Vol. 1(3): 112-131, July 2025

FOREST AND NATURE

Homepage: https://www.greenishpub.com/fornature

RESEARCH ARTICLE

Climate and Biodiversity Nexus: Strategies for Sustainable Forestry in Europe

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ARTICLE INFO

Article History:
Received: 25 March 2025
Revised: 2 June 2025
Accepted: 29 June 2025

Keywords:
Biodiversity conservation
Carbon sequestration
Climate change mitigation
Ecological diversity
EU green deal

Citation: Velayudhan, A. V., & Jaeger, C. (2025). Climate and Biodiversity Nexus: Strategies for Sustainable Forestry In Europe. *Forest and Nature*, *1*(3), 112-131.

ABSTRACT

Balancing climate change mitigation with biodiversity conservation remains a pivotal challenge for sustainable forest management in Europe. This study investigates the nexus between carbon sequestration and biodiversity across European forest regions from 1990 to 2020, integrating data on forest biomass, carbon stock, and biodiversity indicators using statistical modeling in R. Results show a steady increase in forest area and carbon stocks, particularly in Central-East and Central-West Europe, driven by afforestation and adaptive forest policies. However, biodiversity responses vary by region and the intensity of management. Forests under low-intensity or semi-natural management, particularly mixed-species stands, exhibit positive correlations between carbon stock and biodiversity metrics, such as species richness and the Shannon index. In contrast, intensively managed monocultures—such as Eucalyptus plantations in South-West Europe—exhibit rapid carbon gains but reduced ecological resilience, characterized by low evenness and structural diversity. Generalized additive models (GAMs) reveal non-linear, species- and region-specific dynamics in the carbon-biodiversity relationship, emphasizing the importance of ecological context. These findings highlight critical trade-offs and synergies in forest management, calling for integrated policies that consider forest structure, species composition, and long-term ecosystem resilience. The study recommends regionally differentiated strategies, stronger biodiversity monitoring, and enhanced policy coherence to align with the EU Green Deal and Forest Strategy 2030, advancing Europe's path toward climate-smart, biodiversity-rich forestry.

1. Introduction

Addressing climate change while conserving biodiversity poses a significant challenge for sustainable forest management. Forests play a dual role as essential carbon sinks, reducing greenhouse gas concentrations (Bonan, 2016; Nave et al., 2018), and as habitats supporting diverse ecosystems vital to ecological balance (Paillet et al., 2017). However, the relationship between carbon storage and biodiversity is complex, demanding a nuanced understanding of how these objectives may either complement or conflict with one another (Liang et al., 2016; Veldman et al., 2015). Clarifying these interactions is crucial for developing strategies that effectively integrate climate mitigation and biodiversity preservation goals (Reyer et al., 2017). European forests are indispensable for achieving the climate and biodiversity targets outlined in the EU Green Deal (IPCC, 2022; Lindner et al., 2017). These forests contribute not only to climate regulation through carbon sequestration but also support unique and diverse ecosystems (Maes et al., 2016; Meyer et al., 2016). However, increasing anthropogenic pressures such as intensive timber harvesting and land-use changes, combined with the accelerating impacts of climate change, threaten forest resilience and biodiversity (Seidl et al., 2017).

To maintain resilient and biodiverse forests, sustainable management practices that balance competing demands must be prioritized. This requires robust, evidence-based insights into the ecological and climatic roles of forests. By employing a data-driven approach – particularly valuable in this context for providing empirical clarity on the complex and sometimes counterintuitive relationships between carbon storage and biodiversity, thus avoiding oversimplified assumptions—this study seeks to identify synergies and trade-offs in forest management practices. Utilizing statistical analysis in R, the research integrates quantitative data on forest biomass, carbon storage, and biodiversity metrics, including species richness and diversity indices (Maes et al., 2016). The study further investigates how forest management strategies, including intensive timber production, influence both carbon storage and ecological diversity (Meyer et al., 2016; Veldman et al., 2015). Additionally, it explores whether forests with higher carbon stocks tend to support greater biodiversity and examines the influence of factors such as forest age, species composition, and historical land use on these relationships (Paillet et al., 2017; Reyer et al., 2017). The study specifically investigates whether increased carbon sequestration is correlated with higher biodiversity in forests with varying levels of management intensity. The findings aim to provide policymakers and forest managers with actionable insights, fostering the development of integrated management strategies that align with Europe's climate and biodiversity objectives (Bonan, 2016; IPCC, 2022). By addressing these interconnected challenges, this research contributes to promoting forests that are both climate-resilient and ecologically sustainable (Nave et al., 2018).

