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Sustainable forestry and energy production from biomass: Ecological aspects and dynamics of forest ecosystems

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Abstract. The energy use of forest biomass is an important component of modern bioeconomics, which affects the dynamics of forest cover, the balance of greenhouse gases, and the ecological sustainability of forest ecosystems in regions with active harvesting of wood raw materials. The purpose of the study was to assess the environmental impact of using forest biomass in energy, identifying changes in forest cover, and analysing CO_2 emissions compared to fossil energy sources. A combination of theoretical analysis of literature sources and empirical analysis of Sentinel-2 and Landsat satellite data (2015-2024) was used. A comparative analysis of changes in forest cover is performed using Normalised Difference Vegetation Index and normalised burning ratio indices. CO_2 emissions were calculated based on Intergovernmental Panel on Climate Change emission factors for biomass, coal, and natural gas. In the regions of active biomass use (Amazon, Southeast Asia), forest cover is reduced by 0.8-1.5% annually, while in countries with developed forest policies (Canada, Finland), forest areas remain stable. CO_2 emissions from biomass (112 kg/GJ) are higher than natural gas (56 kg/GJ) but lower than coal emissions (97.5 kg/GJ). Assessment of the relationship between forest ecosystems and climatic factors showed that a reduction in forest cover leads to a loss of water retention capacity (up to 20%) and an increase in soil erosion by 3-4 times. The results of the study confirmed the need to introduce environmentally responsible approaches to Forest Resource Management. The use of

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close-to-nature forestry methods, the development of satellite monitoring, and the introduction of certification standards can contribute to maintaining ecosystem balance

Keywords: satellite monitoring; deforestation; carbon balance; greenhouse gases; climate change; anthropogenic impact

Introduction

Sustainable forest development is one of the key areas of environmental and economic policy in the modern world aimed at supporting the ecosystem functions of forests and the rational use of their resources. Forest ecosystems perform critical functions, including preserving biodiversity, regulating carbon balance and climate processes, maintaining water regimes, preventing soil erosion, and providing material resources for society. However, in the face of increasing anthropogenic stress, climate change and increased demand for renewable energy sources, there is a need to develop effective approaches to forest management that will ensure their rational use without compromising environmental balance.

The use of wood biomass as an energy resource contributes to decarbonising the economy and reducing dependence on fossil fuels but requires compliance with the principles of sustainable forest management. It is important to balance the energy needs and environmental sustainability of forest ecosystems by applying evidence-based approaches to resource base assessment, environmentally sound harvesting methods, and monitoring the long-term effects of bioenergy.

International organisations play an important role in shaping the principles of sustainable forestry and bioenergy development. Food and Agriculture Organization (2024) develops global forest management strategies to reduce forest degradation. European Environment Agency (2024) assesses the impact of forest management on climate and biodiversity by developing recommendations for integrating bioenergy into sustainable development strategies. The UN-sponsored REDD+ programme helps reduce greenhouse gas emissions through forest protection and sustainable use. These initiatives provide a framework for the development of forest bioeconomics and decarbonisation.

Research on sustainable forestry and the use of biomass for energy needs is actively conducted in various regions of the world, which indicates a global interest in the development of bioeconomics and ecosystem conservation (Murtezaj *et al.*, 2024). In the Western Balkans, M. Bojović *et al.* (2024) analysed the potential of agroforestry systems for energy development, emphasising the importance of integrated forest management. In Europe, A. Marín *et al.* (2021) investigated the state of forests, assessing their role in maintaining biodiversity and adapting to climate change. Researchers M. Kocoglu *et al.* (2024), in a global study, evaluated the impact of forest ecosystems on carbon balance, and V. Imbrenda *et al.* (2023) reviewed the socio-economic aspects of forestry in Europe. F. Latterini *et al.* (2023) analysed the current state of forest operations in beech forests in Europe and Western Asia, focusing on the impact of timber harvesting and forest management methods. Approaches to the use of biomass vary by region. The EU, Canada, Sweden, Finland, and the United States are actively developing bioeconomics, making comprehensive use of forest resources. In Brazil and Chile, integrated forestry systems are being implemented that combine timber harvesting with forest restoration. In Central and Eastern Europe, attention is paid to balanced forest management to preserve environmental and economic functions (Vasylyshyn *et al.*, 2023). Evaluating the effectiveness of these approaches and their integration into national energy independence strategies is a critical task.

Current research focused on the transition to sustainable bioeconomics, optimal use of forest resources, and assessment of their environmental impact. L. Prendi & A. Murrja (2023) showed that the integration of a "green" economy contributes to economic growth, but its implementation requires effective regulation and substantial investment in the sustainable management of natural resources. Researchers O. Hoda & G. Angjeli (2023) investigated the dynamics of Environmental growth and established that the successful implementation of bioenergy programmes largely depends on government support and compliance with international standards. Analysis performed by Z. Nedić *et al.* (2024) demonstrated that the transition to circular bioeconomics is possible only if economic incentives are created for enterprises that use low-carbon technologies in the forest and energy sectors. In turn, P. Anttila & H. Verkerk (2022) considered the factors that determine the availability of forest biomass for energy needs, establishing a relationship between the level of harvesting, environmental conditions, and long-term resource sustainability. Authors U. Vilhar *et al.* (2022) analysed the consequences of large-scale forest disturbances, noting that such changes substantially affect hydrological processes, in particular, the balance of karst waters, which can lead to ecosystem degradation.

