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Forests and the Economics of Climate Change: A Review of Knowledge, Challenges and Future Directions

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Abstract – Nacrtak

Forests play a growing role in the economics of climate change, functioning simultaneously as major carbon sinks and strategic assets within climate policy, carbon markets and the emerging bioeconomy. This review synthesises recent scientific and policy literature to examine how climate change is reshaping the ecological and economic foundations of European forests. Intensifying droughts, storms and pest outbreaks are altering forest productivity and stability, producing significant fluctuations in wood supply and price dynamics. These ecological impacts generate economic vulnerabilities that extend across value chains and undermine long-term investment certainty.

Forests are increasingly embedded in complex governance systems that include international climate agreements, EU climate legislation and emerging certification frameworks for carbon removals. While their role in most compliance carbon markets remains limited, voluntary carbon markets provide substantial economic opportunities, particularly for nature-based removals. Corporate net-zero strategies and rising demand for high-integrity credits position forests as important contributors to climate mitigation outside regulated systems. At the same time, adaptation measures (such as species diversification, improved forest management and enhanced monitoring) are essential for maintaining both ecological resilience and economic viability.

The review identifies a persistent gap in the literature: the lack of integrated analyses that combine ecological trends, market behaviour and carbon governance. By addressing this gap, the article highlights the potential of forests to contribute meaningfully to climate mitigation through carbon storage, removals and substitution benefits. Realising this potential, however, requires coherent policies, credible market mechanisms and proactive management strategies. Forests can serve as a crucial pillar of Europe's climate transition if ecological, economic and governance dimensions evolve in a coordinated and forward-looking manner.

Keywords: Forest carbon economics, climate-induced risks, carbon markets, bioeconomy

1. Introduction – *Uvod*

Climate change has become one of the defining economic forces of the 21st century. Although its origins lie in atmospheric physics and biogeochemical cycles, the consequences of climate change manifest most clearly through economic systems, resource allocation, and policy choices. At the centre of this global transformation stands carbon – a chemical element whose movement between the atmosphere, biosphere, and lithosphere has always shaped the Earth system, but which in the last century has become the cornerstone of international politics, regulation, and economic design.

As global anthropogenic emissions continued to rise through the late 20th century, the international community responded by creating a political architecture intended to manage humanity's relationship with the carbon cycle. The United Nations Framework Convention on Climate Change (UNFCCC)

established the foundational principles, followed by landmark milestones such as the Kyoto Protocol and the Paris Agreement (UNFCCC 2023). Kyoto introduced binding emission reduction targets and for the first time institutionalised carbon as a tradable commodity through mechanisms like emissions trading and project-based crediting. Paris shifted the global model from top-down burden-sharing to a system based on Nationally Determined Contributions (NDCs), while expanding the scope of carbon governance to include transparency, sinks, and the crucial Article 6 framework for international carbon markets. These agreements collectively reframed carbon from a by-product of industrial activity into a measurable, reportable and ultimately monetisable unit.

This political shift required a new technical backbone – carbon accounting. Accurate measurement, reporting and verification became a precondition for trust in the emerging system. National greenhouse gas inventories, land-sector accounting rules, reference levels for forests, and the development of internationally harmonised methodologies created the infrastructure through which emissions and removals could be quantified. In parallel, concepts such as the global carbon budget offered a simplified way to translate atmospheric science into policy constraints, defining how much CO_2 humanity can still emit while remaining within temperature limits.

Within this landscape, forests occupy a uniquely strategic position. They are among the largest and most dynamic carbon sinks on the planet, capable of absorbing vast quantities of atmospheric CO_2 while providing a wide array of ecosystem services. Unlike technological mitigation options, forests embody both mitigation and adaptation potential: they can remove carbon, store it for decades or centuries, substitute carbon-intensive materials, and buffer societies from climate extremes. As a result, forests have become one of the central components of climate policy frameworks, investment strategies, and national decarbonisation pathways.

In recent years, the economic relevance of forests has expanded dramatically. Markets for carbon removal, mechanisms for ecosystem service payments, corporate sustainability obligations and compliance carbon markets have elevated forestry from a traditional land-use sector to a pivotal actor in climate transition strategies. The integration of forests into emissions trading systems, voluntary carbon markets, and long-term climate planning has shifted the emphasis from viewing forests solely as a renewable resource to understanding them as part of the global carbon infrastructure. Consequently, in wide terms, the economic value of forests increasingly depends not only on wood production, but on their capacity to contribute to national climate targets and corporate decarbonisation commitments.

