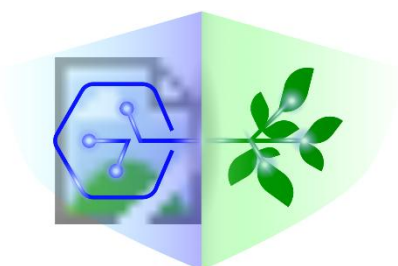


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DTEclimate

Digital Twin Earth Intelligence for Climate Changes

DTEClimate, ctr. nr. 760008/30.12.2022

Bio-industry and bio-economy applications for ESG benefits report

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1 Introduction

The EO4NATURE -"Exploitation of satellite Earth observation data for Natural Capital Accounting and Biodiversity Management -" project represents the subsequent project that differentiates the foundation of the digital twin concept for biodiversity within the DTECLIMATE project. In this sense, the methodological integration of the concepts of natural and anthropogenic ecosystems, the ecosystem services assessment and their capacity to generate services and to quantify service indicators to increase sustainability at the local and regional level is a priority in the conditions of adaptation to climate change.

Climate change is a certainty as presented in the analyzes with scientific bases highlighted by the intergovernmental reports on climate change - IPCC - 2021 and IPCC - 2022 obtained by the United Nations Environment Program (UNEP) with the contribution of the World Meteorological Organization (WMO), and the priorities in reducing the impact, adaptation and identification of vulnerable areas are currently ones of the innovative solutions formulated by the Center of Excellence in Adaptation to Climate Change in Romania (CEASCR).

The establishment of optimal indicators for characterizing the state of evaluation of the structure and functioning of natural and anthropogenic ecosystems in order to maintain their capacity to provide ecosystem services represents an indispensable operational framework on which European agencies such as the European Environment Agency (EEA report, 2021), the European Space Agency through the COPERNICUS Earth and Atmosphere program and the Joint Research Center (JRC) have focused their efforts, but with the involvement of several actors from at the level of the member states. Customizing the use of artificial intelligence and substantiating the structural and functional integrity of ecosystems through specific indicators at the level of the member states in order to support joint European efforts through the participation of CEASCR in the DTECLIMATE project allows the familiarization and standardization of the use of the best technologies in order to increase the potential of adapting to climate change for public and private interest organizations in Romania.

The EO4NATURE project focuses on addressing environmental challenges caused by climate change, referring to ecosystem monitoring, biodiversity management, biosecurity, protection and ecological restoration by integrating EO satellite data into monitoring and assessment processes. This is consistent with the actions recommended at EU level and the current National Guidance on adaptation to climate change which provides for important adaptation actions related to biodiversity and ecosystem protection that require significant ongoing, up-to-date knowledge.

The *D3.2.4 Bio-industry and bio-economy applications for ESG benefits report* presents the findings of the EO4NATURE project through analysis of the resources of the projects' test sites, from the bio-industry and bio-economy perspective. It includes pastures, forests, agricultural lands, aquatic resources and other related resources.

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2 Purpose and approach

2.1 Objective

The main objective is to translate observed and projected ecosystem condition changes and ecosystem service (ES) dynamics, identified in the previous SEES EA assessment phase, into qualitative and semi-quantitative estimates of socio-economic and business impacts. The approach supports decision-making by linking ecological changes with economic vulnerability, resilience and sustainability performance across bioeconomy-related sectors. This link is consistent with natural-capital and ecosystem-service assessment approaches, which emphasize the dependence of economic systems and human well-being on ecosystem condition and service flows (Millennium Ecosystem Assessment, 2005; Banerjee et al., 2020; IPBES, 2019).

The assessment focuses particularly on the implications of ecosystem degradation, climate variability and land-use change for:

- Bio-based industries and the local bioeconomy, including livestock production, forestry, irrigation-dependent agriculture, fisheries, tourism and other nature-dependent sectors. The relevance of ecosystem services for bioeconomy planning is supported by the literature on circular bioeconomy, biomass use and ecosystem-service dependencies (Schneider & Józefowska, 2025; D'Amato et al., 2020; Pedersen et al., 2020).
- Business risks and opportunities, such as supply chain disruption, productivity loss, operational costs, adaptation requirements, reputational exposure and opportunities for nature-positive investments or regenerative practices. These dimensions are aligned with natural-capital and nature-related risk frameworks that connect business decision-making to impacts and dependencies on nature (Natural Capital Coalition, 2016; TNFD, 2023; BioSTEP, 2016).
- Environmental, Social, and Governance (ESG) related benefits and risks, including climate regulation, carbon sequestration, biodiversity conservation, water security, soil protection, employment stability and community resilience. These ESG dimensions are directly linked to ecosystem services, biodiversity status and socio-ecological resilience (Millennium Ecosystem Assessment, 2005; IPBES, 2019; de Schutter et al., 2019).

The assessment integrates ecosystem indicators derived from Earth Observation (EO), field monitoring, drone-based surveys and expert judgment in order to evaluate how ecosystem responses may influence economic activities and sustainability outcomes under different environmental conditions. In this context, the assessment is not limited to biophysical measurement, but also translates observed ecosystem change into sectoral sensitivity, exposure and adaptive-capacity considerations (Banerjee et al., 2020; IPBES, 2019; Natural Capital Coalition, 2016).

The purpose is not to generate precise deterministic forecasts, but rather to provide a structured and transparent methodology for estimating relative impact intensity, uncertainty and sectoral sensitivity in contexts where ecological and socio-economic systems are characterized by complexity, incomplete data and non-linear interactions. This framing is consistent with coupled social-

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ecological systems thinking and with decision-oriented approaches to ecosystem service valuation and bioeconomy transitions (de Schutter et al., 2019; Banerjee et al., 2020; D'Amato et al., 2020). The bioeconomy provides Europe with the opportunity to make effective use of its strategic natural assets, including productive agricultural land, sustainably managed forests and healthy marine ecosystems, in order to support economic growth, food security and long-term societal resilience. Through sustainable agricultural and forestry practices, together with the responsible exploitation of marine resources, the European Union can satisfy an important share of its biomass demand from domestic sources while reducing dependence on external raw materials. In addition, the valorization of by-products, residues and biological waste contributes to greater resource efficiency and strengthens the competitiveness of the European economy in international markets.