Despite substantial progress in the examination of bioenergy, the long-term environmental impact of the use of forest biomass, in particular, its role in regulating the carbon balance and changes in forest ecosystems in various climatic conditions, remains insufficiently investigated. The lack of integrated approaches combining satellite monitoring, emission modelling, and sustainable forest management strategies necessitates further scientific development. The aim of the study was to assess the environmental impact of biomass use on energy needs in the context of sustainable forestry, to determine its impact on the dynamics of forest ecosystems, and to analyse changes in forest cover and CO_2 emissions from burning forest biomass. The following tasks were solved to achieve this goal: analyse the principles of sustainable forest resources management and their importance for the conservation of biodiversity and ecosystem services; assess the efficiency of using forest biomass as an energy source based on the analysis of changes in forest cover from satellite images in regions with active use of biomass; calculate the level of CO_2 emissions from burning forest biomass compared to fossil energy sources, which allowed determining the main factors of environmental sustainability of forest bioenergy systems.

Materials and Methods

The research methodology combined theoretical and empirical approaches for a comprehensive analysis of sustainable forestry and the use of biomass in the energy sector. The theoretical part included an analysis of scientific literature and reports of international organisations devoted to forest resource management, bioeconomics, and the environmental impact of biomass use. Special attention was paid to research on the principles of sustainable forest management, the impact of biomass on greenhouse gas balance, and the role of forest ecosystems in maintaining climate balance (Sorge *et al.*, 2022; Favero *et al.*, 2023; Raihan, 2023a). The object of the study was natural and artificially created forest ecosystems used for bioenergy, in particular, boreal, temperate, and mixed forests. The subject of the study is the ecological aspects of the use of biomass for energy needs and their impact on the sustainability of forest ecosystems.

The geographical focus covered regions with active biomass use, in particular, countries of Northern Europe (Sweden, Finland), as well as Canada and the United States, which have substantial forest resources and are actively developing bioenergy. Countries of the Balkan region, in particular, Albania, where harvesting of wood biomass is an important sector of the economy, were also considered. In addition, the study includes regions of Southeast Asia, Central Africa, and the Amazon, as they experience substantial changes in forest cover due to the use of biomass as the main source of energy and the active transformation of natural forests into agricultural land. The choice of territories was driven by their leading role in the development of bioeconomics, the scale of wood biomass harvesting, and the environmental challenges associated with its use, including deforestation of ancient forests, changes in the natural landscape, and carbon emissions from wood processing.

The study was based on the combined use of quantitative and qualitative analysis methods to assess changes in forest cover, the impact of biomass harvesting on forest ecosystems, and greenhouse gas emissions. Iatellite images obtained from the Sentinel-2 missions conducted by the European Space Agency (France) and Landsat-8/9, which are managed by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration (USA), were used to analyse changes in forest cover. The analysis was conducted for the period 2015-2024, which allowed assessing long-term trends in changes in the area of forests used for biomass harvesting and the impact of anthropogenic stress. The images were selected seasonally to avoid the impact of snow cover and ensure the accuracy of calculations. A comparative analysis was performed between the reference years 2015, 2018, 2021, and 2024 to determine the dynamics of changes in forest ecosystems. Satellite images were processed using geoinformation systems ArcGIS (Esri, USA) and Google Earth Engine (Google, USA), which identified changes in forest cover in regions of active biomass harvesting. The use of the Normalised Difference Vegetation Index provided for the estimation of the density of vegetation cover, while the normalised burning ratio was used to determine degraded areas.

The comparative analysis method was used to assess the impact of biomass use on greenhouse gas emissions. CO_2 emissions from burning forest biomass were calculated compared to fossil energy sources such as coal and natural gas. Data for calculations were obtained from open environmental monitoring databases, in particular, the European Environment Agency (2024), Intergovernmental Panel on Climate Change Emission Factors Database (Greenhouse Gas Protocol, n.d.), reports of the International Energy Agency (n.d.). Carbon dioxide emissions were calculated using the formula (1):

$$E = A \times EF, \tag{1}$$

where E – total CO_2 emissions (tonnes); A – amount of biomass or fossil fuel burned (GJ); EF – emission factor (kg CO_2/GJ), depending on the fuel type. The values of the emission coefficients were taken from the Intergovernmental Panel on Climate Change (2022) database: for wood biomass – 112 kg CO_2/GJ, for coal – 94-101 kg CO_2/GJ, for natural gas – 56 kg CO_2/GJ.

In addition to estimating CO_2 emissions, the study considered the Life Cycle Assessment of biomass, including harvesting, transportation, and incineration processes. This allowed comprehensively assessing the ecological sustainability of forest bioenergy systems, determining their potential for decarbonisation of the energy sector, and assessing the risks of degradation of forest ecosystems as a result of intensive use of wood biomass.

The study was based on the principles of academic integrity and compliance with ethical standards of scientific activity. The use of satellite data and environmental reports was conducted in accordance with open-source licensing requirements.

Results

Sustainable forestry principles and their role in biodiversity conservation

Sustainable forest development is an integral part of global environmental policy aimed at ensuring the long-term use of forest resources while maintaining their environmental sustainability and biodiversity. The main objective is to harmonise the environmental, economic, and social aspects of forest management, which implies compliance with scientifically based principles of sustainable forest management. These include adaptive forest management, reducing the negative impact of timber harvesting on ecosystems, introducing methods for restoring forest areas, and preserving biodiversity through the introduction of regulatory and certification mechanisms (Raihan, 2023b).

One of the most important principles is to ensure ecosystem balance through environmentally responsible logging. The introduction of selective and Mosaic logging instead of continuous logging reduces habitat loss for rare species of flora and fauna. In the Scandinavian countries, in particular, in Sweden and Finland, the approach of "Close-to-Nature Forestry" has long been used, which involves maintaining the natural composition of forests, using mixed plantings and gradual logging that does not disrupt the ecosystem balance (Favero *et al.*, 2023). This approach is also actively used in Germany, where research has shown its positive impact on biodiversity and maintaining the sustainability of forest ecosystems (Sorge *et al.*, 2022).