This review article situates forests within the broader economics of climate change, highlighting their evolving role in climate policy, carbon governance and market-based approaches. By synthesising insights from recent scientific literature, policy documents and international frameworks, the article outlines the key knowledge foundations, emerging challenges and future directions at the intersection of forestry and climate economics.

Across Europe, forests have become one of the most exposed natural systems to the accelerating impacts of climate change. Rising temperatures, shifting precipitation patterns and the increasing frequency of extreme weather events create a complex disturbance regime that is already redefining the structure, productivity and long-term viability of forest ecosystems. Over the last decade, Central Europe has witnessed unprecedented waves of windthrow, drought-induced decline and massive bark beetle outbreaks, resulting in record volumes of salvage logging, destabilised timber markets and large-scale economic losses (Březina et al. 2024). These disturbances are no longer isolated anomalies but an emerging pattern consistent with long-term projections of climate-driven risk escalation (Sandström et al. 2025).

At the same time, Europe's forests are central to the continent's climate ambitions. As the European Union progresses toward its climate neutrality target for 2050, forests are expected to deliver substantial carbon removals, ecosystem services and material substitution benefits. The EU policy architecture – stretching from the Green Deal and Fit for 55 package to the LULUCF Regulation and the forthcoming Carbon Removal Certification Framework – explicitly positions forests as a strategic asset for meeting climate goals. Yet, the stability of this asset is increasingly uncertain. Studies indicate that climate change may erode forest growth in some regions, alter species distributions, and reduce future wood availability by mid-century (Jönsson et al. 2025, Gauli et al. 2022). In several EU Member States, the recent surge in calamity harvesting has already exhausted future harvesting potential, creating the prospect of regional timber shortages and price volatility well before 2050 (Březina et al. 2024).

This interaction between ecological stress and economic vulnerability underscores the need to view forests not only as carbon sinks but as integral components of Europe's climate-economic system. Forest-based industries remain essential contributors to rural economies, the bioeconomy and low-carbon material substitution (Hetemäki 2022). However, their resilience depends on the balance between ecological capacity and market dynamics. When disturbances exceed adaptive thresholds, the effects propagate through supply chains: oversupplied markets depress prices, processing capacities become saturated, cross-border trade flows destabilise, and long-term investment decisions become riskier. These cascading impacts reveal that climate change does not merely affect forest ecology – it reconfigures the economic logic of the entire sector (Winkel et al. 2022).

Moreover, the integration of forests into carbon markets introduces new opportunities and risks. While Article 6 of the Paris Agreement and emerging voluntary markets create pathways for monetising forest-based carbon removals, they also require robust monitoring, verification and long-term permanence. Without credible accounting frameworks, carbon credits generated from forest activities risk market instability or environmental non-equivalence. This adds another layer of complexity: forest managers must now operate simultaneously in ecological, economic and regulatory domains, each shaped by different incentives and uncertainties (Persson et al. 2020, Roitsch et al. 2023).

In this context, understanding the economics of climate change in forestry becomes essential. It requires integrating knowledge from climate science, ecology, finance, policy and market analysis. Recent assessments emphasise that adaptation strategies – such as diversification of species, adaptive silviculture, resilient management systems and risk-sharing mechanisms – will be indispensable for maintaining forest productivity and safeguarding its climate mitigation role (Ludvig et al. 2024, Fraccaroli et al. 2021). Equally important is the need to develop long-term policy coherence, ensuring that climate mitigation objectives, forest health and economic viability are not pursued in isolation.

This review article builds on these insights to provide an integrated understanding of how climate change reshapes the economic foundations of forestry. By synthesising scientific findings, policy frameworks and market trends, it positions forests within the broader climate-economic transition and outlines the critical challenges and strategic pathways that will shape their future.

2. Problem matter – *Problematika*

The central challenge addressed in this review lies in the growing tension between the ecological transformations occurring in Europe's forests, the increasing regulatory demands embedded in climate policy frameworks, and the economic structures that depend on forest resources. Climate change is altering core ecological functions – growth dynamics, species composition, mortality rates and disturbance regimes – in ways that directly reshape the economic foundations of the forestry sector. These ecological shifts are mirrored by policy pressures as EU and international frameworks impose stricter requirements on carbon removals, inventory accuracy and land-sector accounting. At the same time, the timber market faces declining stability due to fluctuations in supply, price volatility and spatially uneven impacts of climate-driven disturbances (Březina et al. 2024). None of these forces operates in isolation. Instead, they interact, reinforce and often magnify one another, creating a complex triad that redefines what it means to manage forests in a climate-constrained economy.