The European Union's Strategy for a Competitive and Sustainable Bioeconomy aims to accelerate innovation and support businesses in the transition towards a greener and more circular economy. By encouraging the sustainable production and utilization of renewable biological resources for materials, products and services, the strategy seeks to reduce environmental pressures, improve resource efficiency and promote climate neutrality. Furthermore, the bioeconomy strategy contributes to the creation of green jobs and new economic opportunities, particularly in rural and coastal regions where local economies are strongly connected to natural resources. Special attention is given to farmers, foresters, industries, small and medium-sized enterprises (SMEs) and innovative startups, which play an essential role in developing sustainable value chains and bio-based industries within the European Union (European Commission, 2018).

2.2 Method – Fuzzy Logic Framework

Given the inherent uncertainty and variability associated with ecosystem processes and socio-economic responses, the assessment applies a Fuzzy Logic Framework to evaluate the relationship between ecosystem condition indicators and sectoral impacts. Fuzzy logic is suitable for environmental and socio-ecological assessment because it allows gradual transitions between categories, supports reasoning with partial membership, and can combine quantitative measurements with expert judgment (Zadeh, 1965; Zimmermann, 2001; Adriaenssens et al., 2004). This approach supports the integration of quantitative measurements with qualitative interpretation. It is based on the definition of linguistic variables and fuzzy membership functions that describe the intensity of ecosystem change and its potential implications for economic sectors and ESG dimensions. Rule-based fuzzy inference is particularly useful when direct deterministic relationships are difficult to quantify, but causal relationships can be expressed through expert-informed IF–THEN rules (Mamdani & Assilian, 1975; Adriaenssens et al., 2004; Zimmermann, 2001).

- **Linguistic Scales**

To standardize the interpretation of ecosystem responses, impact intensity is classified using fuzzy intervals ranging from 0 to 1. The use of linguistic categories is consistent with fuzzy set theory, where concepts such as low, medium or high are represented through degrees of membership rather than binary thresholds (Zadeh, 1965; Zimmermann, 2001; Adriaenssens et al., 2004).

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Impact intensity:

- Very Low Impact: 0.0 – 0.2
- Low Impact: 0.2 – 0.4
- Medium Impact: 0.4 – 0.6
- High Impact: 0.6 – 0.8
- Very High Impact: 0.8 – 1.0

These linguistic categories enable the translation of heterogeneous ecological indicators into comparable sectoral risk estimates. They also improve interpretability for stakeholders by expressing ecological and socio-economic change through transparent and communicable classes rather than only through technical numerical outputs (Adriaenssens et al., 2004; Natural Capital Coalition, 2016; TNFD, 2023).

In parallel, a **confidence** assessment is applied to each indicator and impact estimate based on data quality, spatial coverage, temporal consistency and methodological robustness. Confidence levels are expressed as:

- Low Confidence – limited data availability or high uncertainty;
- Medium Confidence – partial validation through multiple sources;
- High Confidence – strong agreement between EO analysis, field observations, drone imagery, and expert interpretation.

The confidence assessment is essential for understanding the reliability of the estimated impacts and for supporting adaptive decision-making processes. It is also consistent with environmental assessment practices that explicitly communicate uncertainty, evidence quality and limits of inference (IPBES, 2019; Banerjee et al., 2020; TNFD, 2023).

• Fuzzy Rule-Based Analysis

The methodology links ecosystem condition indicators to sectoral impacts using a rule-based inference system. Ecosystem responses identified through the SEES EA process are translated into socio-economic implications through IF-THEN fuzzy rules that capture plausible causal relationships between environmental stressors and economic vulnerability. Such rule-based systems are commonly used when ecological systems are complex, data are incomplete and expert knowledge must be formalized in a transparent decision-support structure (Mamdani & Assilian, 1975; Adriaenssens et al., 2004; Zimmermann, 2001).

Examples:

- IF fodder availability decrease = High AND drought frequency = High, THEN livestock economic risk = High.
- IF forest fragmentation = Medium AND wildfire susceptibility = High, THEN forestry operational risk = High.
- IF wetland degradation = High AND tourism dependence = High, THEN tourism revenue vulnerability = High.

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- IF vegetation productivity = Low AND irrigation demand = High, THEN agricultural water stress = Very High.

The fuzzy inference system allows multiple indicators to interact simultaneously and reflects the reality that ecosystem services and economic systems are interconnected and mutually dependent. This is particularly relevant for bioeconomy-related activities, where production systems depend on soil fertility, water regulation, biodiversity, climate regulation and landscape resilience (Millennium Ecosystem Assessment, 2005; de Schutter et al., 2019; D'Amato et al., 2020).

Integration of Ecosystem Services and ESG Dimensions

The framework also supports the evaluation of broader ESG-related impacts by connecting ecosystem service trends with sustainability dimensions. This is consistent with ecosystem-service assessment frameworks and business-oriented natural-capital approaches, which emphasize that organizations and communities both depend on and affect ecosystem condition (Millennium Ecosystem Assessment, 2005; Natural Capital Coalition, 2016; TNFD, 2023).

- **Relevant ESG-related dimensions include:**

- Climate regulation, including carbon storage, greenhouse gas mitigation and resilience to extreme weather events;
- Water-related services, such as groundwater recharge, water purification and drought regulation;
- Biodiversity conservation, including habitat integrity and ecological connectivity;
- Social benefits, including employment stability, food security, recreational value and community well-being.

This integrated perspective enables stakeholders to identify both risks associated with ecosystem degradation and opportunities linked to restoration, sustainable land management and nature-based solutions. It also supports the interpretation of nature-related dependencies, impacts, risks and opportunities within sustainability reporting and strategic planning (IPBES, 2019; TNFD, 2023; Schneider & Józefowska, 2025).

- **Analytical Advantages**

The fuzzy logic approach provides several methodological advantages for ecosystem-economic assessments. In particular, it is appropriate when relationships between ecosystem condition and socio-economic impact cannot be expressed through precise deterministic models, but can be represented through semi-quantitative categories, expert interpretation and transparent inference rules (Zadeh, 1965; Adriaenssens et al., 2004; Zimmermann, 2001).

Main analytical advantages include:

- It accommodates uncertainty and incomplete environmental datasets;
- It combines quantitative EO-derived indicators with qualitative expert knowledge;
- It supports scenario analysis and adaptive management;
- It allows transparent communication of risk intensity and confidence levels;

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- It is suitable for multi-sectoral sustainability and ESG reporting frameworks.

As a result, it can serve as a practical decision-support tool for public authorities, businesses, financial institutions and local stakeholders seeking to evaluate ecosystem-related risks and dependencies within the context of climate adaptation, biodiversity strategies and sustainable regional development. This function is aligned with ecosystem-service valuation, natural-capital assessment and nature-related disclosure frameworks that aim to make ecological dependencies visible in economic and governance decisions (Banerjee et al., 2020; Natural Capital Coalition, 2016; TNFD, 2023).