Another important aspect of sustainable forest management is certification systems, such as the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification, which define environmental standards for logging companies. In Canada and the United States, more than 80% of industrial forests are subject to these standards, which allows controlling the level of deforestation and restoration of forest areas. In developing countries, in particular, in Latin America and Southeast Asia, certification is less widespread, which creates risks for forest ecosystem services and contributes to illegal logging (Huettmann & Young, 2022).

Biodiversity conservation also depends on measures to restore degraded forest areas. In the countries of the European Union, reforestation programmes are being implemented aimed at restoring natural tree species and the ecosystem functions of forests. For example, the EU Biodiversity Strategy 2030 initiative provides for increasing the area of protected forests and restoring disturbed ecosystems (European Commission, n.d.). Similar programmes are being implemented in the United States and Canada, where government support is aimed at the afforestation of territories after forest fires and anthropogenic deforestation (Favero *et al.*, 2020).

Modern satellite monitoring methods and geographic information systems are widely used for effective forest management. Satellite images Sentinel-2 and Landsat-8/9 are used to analyse changes in forest cover and assess the level of forest degradation as a result of biomass harvesting. Analysis of satellite data for the period 2015-2024 indicates substantial loss of forest cover in areas of intensive forest management, especially in the rainforests of Southeast Asia and the Amazon, where deforestation has a substantial impact on the global balance of CO_2 emissions. Additionally, the geoinformation systems ArcGIS (Esri, USA) and Google Earth Engine are used to identify long-term trends in forest cover changes, assess the level of recovery, and form recommendations for sustainable forest management policies.

Sustainable forest development is based on the introduction of environmentally responsible forest management approaches that consider biodiversity conservation, ecosystem services support, and biomass management (Table 1).

Table 1. Basic principles of sustainable forestry and their implementation in different regions of the world

Principle	Description	Implementation example
Biodiversity conservation	Restriction of deforestation in natural forests, creation of nature protection zones	Forest Stewardship Council certification in Canada, USA
Restoration of forest ecosystems	Afforestation programmes, support for natural renewal	EU Biodiversity Strategy 2030
Close-to-nature Forestry	Use of mixed plantings, selective logging, forest structure regulation	Forestry practices in Finland, Sweden, Germany
Monitoring by satellite systems	Analysis of changes in forest cover and assessment of degradation	Sentinel-2, Landsat-8/9

Source: compiled by the authors based on analysis of the data A. Favero *et al*. (2020; 2023), S. Sorge *et al*. (2022)

These tables show substantial variability in approaches to implementing the principles of sustainable forestry in different regions of the world. Differences in environmental conditions, economic opportunities, and legal requirements affect the nature of forest management strategies. For example, countries with developed environmental regulation systems are more effective in implementing certification systems and satellite monitoring, while regions with high anthropogenic pressure are dominated by measures to restore forest ecosystems. An important factor is the adaptation of close-to-nature forestry methods to local conditions, which allows for a balance between economic benefits and environmental sustainability. The use of technological solutions, such as satellite monitoring, contributes to more accurate monitoring of forest conditions, but its effectiveness depends on political will and institutional support at the national level (Moroz, 2024).

Applying the principles of sustainable forestry is a critical tool for preserving biodiversity and ensuring the long-term ecological sustainability of forest ecosystems. Regional differences in the implementation of these principles indicate the need to adapt management methods to local conditions, considering economic, climatic, and social factors. The integration of modern technologies, such as satellite monitoring and certification systems, allows effectively assessing the state of forests and optimise their use. An integrated approach to forest management, combining environmental, economic, and social aspects, is a prerequisite for achieving sustainable forest sector development.

Use of biomass for energy production and efficient forest management

Forest biomass is an important component of renewable energy, helping to reduce dependence on fossil fuels and providing opportunities for decarbonisation of the energy sector. The use of wood biomass for energy production includes burning wood residues, processing wood into pellets, and producing synthetic fuels. However, the effectiveness of bioenergy largely depends on regional approaches to forest management, in particular, the level of forest regeneration, environmental monitoring, and sustainable forest management policies (Golub *et al.*, 2017).

Estimating CO_2 emissions from biomass use is a critical factor when comparing it with traditional energy sources. Despite the fact that wood is considered a carbon-neutral fuel, the processes of its harvesting, transportation, and incineration are accompanied by greenhouse gas emissions. According to the Intergovernmental Panel on Climate Change (2022) database, the average level of CO_2 emissions from burning wood biomass is 112 kg of CO_2/GJ, which is higher than that of natural gas (56 kg of CO_2/GJ) but lower than that of coal (94-101 kg of CO_2/GJ). Formula (1) was used to estimate carbon emissions in forest bioenergy systems, which accounts for the level of energy consumption and the corresponding Intergovernmental Panel on Climate Change coefficients (Fig. 1).

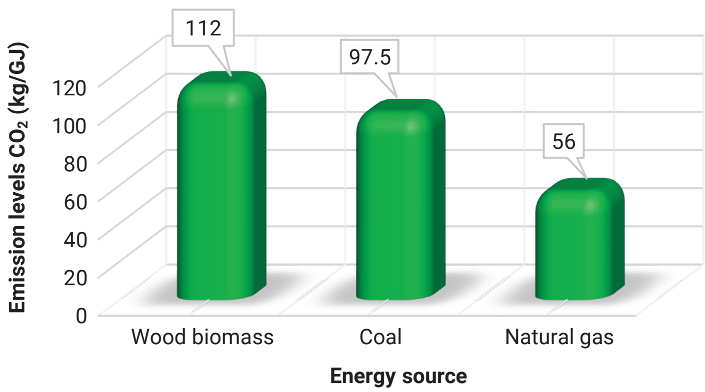

Figure 1. Comparison of CO_2 emissions from different energy sources (kg CO_2/GJ)
Source: compiled by the authors based on analysis of the Intergovernmental Panel on Climate Change (2022)

The comparison results show that the use of wood biomass for energy production has both advantages and limitations. The main argument in favour of biomass is its potential carbon neutrality since trees absorb CO_2 during growth, compensating for emissions from combustion. However, this effect is achieved only if the principles of sustainable forest management are observed and the balance between harvesting and forest regeneration is maintained.