Existing research underscores the significant impact of climate change on European forests and their biodiversity. Studies, such as those published in Forest Ecology and Management (Seidl et al., 2017), demonstrate that climate-induced stresses, including temperature increases, altered precipitation patterns, and pest outbreaks, can disrupt forest ecosystems. For example, species like spruce are particularly vulnerable to heat stress and pests, whereas others, such as beech, may thrive in warmer conditions. These compositional changes lead to deeper ecological consequences – not only altering forest structure but also introducing new challenges for biodiversity. Specifically, climate-driven disturbances can cause habitat fragmentation, reduce the availability of specialized ecological niches, and trigger trophic cascades that destabilize existing food webs. Such changes undermine species coexistence and disrupt ecosystem functionality, making it challenging to achieve conservation outcomes (Hanewinkel et al., 2013; Zimmermann et al., 2015). In response to these challenges, the European Union has implemented strategies that integrate climate change mitigation with biodiversity preservation. The EU Biodiversity Strategy for 2030 – Bringing nature into our lives emphasizes the importance of protecting and restoring ecosystems through initiatives such as planting 3 billion trees and restoring 25,000 km of rivers (European Commission, 2020), implementation faces challenges including funding constraints, conflicting land uses, and regional disparities in policy enforcement (Knorn et al., 2018; Müller et al., 2021). These issues highlight a gap between policy goals and practical outcomes. Research also highlights the importance of sustainable forest management (SFM) in balancing climate mitigation with biodiversity conservation. A study by Brockerhoff et al. (2017) suggests that practices such as mixed-species planting and maintaining forest structure are essential for enhancing forest resilience and supporting diverse species. By adopting these adaptive management strategies, European Forestry can foster ecosystems that are better equipped to respond to climate change while ensuring the continued preservation of biodiversity. Thus, integrating biodiversity conservation into forest management is crucial for building resilient forests that can effectively address the dual challenges of climate change and species loss.

Sustainable forestry practices in Europe focus on maintaining biodiversity, enhancing carbon sequestration, and adapting to climate change. A study by Repo et al. (2024) highlights the increasing adoption of adaptive management techniques, such as continuous cover forestry (CCF) and mixed-species planting, to promote resilience and biodiversity. CCF, through selective logging and a multi-layered canopy, protects soil and water quality, supports various species, and ensures long-term forest health. These practices are integrated into national and EU forest management strategies to mitigate climate impacts and foster ecological diversity.

The EU's Forest Strategy 2030, as detailed in Gregor et al. (2024), outlines actions to enhance sustainable forestry, focusing on carbon storage and biodiversity conservation. Key measures include promoting afforestation, improving forest resilience, and restoring degraded ecosystems. The EU emphasizes integrating biodiversity conservation with climate change mitigation, advocating for forest management that prioritizes ecological services and carbon sequestration to help forests adapt to future climate conditions. Balancing timber production with non-timber services is critical. Earlier studies, such as Bishop (1998), emphasized multifunctionality; however, more recent studies (Thorsen et al., 2019; Stanturf et al., 2021) expand this perspective by incorporating ecosystem services valuation and socioeconomic factors, reflecting the evolving policy and market contexts.