This problem has become particularly urgent in the current decade. Disturbance events (windstorms, prolonged droughts, heatwaves and bark beetle outbreaks) have reached unprecedented magnitudes across Central Europe, pushing salvage logging volumes to historic highs (Sandström et al. 2025). In several regions, the cumulative effect of successive disturbances has depleted future harvesting potential, increasing the likelihood of regional wood shortages and sustained market disruptions (Březina et al. 2024). Simultaneously, climate policy instruments have strengthened expectations for steady or increasing levels of carbon removals from forests, even as their ecological capacity becomes more uncertain. Projections suggest that climate change may reduce forest growth in parts of Europe and shift species distributions in ways that challenge traditional models of wood supply (Jönsson et al. 2025**,** Gauli et al. 2022). On top of this, the rise of carbon markets and certification frameworks imposes more complex monitoring, reporting and verification requirements, increasing administrative burdens for forest managers (Fraccaroli et al. 2021). The convergence of ecological instability, regulatory tightening and economic vulnerability makes this issue not only scientifically relevant but strategically critical for policy, management and investment.

Despite rapid developments in research, significant gaps persist in current knowledge. Many ecological studies provide detailed insights into growth

responses, disturbance dynamics or species-specific vulnerabilities, yet they rarely connect these findings to broader economic implications. Conversely, economic analyses of timber markets or carbon pricing mechanisms often treat ecological processes as exogenous, overlooking their internal variability and sensitivity to climate extremes. Research on natural disturbances is abundant, but far fewer studies systematically analyse how disturbance-driven oversupply affects trade flows, price formation or long-term processing capacities. Policy-oriented literature is extensive on climate mitigation and carbon accounting, yet lacks integrative analyses that link policy requirements with forest ecosystem trends and market realities. Emerging frameworks such as Article 6, the Carbon Removal Certification Framework or evolving EU LULUCF rules are developing faster than the scientific literature can consolidate. In short, the field lacks a comprehensive analytical framework that simultaneously captures climate impacts, market behaviour, carbon governance and forest-sector policy. This review aims to fill that gap by offering a synthetic, multi-dimensional assessment grounded in the most recent scientific and policy evidence.

The purpose of this review is to integrate insights from ecology, economics, governance and climate policy in order to understand how climate change reshapes the economic foundations of forestry. The review identifies points of convergence and divergence between ecological trends and economic responses, clarifies how forests are positioned within carbon markets and regulatory systems, and highlights strategic pathways to enhance resilience and competitiveness. By linking biophysical processes with regulatory architectures and market outcomes, the review provides a coherent analytical basis for decision-making in a sector navigating rapid transformation.

Within this analytical framework, several overarching research questions guide the synthesis presented in the following sections. First, how do climate change impacts and natural disturbances reshape the economic foundations of the European forestry sector? Second, what role do forests play in the evolving architecture of global carbon governance? Third, how do carbon accounting frameworks and climate policies influence the economic value of forests and forest-based products? Fourth, which economic risks and opportunities emerge as the forestry sector adapts to climate transition? And finally, what strategic pathways could strengthen the long-term resilience and competitiveness of forest-based value chains? These questions collectively define the scope of the review and define the thematic structure of the analysis.

The objectives of the review follow directly from these guiding questions. The first objective is to synthesise relevant scientific knowledge on the interactions between forests, carbon and climate policy. The second is to identify the key economic challenges created by climate impacts on forest ecosystems and wood markets across Europe. The third objective is to analyse how forests are being integrated into regulatory and market-based climate instruments, including compliance and voluntary carbon markets. The fourth is to outline strategic opportunities for future management, governance and investment aimed at strengthening forest-based mitigation and adaptation. Together, these objectives create an analytical lens capable of capturing the complexity of the climate–carbon–forest economy system.

The literature included in this review was identified through targeted searches in Web of Science, Scopus and Google Scholar, complemented by EU and UNFCCC policy documents. Priority was given to peer-reviewed studies published after 2015 and policy documents of high relevance to EU forest and climate governance. In total, 22 scientific publications were analysed, supplemented by key policy documents from the EU and UNFCCC. These sources were grouped into thematic clusters that structure the analytical sections of this review.