Studies show that the efficiency of biomass as an energy source is highly dependent on regional conditions. For example, in the Scandinavian countries and Canada, effective forest resource management models have been implemented, which allows maintaining a balance between biomass harvesting and natural forest restoration. In countries with less developed environmental regulatory systems, intensive use of wood biomass can lead to loss of forest cover and reduced ecosystem functions. Additional analysis allowed assessing the potential sustainability of bioenergy systems compared to other fuels and comparing key indicators of biomass efficiency compared to other energy sources (Table 2).

Table 2. Comparative analysis of the efficiency of using biomass and other fuels

Indicator	Biomass	Coal	Natural gas	Solar energy
CO_2 emissions (kg/GJ)	112	97.5	56	0
Energy efficiency ratio (%)	35-45	33-38	45-50	18-22
Resource availability	Renewable	Limited	Limited	Unlimited
Environmental impact	Affects forests	High impact	Moderate impact	Minimal impact

Source: compared by the authors based on the analysis of data from European Environment Agency (2024), Intergovernmental Panel on Climate Change (2022), International Energy Agency (n.d.)

Analysis of the efficiency of using biomass for energy production has shown that it can be an alternative to fossil fuels, but its sustainability depends on compliance with environmental principles. CO_2 emissions from biomass remain higher than those of natural gas but lower than those of coal. Therewith, the life cycle of biomass considers forest regeneration, which potentially reduces its environmental impact. Regional approaches to the use of biomass play a crucial role in its efficiency. Countries with developed forest policies perform substantially better in balancing the use of biomass and ecosystem conservation. Technological development is also an important factor: the combined use of biomass and solar energy can ensure a stable supply of renewable energy with minimal impact on the environment.

The use of wood biomass as an energy source is an important area of renewable energy development, but its effectiveness largely depends on the rational management of forest resources. The results of the study show that a balanced approach to the harvesting and use of biomass can help reduce greenhouse gas emissions and, at the same time, prevent the depletion of forest ecosystems. Innovative methods for monitoring forest cover, regulating wood harvesting, and introducing environmentally friendly biomass processing technologies are instrumental in this process. Optimising these processes will reduce environmental risks and improve the efficiency of the bioenergy sector in the context of global decarbonisation.

Dynamics of changes in forest cover and its environmental consequences

Changes in forest cover reflect the balance between the processes of restoration and degradation of forest ecosystems, determining their resistance to anthropogenic and natural factors. The assessment of changes in forest area was based on an analysis of Sentinel-2 and Landsat-8/9 satellite images over four reference years: 2015, 2018, 2021, and 2024. The use of satellite data allowed analysing long-term changes in forest areas in regions of active biomass harvesting and identifying areas with an increased risk of degradation.

In the period 2015-2024, a gradual reduction in Woodlands was recorded, which is confirmed by the analysis of the Normalised Difference Vegetation Index and the normalised burning ratio. The greatest loss of forest cover was observed in tropical regions, where Normalised Difference Vegetation Index levels were 18% lower in 2024 compared to 2015, indicating intense ecosystem degradation. Thereby, in temperate latitudes, the reduction in forest area during this period ranged from 6% to 10%, depending on the level of wood biomass harvesting and the implementation of forest restoration policies. Data for individual reference years reveal a gradual increase in the intensity of logging. In 2018, forest area losses compared to 2015 amounted to 3.4%, while in 2021, this figure reached 7.8%. The latest analysis for 2024 confirmed further forest declines, especially in regions with high levels of industrial forest use, such as the Amazon, Central Africa, and Southeast Asia.

A comparison of changes in the normalised burning ratio index shows an increase in the number of degraded forest plots. If in 2015 this indicator was stable, then in 2018 it grew by 5%, in 2021 – by 9%, and in 2024 – by 13%. This confirms an increase in deforestation, forest fires, and other processes that contribute to ecosystem destruction. Forest areas bordering agricultural land and areas with a high level of urbanisation were particularly vulnerable. In the Amazon basin, active deforestation leads to a decrease in humidity levels and an increase in the frequency of fires, which further accelerates the degradation processes (Raj *et al.*, 2023). In Indonesia and Malaysia, the deforestation of tropical forests is associated with the expansion of oil palm plantations, which leads to the loss of unique biotopes and negatively affects local ecosystems (Farooq *et al.*, 2022). In Europe, forest degradation is most intensively observed in the Carpathians, where the reduction of continuous forest areas threatens biodiversity and ecosystem functioning (Fatima *et al.*, 2024).

Analysis of satellite images and geoinformation systems ArcGIS, Google Earth Engine also allowed evaluating the effectiveness of forest conservation and restoration measures. The data show that regions where active reforestation programmes are being implemented demonstrate stabilisation or even a slight increase in forest cover. For example, in Northern Europe and Canada, forest areas in 2024 remained virtually unchanged compared to 2015, which is due to the introduction of strategies for close-to-nature forestry and control over logging activities (Salam, 2024). Such technologies provide a comprehensive approach to the analysis of ecosystem changes and help model scenarios for further forest development under the influence of climate change and anthropogenic factors (Fig. 2).