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3 Bio-industry and bio-economy – General framework

According to the COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS- *Strategic Framework for a Competitive and Sustainable EU Bioeconomy*, the bioeconomy is defined as “the activities that deliver sustainable solutions based on biological resources to create added value. These include products, services, science and technologies benefiting sectors ranging from agriculture, forestry, fisheries and aquaculture to value chains based on biomass processing, biomanufacturing and biotechnologies such as in food, health, energy, industry, ecosystem and other services. Biological resources include genetic resources, as well as primary and secondary biomass, such as by-products and residues, and biogenic carbon captured through innovative technologies” (European Commission, 2025).

Several global challenges such as climate change, food security, health, and energy security are addressed in a coherent way through the bioeconomy concept (Bracco, et al., 2019).

FAO, through the “Towards sustainable bioeconomy guidelines” project, had as objective to assess indicators, to monitor and evaluate the performance of sustainable bioeconomy development. The assessment of the indicators is based on 10 principles (Bracco, et al., 2019):

Principle 1. Sustainable bioeconomy development should support food security and nutrition at all levels

Principle 2. Sustainable bioeconomy should ensure that natural resources are conserved, protected and enhanced

Principle 3. Sustainable bioeconomy should support competitive and inclusive economic growth

Principle 4. Sustainable bioeconomy should make communities healthier, more sustainable, and harness social and ecosystem resilience

Principle 5. Sustainable bioeconomy should rely on improved efficiency in the use of resources and biomass

Principle 6. Responsible and effective governance mechanisms should underpin sustainable bioeconomy

Principle 7. Sustainable bioeconomy should make good use of existing relevant knowledge and proven sound technologies and good practices, and, where appropriate, promote research and innovation

Principle 8. Sustainable bioeconomy should use and promote sustainable trade and market practices

Principle 9. Sustainable bioeconomy should address societal needs and encourage sustainable consumption

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Principle 10. Sustainable bioeconomy should promote cooperation, collaboration and sharing between interested and concerned stakeholders in all relevant domains and at all relevant levels

The same document is proposing the grouping criteria for sustainable bioeconomy, by sustainability pillars. Figure 1 presents grouping.

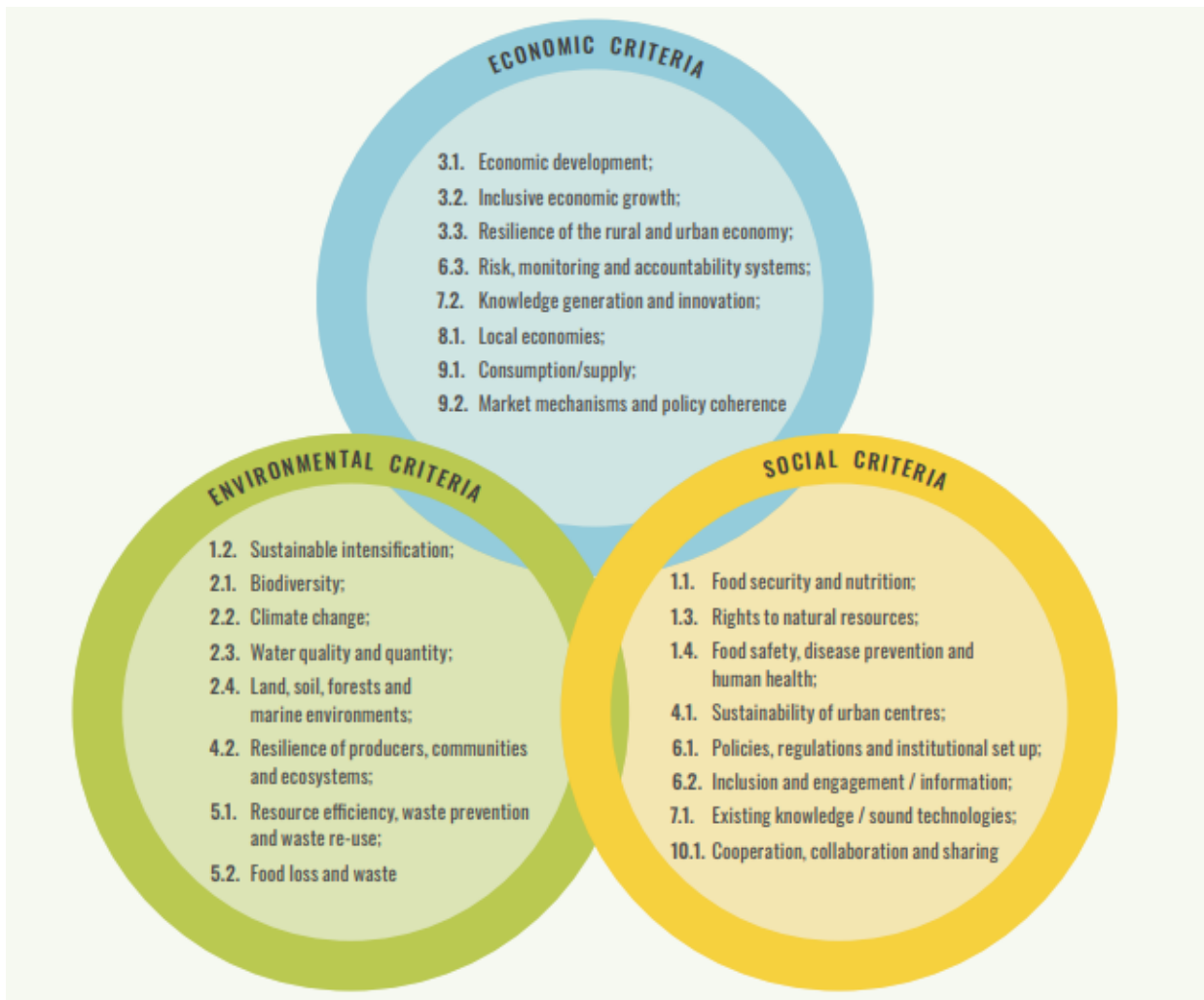


Figure 1 CRITERIA FOR SUSTAINABLE BIOECONOMY GROUPED BY SUSTAINABILITY PILLARS (Bracco, et al., 2019)

According to (European Commission, 2025), a way to build a sustainable and nature-positive bioeconomy includes the following steps:

1. scaling innovation and investments;
2. building new lead markets for bio-based materials and technologies;

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3. ensuring sustainable biomass supply across value chains and
4. harnessing global opportunities.

