of forest cover of the territory and the efficiency of social production is recurrent and, most likely, fractal-like.

Thus, the results establish a close relationship between the forest cover indicators of most European countries (34 countries out of 41 analyzed) and the production of GDP per capita but deny a direct or inverse functional relationship between them. In addition, forest damage caused by fires will not have a direct functional impact on the efficiency of social production.

At the same time, the obtained results reveal two most promising directions for further research. The first is forecasting the dynamics of forest growth and forest damageability in relationship with changes in climate, other natural factors, and the efficiency of social production. Such models are likely to have a network character. The second is testing the hypothesis of fractal-like dependence of social production efficiency on indicators of forest cover and/or forest damage.

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