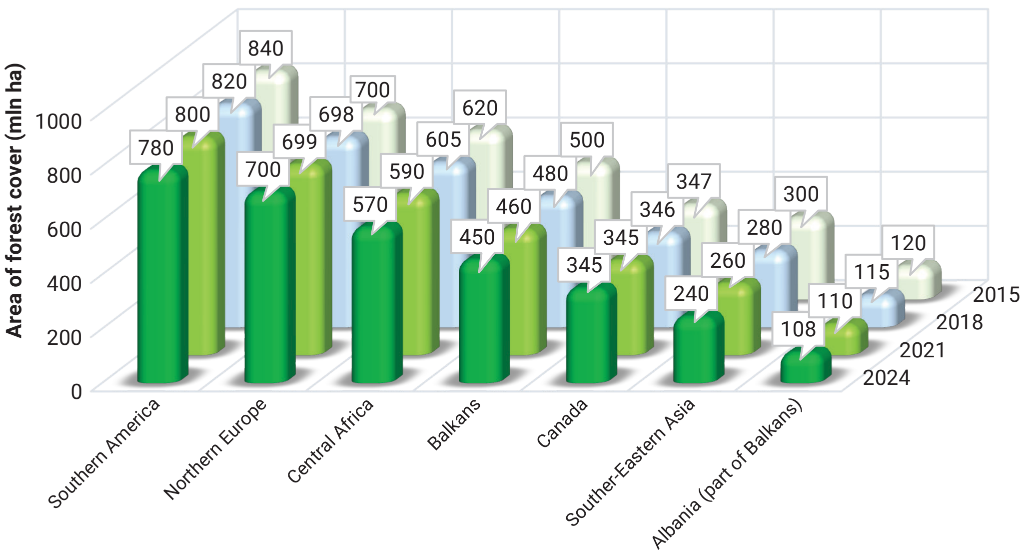

Figure 2. Changes in forest cover in selected regions (2015-2024)
Source: compared by the authors

The graph presents substantial regional differences in forest cover changes over the period 2015-2024, reflecting different levels of Environmental Management and approaches to sustainable forest management. In Northern Europe and Canada, forest areas remained stable due to the introduction of nature conservation and logging controls. Thereby, a substantial reduction in forest cover in the regions of Southeast Asia indicates the intensive exploitation of forest resources for agriculture and energy, which has serious environmental consequences. The Balkans are experiencing a gradual reduction in forest cover due to timber harvesting and the expansion of agricultural land (Bragina *et al.*, 2018). In Albania, as part of the Balkan region, forest cover is also decreasing, which may be due to illegal logging and increased use of wood for energy purposes, despite the implementation of forest restoration programmes (Shumka *et al.*, 2021).

The identified trends highlight the importance of strengthening international cooperation in the field of forest conservation and introducing stricter regulatory mechanisms for controlling logging. In addition, the results obtained confirm the need to develop adaptive forest ecosystem management strategies that consider both environmental and socio-economic factors.

Interaction of forest ecosystems with other natural processes and ecological balance

Forest ecosystems are important regulators of global ecological processes, in particular, the carbon cycle, hydrological balance, and soil cover stability, ensuring the resilience of the biosphere to external changes. One of the main functions of forests is the accumulation and conservation of carbon, which is conducted through the processes of photosynthesis, the accumulation of organic matter, and carbon deposition in the soil. Forests absorb about 2.6 billion tonnes of CO_2 annually, which is equivalent to 30% of anthropogenic greenhouse gas emissions (Ibrahim & Lukman, 2022). The largest carbon reserves are found in the Amazon, Congo, and Indonesia rainforests, but their destruction due to logging and land-use changes leads to CO_2 emissions because of the mineralisation of organic matter (Bălan *et al.*, 2021).

In addition to regulating carbon balance, forests play a fundamental role in water conservation. They retain moisture, regulate the amount and quality of water in catchment areas, affect groundwater levels, and prevent the degradation of aquatic ecosystems. Changes in forest cover can lead to changes in hydrological cycles, which is confirmed by studies on the relationship between forest ecosystems and water resources in Europe, North America, and Asia. Deforestation in mountainous areas leads to an increase in erosion processes, which in turn worsens water quality and reduces its natural filtration potential (Anderson-Teixeira *et al.*, 2013; Dunlap & Schramski, 2024).

Another important ecological process that depends on the state of forests is the protection of soil from erosion. The root system of trees prevents soil erosion, reduces the risk of landslides, and preserves land fertility. In countries with a high level of erosion hazard, in particular, in southern Europe, afforestation programmes are used to stabilise soils and reduce the negative effects of water and wind erosion (Wani & Sahoo, 2021). The impact of forest ecosystems on soil conservation is particularly important in agricultural regions, where land degradation can lead to reduced yields and the deterioration of agricultural landscapes (Melo *et al.*, 2021).

Climate change has a substantial impact on the stability of forest ecosystems, increasing the risks of pest spread, the frequency of fires, and changes in species composition. According to forecasts, an increase in average annual temperatures and changes in precipitation can affect the stability of forests in the middle and northern latitudes, causing a decrease in forest productivity and loss of biodiversity (Baciu *et al.*, 2021; Grebner *et al.*, 2021). It is necessary to introduce approaches to nature forestry, increase the diversity of tree species, and develop strategies for adapting to extreme weather conditions to adapt forest ecosystems to climate change. The interaction of forests with natural processes forms mechanisms of ecological stability that affect CO_2 emissions, hydrological cycles, and soil stability (Table 3).