Bioeconomy allows Europe to capitalize on its own strategic assets — productive agricultural land, sustainably managed forests, and healthy marine ecosystems — in order to support prosperity, economic and food security, and societal resilience. Agriculture and forestry, together with the smart utilization of marine resources, enable Europe to satisfy a significant share of its biomass demand through sustainable domestic production. At the same time, the efficient use of by-products and residues improves resource efficiency while strengthening the European Union’s competitiveness in global markets.

The Strategy for a Competitive and Sustainable EU Bioeconomy seeks to stimulate innovation and assist European companies in successfully advancing the green transition. By promoting the circular and sustainable production and use of biological resources for materials and services, the strategy aims to improve resource efficiency and lessen environmental pressure. In addition, the strategy is intended to strengthen the competitiveness of EU businesses and generate more green employment opportunities while ensuring the protection of natural ecosystems. It primarily targets European farmers, foresters, industries, and enterprises, especially small and medium-sized enterprises (SMEs) and startups located in rural and coastal regions.

According to the UE’s official website on Bioeconomy strategy, some upcoming events regarding bioeconomy are:

Timeline

Previous and upcoming actions



Figure 2 Previous and upcoming actions on bioeconomy (https://environment.ec.europa.eu/strategy/bioeconomy-strategy_en?prefLang=ro)

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Romania doesn't have a national bioeconomy strategy, but it has other policy initiatives dedicated to bioeconomy. Thus, since 2016, Romania participated in BIOEAST, a macro-regional bioeconomy initiative being developed by Central and Eastern European countries. The National Strategy for Research, Development and Innovation 2014-2020 – Ministry of Research and Innovation - sets bioeconomy as one of the areas of "smart" specialization in areas such as agriculture, aquaculture and fish farming, forestry (European Commission, 2026).

Main Romanian policy initiatives dedicated to bioeconomy:

1. National Strategy for the Circular Economy (NSCE) – 2022 (available at: <https://circulareconomy.europa.eu/platform/en/strategies/national-strategy-circular-economy-romania>)

This is currently the most important policy framework related to bioeconomy in Romania.

The strategy:

- supports the transition from a linear to a circular economy,
- identifies agriculture and forestry as sectors with the highest circular potential,
- promotes biomass valorisation, waste reduction, recycling, and sustainable production systems.

2. Romania's Circular Economy Action Plan – 2023 (available at: <https://circulareconomy.europa.eu/platform/en/strategies/romania-circular-economy-action-plan>)

The Action Plan operationalizes the National Circular Economy Strategy through concrete measures scheduled between 2024–2032.

It includes:

- biomass-based solutions,
- sustainable agriculture practices,
- resource efficiency measures,
- support for circular production systems,
- promotion of local production and secondary raw materials

3. National Strategy for Research, Innovation and Smart Specialisation (SNCISI) 2021–2027 (available at: https://www.oecd.org/en/publications/policies-for-the-future-of-farming-and-food-in-romania_6ef8fa3c-en/full-report/agriculture-innovation-system_1058dbfb.html#chapter-d1e18970-98e3a232451)

Romania officially recognizes “bioeconomy” as one of its national smart specialization domains.

The strategy supports:

- biotechnology,
- sustainable agriculture,

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- agroecology,
- forestry innovation,
- food systems,
- agriculture 4.0 technologies,
- digital transformation in bio-based sectors.

4. CAP Strategic Plan 2023–2027 (Common Agricultural Policy) (available at: https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans/romania_en)

Romania's CAP Strategic Plan integrates several bioeconomy objectives through:

- sustainable farming,
- organic agriculture,
- innovation in rural development,
- biomass use,
- climate-smart agriculture,
- and food processing investments

5. BIOEAST Initiative and Romania National Hub (available at: <https://bioeast.eu/countries/romanian-national-hub/>)

Romania participates in the BIOEAST macro-regional initiative for Central and Eastern Europe.

The Romanian BIOEAST Hub promotes:

- circular bioeconomy development,
- research collaboration,
- innovation ecosystems,
- renewable technologies,
- and sustainable use of biological resources.

6. Sustainable Development Strategy of Romania 2030 (available at: <https://dezvoltaredurabila.gov.ro/>)

Romania's sustainable development agenda indirectly supports bioeconomy through:

- green growth,
- resource efficiency,
- sustainable consumption,
- biodiversity protection,
- renewable resources,
- and climate resilience.

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4 Ecosystem Responses and Fuzzy Impact Rules

Ecosystems provide a wide range of provisioning, regulating, supporting and cultural services that are essential for environmental stability and the functioning of local bioeconomies. Climate change, land-use intensification, biodiversity loss and increasing environmental pressures are already altering ecosystem structure and functionality across Europe and globally. In this context, fuzzy logic approaches are increasingly used to model ecosystem responses as they allow the integration of uncertainty, gradual transitions and qualitative expert knowledge into environmental assessment frameworks. Unlike rigid binary models, fuzzy systems can better capture ecological complexity by assigning degrees of impact or vulnerability rather than absolute states (OECD, 2023; Millennium Ecosystem Assessment, 2005).

4.1 Grasslands (E1.x, E2.x, E4.3)

Grasslands represent one of the most important semi-natural ecosystems in Europe, providing essential ecosystem services such as fodder production, soil stabilization, carbon sequestration, biodiversity conservation and cultural landscape maintenance (EEA, 2020). These ecosystems are particularly vulnerable to climatic variability, prolonged droughts, overgrazing and land abandonment. Satellite-derived vegetation indicators such as NDVI (Normalized Difference Vegetation Index) are widely used to monitor grassland productivity and ecosystem health over time (IPCC, 2022).

4.1.1 Key ecosystem responses

One of the most visible ecosystem responses is the **decrease in NDVI integral**, which indicates a reduction in total seasonal vegetation productivity and fodder biomass availability. Lower biomass production directly affects grazing systems because livestock become increasingly dependent on external feed inputs, increasing operational costs for rural communities and agricultural producers (FAO, 2006).

Another important response is the **shortening of the green period**, also referred to as the reduction of the grazing window. Climate warming and altered precipitation regimes can accelerate vegetation senescence, leading to shorter periods during which grasslands remain productive and nutritionally valuable for grazing animals. This phenomenon is especially problematic in mountain and semi-arid regions where pastoral systems depend heavily on seasonal vegetation dynamics (IPCC, 2022).