3. Thematic Literature Overview – *Pregled tematske literature*

Climate impacts on forests – *Klimatski utjecaji na šume*

Recent scientific work consistently shows that European forests are entering a period of accelerated ecological stress driven by climate change. Across Central and Northern Europe, shifts in temperature, precipitation and seasonal patterns are altering growth dynamics and species competitiveness. Observational and modelling studies indicate that climate-driven variation in growth may lead to spatially uneven changes in productivity, with some regions experiencing declines in dominant commercial species (Gauli et al. 2022). Several analyses emphasise that climate change is not only modifying long-term growth trajectories but also increasing the frequency and magnitude of acute disturbance events. Large-scale windthrow episodes, prolonged droughts, and successive bark beetle outbreaks have

become defining features of recent decades, producing volumes of salvage timber unprecedented in modern forest management (Březina et al. 2024, Sandström et al. 2025, Gauli et al. 2022, Jönsson et al. 2025). Disturbance patterns described by Sandström et al. (2025) show clear signals of intensification, with interacting drivers – heat stress, water deficits, pathogen spread and extreme winds – continually pushing forest ecosystems beyond previously observed thresholds

Climate data products tailored for forestry further reinforce these findings. Fraccaroli et al. (2021) highlight the importance of integrated climate information systems capable of linking high-resolution climate projections with stand-level processes, reinforcing that reliable climate datasets are becoming an essential component of decision-making in forest management and long-term planning. Projections of future wood supply indicate considerable uncertainty: Jönsson et al. (2025) demonstrate that European wood availability may decline under plausible climate scenarios, with significant implications for both harvesting potential and market stability. Similarly, studies on productivity trends underline that species composition will play a central role in determining future resilience, particularly in regions where traditional conifer-dominated structures are highly vulnerable to heat and drought stress (Jönsson et al. 2025). Taken together, this body of literature portrays a forest sector whose ecological foundation is being reshaped by climate change at multiple spatial and temporal scales.

Timber markets and economic risks – *Tržišta drva i ekonomski rizici*

The ecological pressures documented above translate directly into economic volatility. Several studies (i.e. Březina et al. 2024, Sandström et al. 2025) highlight that the increasing scale of climate-induced disturbances is destabilising timber markets across Europe. Excessive volumes of calamity wood entering the market following large disturbance events have repeatedly driven prices downward, challenging processing capacities and disrupting cross-border trade flows (Březina et al. 2024). Analyses of short-term wood supply reveal that disruptions caused by drought and bark beetle outbreaks, such as those documented in Poland, Czechia and Germany, are leading to cyclical oversupply followed by medium-term deficits, creating long-term mismatches between harvest capacity and industrial demand (Kotlarz et al. 2024).

Market-oriented studies emphasise that these cycles are not isolated events but reflect structural vulnerabilities within the European forestry sector. Economic assessments of species-change scenarios suggest that climate-driven shifts in species composition can alter production costs, wood quality and long-term revenue potential. In addition, macroeconomic analyses underscore the economic role of forests not only as timber suppliers but also as providers of multiple ecosystem services, which becomes increasingly relevant in periods of market instability (Winkel et al. 2022). The literature on bioeconomy transitions also stresses the rising importance of forest-based sectors for material substitution, yet warns that climate-induced fluctuations in raw material availability may impede these transitions unless risk-aware planning frameworks are adopted (Hetemäki 2022). Overall, the evidence suggests that timber markets in Europe are entering a phase of heightened instability, closely linked to the intensification of climate pressures on forest ecosystems.

Policy and governance frameworks – *Politika i okviri upravljanja*

A significant strand of the literature focuses on the policy environment that governs the role of forests in climate mitigation and adaptation. The European forest sector is embedded in an increasingly complex regulatory system that includes climate legislation, biodiversity strategies, renewable energy directives and emerging carbon removal certification standards. Nabuurs et al. (2019) outline how EU post-2020 forest policy integrates mitigation objectives with broader sustainability and bioeconomy goals, positioning forests as a central component of the EU's long-term climate neutrality vision. Winkel et al. (2022) examine governance challenges associated with managing forests for multiple ecosystem services, highlighting tensions between climate mitigation, biodiversity protection and economic objectives.