Table 3. Relationship between forest ecosystems, carbon balance, water regime and erosion processes in different regions of the world

Region	Biomass carbon Reserve (MT/ha)	Water retention capacity of forests (mm/year)	Soil erosion rate (t/ha/year)
Amazon	230	850	0.5
Northern Europe	150	780	2.1
Central Africa	220	810	0.5
East Asia	170	690	3.5
Southeast Asia	190	720	2.9
Canada	180	760	1.8
United States (continental)	160	700	2.6
Australia	140	670	3.9

Source: compiled by the authors based on analysis of the data E.M. Bălan *et al*. (2021), A. Ibrahim & A.H. Lukman (2022)

These tables present substantial regional differences in the ability of forest ecosystems to maintain carbon balance, regulate water regimes, and prevent soil erosion. High water retention capacity and carbon storage are characteristic of rainforests, which ensures their important role in global climate processes. However, in regions with active anthropogenic impact, in particular, in areas of intensive forest management, there is increased soil erosion, which can negatively affect the productivity of ecosystems and the sustainability of local water resources. The identified patterns highlight the importance of adaptive forest management strategies aimed at minimising degradation processes and maintaining the stability of natural systems.

The results confirm that forest ecosystems are an important regulator of natural processes, ensuring carbon balance, water stability, and soil protection from erosion. Analysis of regional features shows that the effectiveness of these functions depends on climatic conditions, the type of forest, and the level of anthropogenic impact, which highlights the need for an adaptive approach to forest management. Implementing sustainable forest management strategies can help strengthen ecosystem balance, minimise the negative impact of climate change, and preserve critical ecosystem services.

Recommendations for optimising the use of forest biomass in the context of climate change

The use of forest biomass as a renewable energy source plays an important role in the global decarbonisation strategy, but the effectiveness of its application largely depends on forest management methods. In the face of climate change, it is necessary to introduce integrated approaches to biomass harvesting that will contribute to the conservation of biodiversity and ecological sustainability of forest ecosystems. It is proved that sustainable development of the forest sector is possible only if ecosystem approaches to forest management are integrated, including adaptation to extreme climatic phenomena, improving resource efficiency, and introducing innovative wood processing technologies (Baciu *et al.*, 2021).

Climate change has a substantial impact on forest ecosystems, causing changes in temperature and precipitation regimes, the spread of pests, an increase in the frequency of fires and forest degradation. Studies show that an increase in the average annual temperature by 1.5-2°C over the next decades can substantially reduce the productivity of forests in the middle and northern latitudes. In addition, climate change affects the carbon balance: reduced forest cover and increased carbon load due to frequent fires can lead to a loss of the natural ability of forests to absorb CO_2 (Table 4).

Table 4. Impact of climate change on forest ecosystems in different regions of the world

Region	Main climate changes	Impact on forests	Possible adaptation measures
Amazon	Reduced precipitation, increased periods of drought	Increased frequency of forest fires, rainforest degradation	Expansion of afforestation programmes, fire control
Northern Europe	Rising temperatures, increasing storms	Increased damage from hurricanes, pest spread	Strengthening selective forestry, monitoring forest health
Central Africa	Increase in the average annual temperature	Reduced tree growth, reduced biomass	Use of drought-resistant species, forest reclamation
East Asia	Uneven precipitation, monsoon changes	Increased risk of soil erosion and flooding of woodlands	Engineering soil protection, flood control
Canada	Reducing the freezing period of soils	Loss of boreal forests, migration of tree species	Transition to more sustainable forest species

Source: compiled by the authors based on analysis of the data D.L. Grebner *et al.* (2021), A. Kumar *et al.* (2022)

These tables indicate substantial variability in the impact of climate change on forest ecosystems depending on the region. In tropical and subtropical forests, rising temperatures and changes in humidity conditions cause biodiversity degradation and increase the risk of forest fires. In temperate climates, the main threats are changes in the structure of forest stands and the spread of pests, while in arid regions such as Australia, there is an increase in the frequency of catastrophic fires.

One of the key areas of adaptation of the forest sector is the introduction of principles of close-to-nature forestry. This includes maintaining mixed plantings, selective logging, and regulating the age structure of woodlands. Such methods can reduce the impact of logging on the environment, improve the restoration of stands, and increase the resistance of forests to droughts, diseases, and pests (Hernández-Morcillo *et al.*, 2022). In addition, it is important to expand the use of agroforestry – the integration of forest ecosystems into agricultural landscapes. This will help increase the sustainability of forest systems, minimise degradation risks, and provide additional sources of biomass without putting excessive strain on natural forests (Raihan, 2023a).

The development of technologies for generating energy from biomass plays an essential role in improving the efficiency of resource use. The use of cogeneration plants, the biochemical processing of wood biomass, and advanced gasification technologies can increase the efficiency of biofuel systems and reduce CO_2 emissions (Tampekis *et al.*, 2024). Another important area is the introduction of certification standards for sustainable forest management, such as Forest Stewardship Council and Programme for the Endorsement of Forest Certification, which guarantee the environmental responsibility of bioenergy companies (Mishra & Agarwal, 2024). This contributes to the transparency of the biomass market and ensures the environmental compliance of production.

Adapting the forest sector to climate change requires an integrated approach, including the introduction of environmentally friendly harvesting methods, the development of monitoring systems, and increased regulation in the field of forest management. It is important to ensure a balance between the energy potential of forest biomass and the preservation of the ecosystem functions of forests. The introduction of modern bioenergy technologies and improved sustainable development policies will help reduce greenhouse gas emissions and supplement the resilience of forest resources to climate change. The implementation of these measures will ensure the long-term stability of the bioenergy sector and contribute to the efficient use of natural resources.

Discussion

The results show substantial variability in approaches to forest management and biomass use, which is confirmed by a comparative analysis with other studies. Comparing the obtained data with the scientific works of international researchers allows identifying general trends and conflicting aspects regarding the environmental sustainability of forest management.

Examination of the efficiency of using biomass for energy needs has shown that its potential largely depends on regional forest management strategies. Similar conclusions were drawn by A. Favero *et al*. (2023), who emphasise the need to integrate bioenergy into the overall decarbonisation policy, nevertheless note that uncontrolled harvesting of wood biomass can lead to negative environmental consequences. The results obtained confirm this statement because the analysis of satellite images indicates a decrease in the area of forest cover in regions of intensive biomass use. A. Favero *et al*. (2020) demonstrate that, despite the reduction of forest areas, their role in carbon sequestration remains substantial if sustainable forest management measures are implemented.