In parallel, the **increase in bare soil exposure and erosion features** reflects progressive land degradation processes. Reduced vegetation cover weakens soil protection against water and wind erosion, resulting in nutrient losses, reduced water retention capacity and declining long-term ecosystem resilience. Studies have shown that degraded grasslands often enter feedback loops where erosion further reduces vegetation recovery capacity (UNEP, 2021).

4.1.2 Fuzzy impact on bioindustries & local bioeconomy

The impacts of grassland degradation extend beyond ecological processes and directly influence local bioeconomic sectors.

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➤ Sector: Livestock (meat, milk, wool, cheese)

Livestock production systems are highly dependent on the quantity and quality of available fodder. Therefore, fuzzy logic rules can be used to express how combined ecological stressors translate into production risks (MDPI Sustainability, 2022).

Rule example:

- IF (Fodder decline = High) AND (Grazing window shortening = Medium–High)
THEN (Livestock production risk = High; score \approx 0.7–0.8).

This rule reflects the strong relationship between reduced forage availability and declining livestock productivity. Lower fodder availability may reduce milk yields, animal weight gain, reproductive success and overall farm profitability. In regions where traditional grazing systems dominate, these pressures can threaten the viability of small-scale pastoral economies (FAO, 2006).

Another relevant fuzzy rule concerns land degradation:

- IF (Degradation/erosion = High)
THEN (Long-term carrying capacity loss = High; score \approx 0.7).

This relationship highlights the cumulative effects of soil degradation on the long-term sustainability of grazing systems. Carrying capacity refers to the maximum livestock density that grasslands can support without ecological deterioration. Persistent erosion reduces soil fertility and vegetation regeneration potential, thereby lowering sustainable stocking rates over time (EEA, 2024).

➤ Sector: Local feed and hay markets

Grassland productivity variability also affects local and regional feed supply chains.

- IF (Fodder interannual variability = High)
THEN (Price volatility for hay/feed = High; score \approx 0.7).

High interannual variability in biomass production may generate instability in fodder markets, particularly during drought years. This can increase dependence on imported feed resources and expose local agricultural systems to broader market fluctuations (OECD, 2023).

➤ Sector: Nature-based tourism and pastoral landscapes

Traditional pastoral landscapes contribute significantly to regional identity, cultural heritage and tourism attractiveness.

- IF (Landscape degradation = Medium–High)
THEN (Tourism attractiveness impact = Medium; score \approx 0.5).

Landscape degradation, visible soil erosion, reduced vegetation cover and biodiversity decline may reduce the aesthetic and recreational value of rural landscapes. This can negatively affect ecotourism, agritourism and outdoor recreation activities that depend on well-preserved natural environments (Millennium Ecosystem Assessment, 2005).

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4.1.3 Fuzzy ESG link Environmental (E)

Healthy grasslands contribute significantly to soil conservation and ecosystem stability.

- IF (Grassland condition = Good)
THEN (Soil erosion mitigation benefit = High).

Well-managed grasslands can reduce runoff velocity, stabilize soils and improve water infiltration. In addition, permanent grasslands contribute to carbon storage and biodiversity conservation (EEA, 2024).

Social (S)

Many rural communities depend directly on livestock grazing and grassland ecosystem services.

- IF (% households with livestock = High) AND (Fodder risk = High)
THEN (Social vulnerability = High).

In economically vulnerable rural regions, reduced grazing productivity can lead to declining household income, increased poverty risks, and rural depopulation. Social resilience therefore depends strongly on ecosystem stability (FAO, 2006).

Governance (G)

As degradation intensifies, governance interventions become increasingly necessary. The need for grazing regulations, restoration programs, rotational grazing schemes and sustainable land management policies increases proportionally with ecosystem degradation scores. Adaptive governance mechanisms are therefore critical for maintaining long-term grassland resilience (UNEP, 2022).

4.2 Forests (G1.x, G3.x)

Forests are among the most valuable ecosystems in terms of biodiversity conservation, climate regulation, water protection, and economic production. They provide timber, non-timber forest products, recreational opportunities, and important regulating ecosystem services such as carbon sequestration and erosion control (European Commission, 2021). However, forest ecosystems are increasingly affected by climate-induced disturbances including drought stress, pest outbreaks, storms, and wildfires (IPCC, 2022).

4.2.1 Key ecosystem responses

One of the primary indicators of forest ecosystem stress is the **decline in canopy vitality**, often measured through long-term NDVI trends and remote sensing analyses. Reduced canopy vitality may indicate drought stress, reduced photosynthetic activity, or tree mortality processes (EEA, 2024).

Another major response involves the **increase in disturbance events**, including pest infestations, pathogen outbreaks, windthrow and dieback phenomena. Climate change is expected to intensify

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disturbance frequency and severity, particularly in forests already exposed to environmental stress (IPCC, 2022).

In addition, forests are experiencing **phenological shifts**, such as earlier leaf emergence and delayed senescence. Although these changes may initially increase growing season length, they can also expose forests to late frost risks, water stress and ecological mismatches between species interactions (FAO, 2020).

4.2.2 Fuzzy impact on bioindustries local bioeconomy

➤ Sector: Forestry and wood processing

Forest condition directly influences timber availability and the stability of wood-processing industries.

- IF (Canopy vitality decline = Medium–High)
THEN (Future sustainable harvest potential = Medium risk; score \approx 0.5–0.6).

Declining forest vitality may reduce long-term timber productivity and increase uncertainty regarding future wood supply. This creates planning challenges for forest managers and wood-processing industries (European Commission, 2021).

- IF (Disturbance frequency = High)
THEN (Operational risk and salvage logging instability = High; score \approx 0.7).

High disturbance frequency often leads to sudden increases in salvage logging activities, generating fluctuations in timber markets, reduced wood quality, and logistical instability (FAO, 2020).

➤ Sector: Drinking water and hydropower catchments

Forests play a critical role in regulating water cycles and stabilizing mountain catchments.

- IF (Forest cover loss on steep slopes = Medium–High)
THEN (Erosion/sediment risk to reservoirs = High; score \approx 0.7).

Forest degradation may increase sediment transport into reservoirs and rivers, reducing water quality and hydropower infrastructure efficiency. Sedimentation also increases maintenance costs and decreases reservoir storage capacity (UNEP, 2022).

➤ Sector: Eco-tourism and recreation

Forests provide important recreational and aesthetic benefits that support local tourism economies.

- IF (Disturbance severity = High) AND (Accessibility = High)
THEN (Short-term tourism attractiveness loss = Medium–High; score \approx 0.6–0.7).