Policy-focused research emphasises that climate mitigation commitments under EU LULUCF accounting rules are shaping forest management strategies in ways that differ substantially across Member States. Studies by Gren et al. (2018) underscore the economic implications of meeting EU climate targets, particularly as the cost of forest carbon sequestration becomes increasingly sensitive to climate-induced disturbances and pathogen outbreaks. Kauppi et al. (2022) place forests within a

broader mitigation hierarchy, emphasising that sustainable management, carbon storage and material substitution together determine the net climate contribution of forest sectors. Additionally, documents addressing systemic transformation (i.e. Moallemi et al. 2025) stress the need for governance models that support long-term resilience rather than short-term optimisation. Taken together, these works demonstrate that policy and governance considerations are inseparable from ecological and economic realities, making them essential to any integrated analysis of the forestry sector under climate change. These dynamics are also reflected in broader EU policy frameworks, such as the EU Forest Strategy for 2030 and the EU Biodiversity Strategy for 2030, both of which emphasise stricter forest protection, enhanced resilience and long-term sustainability of forest ecosystems.

Adaptation, resilience and forest management responses – *Prilagodba, otpornost i odgovori gospodarenja šumama*

A substantial portion of the literature addresses strategies designed to enhance forest resilience and maintain economic and ecological function in a changing climate. Adaptation-oriented studies suggest that diversification of species composition, structural heterogeneity and adaptive silvicultural systems are central to reducing vulnerability to climate-induced disturbances (Augustynczik et al. 2025). Large-scale assessments highlight that resilience-oriented interventions, such as altering rotation lengths, enhancing mixed-species stands or strengthening landscape-level connectivity, can substantially reduce susceptibility to disturbance cascades (Verkert et al. 2022).

Empirical research further underscores the necessity of integrating adaptation and mitigation. Ludvig et al. (2024) identify a range of resilience-enhancing practices that address both ecological and economic risks, emphasising the role of stakeholder collaboration and governance innovation in implementing such strategies. Studies exploring the effects of species change (Remeš et al. 2020) provide insights into economic trade-offs associated with managing forests for long-term resilience. Sandström et al. (2025) demonstrate that disturbance regimes themselves are evolving, requiring management systems that are not merely reactive but anticipatory. Overall, the literature portrays adaptation as a multidimensional process requiring coordinated action across ecological, economic and policy domains.

Forests in climate economy and bioeconomy transition – *Šume u klimatskoj ekonomiji i tranziciji bioekonomije*

The final thematic cluster links forests to broader socio-economic transformations associated with climate policy and sustainable development. Research on forest-based bioeconomy pathways highlights forests as essential providers of renewable materials that can substitute carbon-intensive products, thereby reducing lifecycle emissions across multiple sectors (Hetemäki 2022). Kauppi et al. (2022) demonstrate that achieving climate neutrality in Europe will require a combination of increased carbon storage in forests, reduced emissions from land use and expanded use of harvested wood products in long-lived applications. Nabuurs et al. (2019) further emphasise forests as strategic assets in the EU's climate transition, capable of supporting both economic development and climate mitigation objectives.

Governance-focused literature (Winkel et al. 2022) indicates that the bioeconomy transition introduces new policy challenges around sustainability, land-use competition and long-term resource availability. System-level analyses (Moallemi 2025) highlight that achieving a sustainable forest-based economy requires transforming value chains, enhancing innovation capacity and integrating climate risk into long-term planning. These studies collectively show that the role of forests in the climate economy is broadening, moving beyond traditional timber production to include carbon removal, material substitution, biodiversity protection and socio-economic contributions to rural regions.

4. Economic potentials of forests regarding climate change economics – *Ekonomski potencijali šuma u odnosu na ekonomiku klimatskih promjena*

Forests have become increasingly relevant within the broader architecture of climate change economics as carbon markets expand, diversify and adapt to global decarbonisation pathways. Their role derives from the ability of forest ecosystems to remove atmospheric carbon dioxide, store it in biomass and soils, and generate climate-relevant benefits with both environmental and monetary value. As carbon markets evolve, forests stand at the intersection between ecological processes and economic mechanisms, especially through their capacity to produce carbon credits (certified units representing quantified greenhouse gas removals or avoided emissions).

Understanding this economic potential requires distinguishing between two fundamentally different types of carbon markets: compliance (mandatory) markets and voluntary markets, each with distinct rules, incentives and opportunities for forestry.