The study confirmed that the effective use of forest biomass as an energy resource directly depends on forest ecosystem management strategies and forest restoration measures. The results prove that regions with clear mechanisms for controlling and regulating logging have a higher level of forest cover conservation, which is consistent with the findings of T. Farooq *et al*. (2022), which established a relationship between the intensity of wood biomass harvesting and the spatial distribution of carbon in forest ecosystems. Similar conclusions were drawn by S. Fatima *et al*. (2024), noting the importance of an integrated approach to agroforestry to ensure the sustainability of the bioenergy sector.

In matters of forest ecosystem management, the results of the analysis partially coincide with the conclusions of S. Sorge *et al*. (2022), emphasising the importance of socio-ecological aspects in forest management. The authors state that the lack of an integrated approach to forest management can lead to a conflict between economic and environmental goals. This study supports this thesis, as the regions with active logging have a higher level of soil erosion and a lower ability of forests to retain moisture. In addition, A. Raihan (2023b) underlines that the sustainability of the forest sector is determined not only by economic incentives but also by policy decisions and the availability of effective environmental programmes.

Regarding the changes in forest cover, the results are consistent with the conclusions made by F. Huettmann & B. Young (2022) that modern approaches to able forestry are not always effective since they allow the depletion of natural forests even in certified regions. This study showed that regions with active implementation of close-to-nature forestry, such as Scandinavia, have shown a stable level of forest cover over the past decade. This confirms the hypothesis put forward by A. Raj *et al*. (2023) that adaptive forest management is a fundamental factor in maintaining their ecological balance.

The assessment of CO_2 emissions from burning forest biomass compared to fossil fuels confirmed that bioenergy can play a positive role in reducing carbon emissions only if the scale of harvesting is strictly controlled and forest resources are effectively managed. This is consistent with the results of A. Salam (2024), stressing the role of digital technologies and remote monitoring tools in optimising the use of woodlands. Similar conclusions are presented in a paper of A. Ibrahim & A. Lukman (2022), which emphasises the need to estimate carbon reserves in biomass to determine its real potential as an energy source. The results of the analysis of the impact of large-scale biomass harvesting on the ecological balance of forest ecosystems showed an increase in the level of soil degradation and changes in the water regime in regions with high logging intensity. Findings alike were discovered by E. Bălan *et al*. (2021), investigating the impact of agricultural and bioenergy activities on the state of forest landscapes. J. Dunlap & J. Schramski (2024) confirm that estimating biomass losses that can store carbon in the long term is crucial for developing strategies for the environmentally sustainable use of forest resources. An assessment of the impact of changes in forest cover on the water balance and carbon cycle has shown that forest ecosystems are important regulators of greenhouse gas emissions and water regimes, which is consistent with the statement of F. Melo *et al*. (2021). A study by these authors confirmed that changes in forest cover substantially affect the relationship between water, energy, and food resources. In turn, G. Baciu *et al*. (2021) focus on the need to integrate the economic and environmental aspects of forest ecosystem services assessment, which correlates with the data obtained on the substantial impact of large-scale logging on the stability of natural processes.

The study on the dynamics of changes in forest cover and its ecological functions confirmed the importance of integrated approaches to forest ecosystem management. Analysis of satellite data and vegetation indices showed a close relationship between anthropogenic impact, climate change, and forest bioproductivity, which is consistent with the results of K. Anderson-Teixeira *et al*. (2013), who determined that climate change affects the dynamics of forest restoration, slowing their growth and changing the structure of ecosystems. Similar conclusions were drawn by A. Wani & G. Sahoo (2021), highlighting the critical role of forests in maintaining biodiversity and the stability of ecosystem processes. The results of the forest management effectiveness study indicated that regions with a high level of use of geoinformation technologies and monitoring systems show lower rates of degradation of forest ecosystems, which is consistent with the conclusions of D. Grebner *et al*. (2021). A study by A. Kumar *et al*. (2022) also affirms that the introduction of geoinformation technologies, satellite monitoring, and algorithms for assessing the state of forests helps to reduce the risks of ecosystem degradation and increases the efficiency of forest management. The use of integrated spatial data analysis models makes it possible to predict changes in forest cover and their consequences for ecosystem services, which is confirmed by M. Hernández-Morcillo *et al*. (2022).

The results of this study also showed that adaptive measures for the sustainable use of biomass and the prevention of negative environmental impacts are critical to maintaining the sustainability of forest ecosystems. This is supported by a publication by A. Raihan (2023b), who analysed integrative approaches to the assessment of ecosystem services and proved the importance of combining environmental, social, and economic aspects in forest management. Thereby, S. Tampekis *et al*. (2024) note the need to improve forest management planning to increase the resilience of forest landscapes to climate change, which is confirmed by the data obtained in this study. The assessment of forest restoration measures and the reduction of the impact of logging activities on ecosystems confirmed the effectiveness of programmes aimed at afforestation and the natural renewal of forests (Ivanyuk *et al*., 2024). This is in line with the results of R. Mishra & R. Agarwal (2024), who review approaches to restoring degraded forests and argue that long-term adaptive management strategies ensure environmental stability. A similar conclusion was achieved by E. Nungula *et al*. (2024), who proved that the combination of forest and agroforestry management contributes to improving soil quality and water balance.