Severely disturbed forests may temporarily lose recreational value due to damaged landscapes, safety concerns and reduced biodiversity attractiveness (Millennium Ecosystem Assessment, 2005).

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4.2.3 Fuzzy ESG link Environmental (E)

Forests are essential climate-regulating systems because of their carbon sequestration capacity.

- IF (Forest condition = Good–High)
THEN (Climate mitigation benefit = High; ≥ 0.8).

Healthy forests store significant amounts of carbon in biomass and soils, thereby contributing to climate change mitigation objectives (European Commission, 2021).

Social (S)

Forests also possess substantial cultural, spiritual and recreational value.

- IF (Old growth/semi-natural forest share = High)
THEN (Cultural and heritage value = High).

Traditional and old-growth forests often support local identity, educational activities and nature-based tourism while preserving biodiversity-rich habitats (EEA, 2021).

Governance (G)

Climate-related risks increase the importance of adaptive governance and sustainable forest management.

- IF (Climate sensitivity and disturbance risk = High)
THEN (Priority for adaptive forest management = High).

Adaptive forest governance may include species diversification, close-to-nature silviculture, monitoring systems, disturbance preparedness, and restoration planning (IPCC, 2022).

4.3 Aquatic Ecosystems (C2.2, C2.3, reservoirs)

4.3.1 Key ecosystem responses

Aquatic ecosystems are increasingly affected by climate variability, prolonged drought periods and the intensification of extreme hydrological events. In many European regions, especially in areas already exposed to seasonal water stress, climate change contributes to the reduction of river flows during summer months, changes in sediment transport and deterioration of water quality.

According to the European Environment Agency (EEA), the frequency and severity of droughts and floods are expected to increase, with direct consequences for freshwater ecosystems, biodiversity and water-dependent economic sectors (EEA, 2024).

One of the most visible responses of aquatic ecosystems is the reduction in minimum summer water extent and flow. Lower discharge rates during warm seasons decrease habitat availability for aquatic species, increase water temperature and reduce dissolved oxygen concentrations, affecting fish populations and aquatic vegetation (EEA, 2021).

At the same time, increased intermittency of small channels and tributaries becomes more common in drought-prone regions. Temporary drying of streams and secondary channels disrupts

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ecological connectivity, reduces spawning areas and alters nutrient cycling processes. These processes are particularly relevant in vulnerable European regions where water scarcity and hydrological instability are expected to intensify under future climate scenarios (EEA, 2012). Another important impact is represented by more intense, short-duration flood peaks. Climate projections indicate that heavy rainfall events are becoming more concentrated in shorter periods of time, generating flash floods and rapid runoff processes. Such events accelerate riverbank erosion, increase sediment transport and create additional pressure on hydraulic infrastructure and reservoirs (EEA, 2024).

Periodic high turbidity events are also expected to become more frequent. Increased sediment loads during storms or flood episodes reduce water transparency, affect photosynthetic aquatic organisms and contribute to the degradation of aquatic habitats. High turbidity additionally impacts drinking water treatment systems and irrigation infrastructure, increasing operational costs.

Main ecosystem responses

- Reduction in minimum summer water extent and flow.
- Increased intermittency of small channels.
- More intense, short-duration flood peaks.
- Periodic high turbidity events.

4.3.2 Fuzzy impact on bioindustries local bioeconomy

The degradation of aquatic ecosystems has direct and indirect consequences on local bio-economies, particularly in sectors that depend on stable water availability and ecosystem services. Agriculture, food processing industries, fisheries and recreation activities are among the most vulnerable sectors.

➤ Sector: Irrigation-dependent agriculture

Agriculture remains one of the largest freshwater consumers in Europe. Reduced summer flows and increasing hydrological variability directly affect irrigation reliability and crop productivity. Water scarcity conditions can lead to lower agricultural yields, increased production costs and conflicts between agricultural and domestic water uses. According to the European Commission, water scarcity and droughts already affect a significant part of the European territory every year, generating substantial economic losses across agriculture, energy production and water supply systems. (European Commission, Environment Directorate-General, n.d.)

- IF (Low flow severity = High) AND (Intermittency = Medium–High)
THEN (Irrigation water supply risk = Very High; score \approx 0.8–1.0).

In parallel, more frequent flash floods may damage irrigation canals, pumping stations and agricultural infrastructure. Flood-related sediment deposition may also reduce soil quality and affect crop performance.

- IF (Flood flashiness = High)
THEN (Infrastructure damage risk = Medium–High; score \approx 0.6–0.7).

➤ Sector: Agro-processing & food industry

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Agro-processing industries are strongly dependent on stable agricultural outputs and predictable water availability. Variability in irrigated crop production generates uncertainty across supply chains, affecting production planning, storage systems and food prices.

- IF (Irrigated crop yield variability = High)
THEN (Supply chain instability = Medium–High; score ≈ 0.6 –0.7).

Moreover, lower water quality associated with high turbidity or pollutant concentration during low-flow periods may increase operational costs for food processing facilities, especially those requiring high-quality freshwater inputs.

➤ **Sector: Fisheries and recreation**

Freshwater fisheries and recreational activities are particularly sensitive to ecosystem degradation. Stream intermittency, habitat fragmentation and declining water quality reduce fish abundance and biodiversity. Recreational uses such as angling, ecotourism and water sports may also decline in regions affected by persistent drought and degraded aquatic conditions.

- IF (Intermittency = High) AND (Water quality proxies = Poor)
THEN (Recreational & small-scale fishery potential = Low; score ≈ 0.2 –0.3).

Consequently, local communities dependent on tourism and ecosystem-based economic activities may experience declining revenues and increasing socio-economic vulnerability.

4.3.3 Fuzzy ESG link

The impacts generated by hydrological instability and aquatic ecosystem degradation are strongly connected with Environmental, Social and Governance (ESG) dimensions. Water availability and ecosystem integrity are increasingly recognized as strategic sustainability indicators for both public authorities and private stakeholders.

Environmental (E)

Alterations in river flow regimes and increasing hydrological stress significantly affect ecological status, biodiversity and ecosystem functioning. Reduced environmental flows may lead to habitat loss, eutrophication processes and declining ecological resilience.

- IF (Flow regime alteration = High)
THEN (Ecological status risk = High).

In addition, deteriorating water quality and sediment-related disturbances can compromise the achievement of Water Framework Directive ecological objectives.

Social (S)

Communities that depend on irrigation agriculture, fisheries or water-intensive industries are increasingly exposed to social and economic risks associated with climate-induced water stress. Employment instability, reduced agricultural income and increased competition for water resources may intensify regional inequalities.