Compliance carbon markets, such as the EU Emissions Trading System (EU ETS), the Swiss ETS and regional systems (e.g. California Cap-and-Trade) are designed to regulate emissions by limiting the total quantity allowed and enabling trading of emission allowances. Forestry has historically had limited or no direct access to most compliance systems in the world, largely due to concerns over permanence, leakage and monitoring uncertainty. Under the Paris Agreement, countries may use Internationally Transferred Mitigation Outcomes (ITMOs) to meet their Nationally Determined Contributions. Though forest-based ITMO transactions remain rare due to the rigorous accounting requirements and long-term risks associated with land-based carbon (UNFCCC 2023). In the European Union, future pathways may open through the Carbon Removal Certification Framework (CRCF), which aims to define standards for certified carbon removals, including nature-based options. However, CRCF is still a certification framework (not a trading market) and its integration into future EU climate instruments remains uncertain. For now, forestry plays only a marginal role in compliance markets, with a potentially growing but still constrained future.

In contrast, the voluntary carbon market (VCM) has emerged as the primary arena in which forests can generate significant climate-economic value. Voluntary markets allow organisations to purchase carbon credits to meet self-imposed climate commitments, such as net-zero targets or ESG (Environmental, Social and Governance) requirements. According to the World Bank (2024), voluntary markets have grown into a global ecosystem involving independent crediting mechanisms, third-party verifiers and a wide range of project developers. Forest-related carbon credits, particularly those derived from afforestation, reforestation, improved forest management and other nature-based solutions, make up a substantial share of voluntary transactions. Since voluntary markets are not tied to national emissions accounts, they offer a more flexible environment for forestry activities and have, in recent years, become the dominant marketplace for forest carbon credits.

Carbon crediting itself refers to the process of generating certified units that represent one tonne of CO_2-eq avoided or removed from the atmosphere. Under UNFCCC principles, valid carbon credits must meet core criteria: additionality (the climate benefit would not have occurred without the project), permanence (the benefit persists for a defined period), measurability, verifiability and avoidance of double counting. Mechanisms that issue credits can be grouped into three broad categories: international mechanisms, such as those established under Article 6 of the Paris Agreement; independent mechanisms, such as the Verified Carbon Standard (Verra) and the Gold Standard; and governmental mechanisms, operated by national jurisdictions (states). The World Bank's global assessment indicates that governmental crediting schemes represent the majority of active mechanisms worldwide, though independent schemes dominate in voluntary markets due to their flexibility and global reach.

Forest-based carbon credits are typically produced by project developers (public agencies, private landowners, cooperatives or companies) who undertake measurable land-use or forestry actions that sequester carbon or avoid emissions. Credits are verified by accredited auditors and issued by a crediting mechanism, then sold on voluntary markets where buyers use them to meet climate-related commitments. Buyers in voluntary markets include multinational corporations seeking to offset unavoidable emissions, financial institutions incorporating offsets into sustainability portfolios, and organisations aiming to strengthen ESG performance (Environmental, Social and Governance).

The broader economic potential of forests in climate change economics extends beyond direct revenue from carbon credits. Forests function as long-term carbon infrastructure, supporting corporate and national net-zero strategies. They offer a diversified portfolio of ecosystem services (climate regulation, biodiversity, water protection) that can be monetised under emerging payment schemes. In addition, forests contribute to climate mitigation indirectly through material substitution, reducing emissions in the construction and industrial sectors. As climate policies increasingly converge toward net-zero pathways, forests are positioned as both ecological assets and economic instruments within the global transition.

Ultimately, forests hold limited but evolving potential in compliance markets and dominant, immediate potential in voluntary carbon markets. As regulatory frameworks mature and new mechanisms emerge, particularly within the EU, the role of forests in climate change economics will continue to expand. Their capacity to absorb and store carbon makes them indispensable not only ecologically but

also economically, underpinning the development of carbon markets and supporting global climate objectives.

5. Economic Synthesis and Perspectives – *Ekonomska sinteza i perspektive*

Recent research highlights that the economic value of forests extends far beyond timber. Carbon storage, removals and material substitution now drive much of their relevance within climate mitigation strategies. Carbon markets reinforce this trend. Although forestry remains constrained in most compliance systems, voluntary carbon markets have become the principal arena for monetising forest-based climate benefits, fuelled by corporate net-zero commitments and strong demand for nature-based removals. Instruments such as the EU Carbon Removal Certification Framework may expand regulated opportunities in the future, but voluntary markets currently hold the greatest potential.