The review of the effectiveness of modern forest management technologies also revealed that the use of automated systems for planning and forecasting the dynamics of forest ecosystems improves the efficiency of biomass harvesting and reduces environmental risks. The findings of A. McEwan *et al*. (2020), who analysed the prospects for industrial forestry and emphasised the importance of innovative approaches in planning logging operations, support this statement. R. Gupta & L. Sharma (2019) confirmed that the use of process-oriented models, such as 3-PG, allows predicting the growth of forest ecosystems, optimising management decisions, and ensuring a balance between biomass harvesting and forest conservation. The results of the study also confirmed the importance of a trade-off between biomass production and biodiversity conservation, which correlates with the findings of J. Rybar & M. Bosela (2023), who analysed the correlation between the intensive use of forest resources and the conservation of natural ecosystems in Europe.

Summarising the results of the study showed that effective forest management requires a balance between environmental sustainability, economic interests, and the impact of climate change. The analysis confirmed the correlation between the introduction of sustainable forest management methods and the reduction of the negative impact of the bioenergy sector on forest ecosystems. Comparison with other studies has shown that the use of technological solutions, adaptive forestry, and integrated approaches to biomass management contributes to the conservation of biodiversity and the maintenance of natural processes. The results obtained are consistent with the conclusions of international scientific papers and emphasise the need for further research in the direction of optimising the use of forest biomass in the context of climate change.

Conclusions

The study allowed assessing the impact of sustainable forestry and biomass use on ecological balance and identifying trends in changes in forest ecosystems in the context of climate change and the growth of the bioenergy sector. Analysis of current approaches to forest management has shown that the most effective strategies include limiting deforestation in natural forests, creating protected areas, certifying forest products (Forest Stewardship Council, Programme for the Endorsement of Forest Certification), and taking measures for active forest restoration. In regions where close-to-nature forestry has been introduced, forest areas remain stable or show a tendency to recover, for example, in Canada and the Nordic countries.

Comparison of CO_2 emissions with different energy sources confirmed that burning wood biomass (112 kg CO_2/GJ) generates less greenhouse gases compared to coal (average 97.5 kg CO_2/GJ) but more than natural gas (56 kg CO_2/GJ). However, the long-term balance of emissions depends on the level of forest restoration: in countries with high standards of forest management (Sweden, Finland), the level of biomass harvesting is compensated by the natural reproduction of forest ecosystems.

Dynamics of changes in forest cover and its environmental consequences Based on the analysis of Sentinel-2 and Landsat satellite images for the period 2015-2024, it was determined that in tropical regions such as the Amazon and Southeast Asia, forest areas decreased by 0.8-1.5% annually due to intensive biomass harvesting and land use changes. Therewith, in the European Union and Canada, forest areas remained stable or showed an increase of 0.2-0.5% because of the afforestation and natural renewal programmes.

Forest ecosystems perform crucial functions in maintaining climate stability. Carbon reserves in biomass vary substantially depending on the region: in the Amazon, this figure reaches 230 MT/ha, while in Northern Europe – 150 Mt/ha. Thereby, the water retention capacity of forests is crucial for maintaining water balance, especially in regions with arid climates such as Australia (670 mm/year). It was established that the loss of forests in tropical regions leads to an increase in the level of soil erosion by 3-4 times, which leads to land degradation and a decrease in their productivity.

Optimising the use of forest biomass in the face of climate change requires combining sustainable harvesting methods with effective forest management policies. The introduction of low-emission technologies for biomass processing and an increase in the share of fast-growing tree crops will help reduce the environmental burden. The expansion of satellite monitoring will provide for a more accurate monitoring of the dynamics of changes in forest cover, and economic incentives for certified forestry will increase environmental responsibility. Further studies should include more detailed regional estimates and use multi-year carbon balance data. It is also important to consider the socio-economic factors that affect the development of the bioenergy sector and its impact on the environment.

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Conflict of Interest

None.

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Стале лісове господарство та виробництво енергії з біомаси: екологічні аспекти та динаміка лісових екосистем

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Анотація. Енергетичне використання лісової біомаси є важливою складовою сучасної біоекономіки, яка впливає на динаміку лісового покриву, баланс парникових газів та екологічну стійкість лісових екосистем у регіонах з активною заготівлею деревної сировини. Метою дослідження є оцінка екологічних наслідків використання лісової біомаси в енергетиці, виявлення змін у лісовому покриві та аналіз викидів CO_2 порівняно з викопними джерелами енергії. Використано поєднання теоретичного аналізу літературних джерел та емпіричного аналізу даних супутників Sentinel-2 та Landsat (2015-2024 рр.). Порівняльний аналіз змін лісового покриву виконано з використанням індексів нормалізованого різницевого вегетаційного індексу та нормалізованого коефіцієнта випалювання. Викиди CO_2 розраховані на основі коефіцієнтів викидів Міжурядової групи експертів зі зміни клімату для біомаси, вугілля та природного газу. У регіонах активного використання біомаси (Амазонія, Південно-Східна Азія) лісистість скорочується на 0,8-1,5 % щорічно, тоді як у країнах з розвиненою лісовою політикою (Канада, Фінляндія) лісові площі залишаються стабільними. Викиди CO_2 з біомаси (112 кг/ГДж) вищі, ніж з природного газу (56 кг/ГДж), але нижчі, ніж з вугілля (97,5 кг/ГДж). Оцінка взаємозв›язку між лісовими екосистемами та кліматичними факторами показує, що зменшення лісистості призводить до втрати водоутримуючої здатності (до 20 %) та збільшення ерозії ґрунтів у 3-4 рази. Результати дослідження підтверджують необхідність впровадження екологічно відповідальних підходів до управління лісовими ресурсами. Використання наближених до природи методів ведення лісового господарства, розвиток супутникового моніторингу та запровадження стандартів сертифікації можуть сприяти збереженню екосистемної рівноваги

Ключові слова: супутниковий моніторинг; вирубка лісів; вуглецевий баланс; парникові гази; зміна клімату; антропогенний вплив