- IF (Agricultural jobs dependent on irrigation = High) AND (Water risk = High)

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THEN (Social & economic vulnerability = High).

Water insecurity can also affect public health and access to essential ecosystem services, particularly in rural regions with limited adaptive capacity. Floods, droughts and deteriorating water quality are increasingly associated with health risks, psychological stress and socio-economic inequalities, especially among vulnerable population groups (EEA, 2024).

Governance (G)

Increasing climate pressure on water resources highlights the need for stronger governance mechanisms, integrated watershed management and adaptive allocation systems. Efficient monitoring, transparent water allocation policies and investments in resilient infrastructure are becoming critical governance priorities.

- IF (Water risk = High)

THEN (Need for water allocation / efficiency governance = Very High).

Furthermore, governance frameworks should integrate climate adaptation strategies, nature-based solutions and cross-sectoral coordination mechanisms in order to improve long-term water resilience.

4.4 Wetlands (D5.x, D1.x, E3.4)

4.4.1 Key ecosystem responses

Wetlands represent some of the most valuable and vulnerable ecosystems in Europe due to their essential role in biodiversity conservation, water regulation and climate adaptation. However, increasing temperatures, prolonged droughts and changes in hydrological regimes are contributing to the degradation of wetland systems across many regions. According to the European Environment Agency (EEA), wetland ecosystems are increasingly threatened by water scarcity, land use change and altered flood dynamics (EEA, 2021).

One of the most significant ecosystem responses is the *decline of permanent water areas* and the drying of *fringe zones*. Reduced water availability affects habitat stability, decreases aquatic biodiversity and alters ecological processes within wetland environments. In many cases, peripheral wetland areas become seasonally dry, reducing habitat connectivity and ecosystem resilience.

Another important response is the *contraction of permanently wet patches and wetland cores*. As hydrological conditions become less stable, wetlands lose their capacity to retain water during dry periods, which negatively affects vegetation structure, soil moisture and nutrient cycling. These processes may also reduce the role of wetlands as natural flood buffers and water purification systems (Ramsar Convention Secretariat, 2018).

Additionally, *reduced extent and productivity of wet meadows (E3.4)* represent a growing ecological concern. Wet meadows are highly dependent on seasonal flooding and groundwater availability. Lower soil moisture and modified flood regimes reduce biomass productivity and affect plant diversity, particularly in semi-natural grassland systems.

Main ecosystem responses

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- Decline of permanent water areas; drying of fringe zones.
- Contraction of permanently wet patches and wetland core.
- Reduced extent/productivity of wet meadows (E3.4).

4.4.2 Fuzzy impact on bioindustries local bioeconomy

Wetland degradation generates multiple socio-economic impacts, especially for sectors that directly depend on ecosystem services provided by wetland environments. Agriculture, livestock farming and nature-based tourism are among the most exposed activities.

➤ Sector: Livestock based on wet meadows (hay, grazing)

Wet meadows provide important grazing surfaces and high-quality hay production for local livestock systems. Declining vegetation productivity caused by drought and altered flood regimes reduces fodder availability and increases pressure on rural farming systems.

- IF (Wet meadow NDVI decline = High) AND (Flood regime change = High)
THEN (High-quality hay production risk = High; score \approx 0.7–0.8).

In addition, lower biomass productivity may increase operational costs for farmers and contribute to the abandonment of traditional agricultural practices in vulnerable rural regions (EEA, 2021).

➤ Sector: Irrigation (indirect storage & baseflow)

Wetlands contribute significantly to groundwater recharge and baseflow maintenance, supporting water availability during dry periods. The reduction of wetland storage capacity decreases the ability of ecosystems to regulate hydrological flows naturally.

- IF (Wetland storage reduction = Medium–High)
THEN (Baseflow support for irrigation = Reduced; risk \approx 0.6–0.8).

As a result, irrigation systems may become more vulnerable to seasonal water shortages, particularly during prolonged drought conditions (European Commission, 2022).

➤ Sector: Nature-based tourism & birdwatching

Wetlands are important destinations for ecotourism, birdwatching and recreational activities due to their biodiversity and landscape value. Habitat degradation, declining bird populations and water scarcity can reduce the attractiveness of these ecosystems for tourism activities.

- IF (Wetland habitat degradation = Medium–High)
THEN (Tourism value decline = Medium; score \approx 0.5–0.6).

Consequently, local communities that depend on tourism revenues may experience economic losses and reduced development opportunities.

4.4.3 Fuzzy ESG link

Wetlands provide essential ecosystem services that are directly connected to Environmental, Social and Governance (ESG) objectives. Their conservation is increasingly recognized as a strategic component of climate resilience and sustainable land management policies.

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Environmental (E)

Healthy wetlands contribute to flood regulation, carbon storage, biodiversity conservation and water purification. Well-preserved wetland systems can significantly improve ecological resilience under changing climate conditions. According to the European Environment Agency, wetlands provide essential ecosystem services such as water retention, climate regulation and biodiversity support, all of which are becoming increasingly important under conditions of growing climate stress and hydrological instability (EEA, 2019).

- IF (Wetland condition = Good–High)
THEN (Flood regulation + purification benefit = High; score ≥ 0.8).

According to the Ramsar Convention Secretariat (2018), wetland restoration represents one of the most effective nature-based solutions for climate adaptation and ecosystem resilience.

Social (S)

Many local communities maintain strong cultural and economic connections with wetland ecosystems through traditional agriculture, fisheries and tourism activities. Wetland degradation may therefore generate important social and livelihood impacts.

- IF (Local identity / livelihoods linked to wetlands = High) AND (Degradation risk = High)
THEN (Community impact = High).

Loss of ecosystem services may also contribute to rural vulnerability and reduced adaptive capacity in economically dependent regions.

Governance (G)

Given their role in climate adaptation and water management, wetlands are increasingly prioritized within environmental governance frameworks and restoration strategies.

- IF (Wetland's role in climate and water resilience = High)
THEN (Priority for protection / restoration = Very High).

Integrated wetland management, ecological restoration programs and sustainable land-use policies are considered essential for improving long-term ecosystem resilience and supporting EU biodiversity objectives (European Commission, 2020).