Ecological instability already generates clear economic impacts. Salvage-driven oversupply depresses prices, while mortality and productivity declines create medium-term scarcity risks. These shocks cascade along value chains, affecting processing capacity, trade flows and regional economies. Adaptation therefore has both ecological and financial importance. Measures such as species diversification, adaptive silviculture, enhanced monitoring and resilience-focused management are essential for reducing exposure to biophysical and market risks.

Policy coherence will strongly influence future outcomes. Forests sit within overlapping agendas for mitigation, biodiversity, rural development and energy, and misalignment can undermine long-term climate goals. Strengthened monitoring, reporting and verification systems are necessary to ensure the credibility and durability of forest-based carbon contributions, particularly as nature-based removals gain prominence.

Looking ahead, the economic potential of forests will depend on aligning ecological dynamics, credible market structures and forward-looking governance. High-quality removals, resilient forest systems and harmonised policy frameworks will be key to ensuring that forests remain a central pillar of Europe's climate transition and contribute effectively to both mitigation and the emerging low-carbon bioeconomy. A key conclusion is the rising importance of carbon crediting in forestry as a direct link between ecosystem processes and climate economics. By converting forest-based removals into verified carbon credits, forests generate measurable climate benefits that can be monetized (especially in voluntary markets, where high-quality nature-based credits are increasingly demanded). When supported by strong standards of additionality, permanence and MRV, carbon crediting provides forests with a durable economic role in global decarbonisation, reinforcing their value beyond timber and helping finance adaptation and resilience in a changing climate.

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Sažetak

Uloga šuma u ekonomici klimatskih promjena: stanje, izazovi i perspektive

Šume imaju sve važniju ulogu u ekonomici klimatskih promjena jer djeluju istodobno kao veliki ponori ugljika, proizvođači obnovljivih materijala i strateški resurs unutar klimatskih politika i tržišta ugljika. Ovaj pregledni rad sintetizira najnovije znanstvene i političke spoznaje o tome kako klimatske promjene mijenjaju ekološke i ekonomske temelje europskih šuma. Učestali klimatski poremećaji – suše, vjetroizvale, toplinski valovi i gradacije potkornjaka – utječu na produktivnost, strukturu i stabilnost šuma te uzrokuju velike oscilacije u ponudi drva i njegovoj tržišnoj cijeni. Takvi ekološki poremećaji stvaraju ekonomsku ranjivost duž cijeloga vrijednosnoga lanca proizvodnje, uključujući preradu, trgovinu i dugoročno ulaganje.

Istodobno se uloga šuma sve snažnije utvrđuje u okvirima klimatskih politika, uključujući međunarodne sporazume, klimatsko zakonodavstvo EU-a i nove mehanizme certificiranja uklonjenoga ugljika. Premda je izravno sudjelovanje šumarstva u obveznim (engl. compliance) tržištima ugljika ograničeno, dobrovoljna tržišta ugljika postala su glavni prostor u kojem šume ostvaruju ekonomsku vrijednost zbog uklanjanja ugljika. Potražnja za visokokvalitetnim, prirodno utemeljenim ugljičnim kreditima potaknuta je upravo korporativnim strategijama nulte neto stope emisije.

Pregled literature pokazuje nedostatak integriranih analiza koje istodobno uzimaju u obzir ekološke trendove, tržišno ponašanje i instrumente klimatskoga upravljanja. Ovaj rad pridonosi popunjavanju te praznine uspostavljanjem analitičkoga okvira koji povezuje klimatske utjecaje, poremećaje u opskrbi drvom, funkcioniranje tržišta te regulaciju uklanjanja ugljika. Rezultati naglašavaju da će budući ekonomski potencijal šuma ovisiti o usklađivanju ekološke otpornosti vjerodostojnih tržišnih mehanizama i dugoročno stabilnih politika. Šume će imati ključnu ulogu u klimatskoj tranziciji Europe samo ako se biološke, ekonomske i upravljačke dimenzije razvijaju usklađeno, a mehanizmi tržišta ugljika ostanu transparentni i znanstveno utemeljeni.

Ključne riječi: ekonomika šumarstva, klimatske promjene, tržišta ugljika, bioekonomija

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