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5 CrossEcosystem Fuzzy Impact Matrix

Ecosystem group	Main affected sectors	Overall climate-driven impact (0–1)	Confidence	Key ESG issue
Grasslands	Livestock, hay trade, rural tourism	0.7 (High)	High	Fodder security, soil & erosion
Forests	Forestry, wood processing, water supply	0.5 (Medium)	Medium	Carbon, slope stability, water regulation
Aquatic	Irrigation agriculture, agro-industry	0.8 (Very High)	Medium–H	Water scarcity, flood risk
Wetlands	Hay/meadow livestock, tourism	0.6 (Medium–High)	Medium	Flood buffering, purification, habitat loss

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6 Implications for Local BioEconomy & Business Models

6.1 Risk and Opportunity Mapping

6.1.1 Main Applications of Bioeconomy in Agriculture (Toplicean, I.-M., & Datcu, A.-D. (2024).)

Bioeconomy has multiple applications in agriculture, contributing to sustainability, resource efficiency, and rural development. One of the most important applications is **precision and smart agriculture**, which uses digital technologies such as sensors, drones, artificial intelligence (AI), and satellite monitoring to optimize agricultural production and reduce environmental impact.

Another major application is **biomass valorisation and bioenergy production**, where agricultural residues, organic waste, and by-products are transformed into biofuels, biogas, biofertilizers, and other bio-based products. This supports renewable energy generation and reduces waste.

The bioeconomy also promotes **organic and sustainable farming systems**, encouraging environmentally friendly agricultural practices that improve soil quality, preserve biodiversity and reduce dependence on synthetic chemicals.

In addition, **circular agriculture and waste recycling** represent important applications of the bioeconomy. These include composting organic waste, nutrient recycling, wastewater reuse, and converting agricultural waste into secondary resources or energy.

Another significant application is **agricultural biotechnology**, which involves the development of disease-resistant crops, biofertilizers, biopesticides and other biological innovations that improve productivity and climate resilience.

Finally, the bioeconomy contributes to **sustainable food system development** by reducing food waste, improving local value chains and promoting sustainable consumption and production practices.

6.1.2 Applications for aquatic ecosystems

The bioeconomy helps Europe use its natural strengths, such as productive agricultural land, sustainably managed forests and healthy marine ecosystems, to support economic growth, food security and resilience. By combining farming, forestry, and the more efficient use of ocean resources, Europe can satisfy most of its biomass demand through sustainable domestic production. In addition, using agricultural and industrial by-products more effectively increases resource efficiency and strengthens the EU's competitiveness in global markets.

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In the agricultural sector, circular and sustainable practices help improve soil fertility while also lowering production costs. At the same time, aquatic resources provide an additional and diverse source of biomass, contributing to a more resilient supply system while protecting sensitive ecosystems. EU initiatives such as the Aquaculture Guidelines and the Algae Initiative promote the sustainable production and use of algae and shellfish, while the Ocean Pact supports innovation in the blue bioeconomy by developing new value chains and making better use of marine by-products like fish waste and shells.

Water resilience is a key element of a strong bioeconomy. Efficient water use, integrated management systems, and climate risk assessments need to be included in investment planning, in line with the Water Resilience Strategy. Healthy soils and stable water cycles form the essential foundation for long-term productivity, environmental balance and climate stability.

(COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, A Strategic Framework for a Competitive and Sustainable EU Bioeconomy, {SWD(2025) 895 final}, Brussels, 27.11.2025, COM(2025) 960 final, available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52025DC0960>)

6.1.3 Applications for forest resources

The strength of Europe's bioeconomy relies heavily on the health and resilience of its natural environment. Primary production forms the foundation of the bioeconomy, where sustainability and economic competitiveness can work together. Farmers, foresters, and fishers play a key role in managing Europe's natural resources, ensuring a balance between productive use of land and water and environmental protection. Their work supports food security, the supply of renewable materials, and the livelihoods of rural communities.

In forestry, sustainable management adapted to local conditions can ensure a stable long-term supply of raw materials for industry while preserving forests as important carbon sinks. This helps maintain both economic value and environmental stability over time.

Nature can also contribute directly to Europe's economic competitiveness. New and emerging markets, such as carbon and biodiversity credits, can financially reward efforts to restore and protect natural ecosystems, creating additional income opportunities for rural areas. In this context, the European Commission is developing carbon farming approaches and setting up an EU registry under the CRCF Regulation. It is also advancing the Nature Credits Roadmap to support voluntary, high-quality markets that complement carbon farming initiatives.

(COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, A Strategic Framework for a Competitive and Sustainable EU

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The BIOEAST initiative (Central and Eastern European initiative for knowledge-based agriculture, aquaculture, and forestry in the bioeconomy) was created by Central and Eastern European countries to strengthen cooperation, research, and policy development in the field of bioeconomy. It promotes collaboration between these countries in order to support knowledge-based innovation in agriculture, forestry, and aquaculture.

While BIOEAST countries are not directly involved in building the future EU bioeconomy monitoring system, they aim to influence its direction, priorities, and areas of focus. This is achieved through the BIOEAST Strategic Research and Innovation Agenda (SRIA), which helps guide research and innovation efforts across the region and aligns them with broader European bioeconomy goals (EC JRC, 2018a).

Forest resources provide a wide range of applications that are essential to both human society and the global economy. One of the most important uses is the production of timber, which is used in construction, furniture making, paper production, and various engineered wood products. Wood remains a renewable and versatile material, making forests a key supplier for sustainable building materials when managed responsibly. (<https://evs.institute/sustainable-natural-resource-management/forest-resources-productive-protective-roles/>)

Beyond timber, forests offer a variety of non-wood products, often referred to as non-timber forest products (NTFPs). These include fruits, nuts, mushrooms, medicinal plants, resins, paper and essential oils. Many communities around the world rely on these resources for food, traditional medicine, and income generation. In some regions, these products are even more economically valuable than timber itself. (<https://www.cambridge.org/core/books/abs/global-resources-and-the-environment/forest-commodity-and-noncommodity-values/52BCBA8CFEDE806623F53FB5E0E1DDA8>)

Forests also play a critical role in environmental applications. They act as carbon sinks, absorbing carbon dioxide from the atmosphere and helping to mitigate climate change. Additionally, forest ecosystems regulate water cycles, prevent soil erosion and maintain biodiversity by providing habitats for countless species of plants and animals. These ecological services are vital for maintaining environmental stability. (<https://www.intechopen.com/chapters/1193414>)

Finally, forest resources have significant recreational and cultural applications. Forests support tourism, hiking, ecotourism, and educational activities, offering people opportunities to connect with nature. They also hold cultural and spiritual importance for many indigenous and local communities. Overall, forest resources are indispensable, not only for their material products but also for their broader environmental and social benefits. (<https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/forest-resource>)

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