Integrating biodiversity conservation with climate action is crucial to achieving sustainable outcomes, but knowledge gaps hinder the development of effective nature-based solutions (NbS). A unified framework for measuring biodiversity outcomes is needed, incorporating tools such as ecosystem risk assessments and functional diversity metrics, as noted by Diaz et al. (2019) in Science. To ensure resilience under changing conditions, monitoring ecosystem shifts and risks associated with climate change requires standardized systems to anticipate and effectively manage these transitions (Williams et al., 2022). Additionally, improving predictive models for site-specific climate conditions is essential to ensure NbS resilience. Expanding restoration strategies to address global biodiversity and climate threats is critical, with adaptive restoration approaches – such as those outlined by Frietsch et al. (2023) offering scalable future-proof solutions, while strengthening a risk assessment framework integrating NbS into environmental risk management will ensure NbS are sustainable and impactful (Accastello et al., 2019). Addressing these areas will enhance NbS' effectiveness in achieving both biodiversity and climate goals by 30-50%. Targeted advancements in biodiversity metrics, predictive modelling, and risk assessment will not only improve the design and resilience of NbS but also enable more accountable, evidence-based implementation that supports long-term biodiversity and climate policy goals.

2. Materials and Methods

2.1. Data Sources and Collection Methods

The study utilizes various data sources to analyze the relationship between carbon sequestration and biodiversity in European forests. Key data sources include the European Environment Agency (EEA), FAO Forest Resource Assessments, and biodiversity databases like the Global Forest Watch. Carbon stock data were extracted from official reports and climate-related datasets (EEA, 2021; FAO, 2020). Biodiversity indices, including species richness and Shannon diversity, were gathered from biodiversity monitoring programs across different forest types in Europe. Data selected for analysis cover the period from 2010 to 2020, providing a longitudinal view of forest ecosystem dynamics. The study focused on forest regions representing diverse ecosystem types and management regimes, selected based on data availability, ecological significance, and representation of major European forest biomes. Limitations of these secondary data include inconsistencies in spatial and temporal resolution, as well as potential reporting biases, which are acknowledged and addressed through data cleaning and quality control processes.

2.2. Carbon Sequestration Strategies in the EU and China

Carbon sequestration through forest management is a key strategy for mitigating climate change in the EU and China. Both regions focus on afforestation, reforestation, and sustainable forest management (SFM) to enhance forest carbon stocks. In the EU, strategies have evolved from a predominant emphasis on timber production to more multifunctional and integrated frameworks. These now include adaptive management practices that simultaneously support climate mitigation, biodiversity preservation, and broader ecosystem services. This development reflects a growing recognition that forests serve multiple roles beyond resource extraction, such as carbon sinks, biodiversity reservoirs, and providers of cultural and recreational value. A study by Kilpeläinen and Peltola (2022) highlights that EU forests serve as significant carbon sinks, with practices such as mixed-species planting and selective logging contributing to increased forest carbon stocks. The EU also supports forest restoration through initiatives such as the European Green Deal, aiming to enhance carbon storage.

In China, forest carbon sequestration plays a central role in climate change mitigation, with massive afforestation programs expanding forest cover and enhancing carbon storage. Research by Ingrosso and Pausata (2024) highlights projects, such as the Green Great Wall initiative, which help combat desertification. However, challenges remain regarding biodiversity and forest health. China is integrating SFM practices to balance carbon sequestration with ecological resilience. Both regions recognize the need to manage forest ecosystems (**Table 1**) to maximize carbon sequestration while ensuring biodiversity conservation. Forest management strategies must consider the interactions between forest structure, species composition, and carbon storage. Integrating biodiversity-friendly practices, such as protecting native species and promoting mixed-species forests, is crucial for enhancing long-term carbon sequestration in both regions.

Table 1. Comparison of forest carbon sequestration practices: China versus EU

Category	China	European Union (EU)
Afforestation and Reforestation	Large-scale afforestation programs like Grain for Green and Three-North Shelterbelt	The EU Forest Strategy 2030 aims to plant 3 billion trees by 2030
Sustainable Forest Management (SFM)	Selective logging, bamboo forests, and fire/pest management	Continuous Cover Forestry (CCF), deadwood retention, and mixed-species forests
Agroforestry and Carbon Farming	Expanding bamboo forests and integrating agroforestry systems	Promotes agroforestry and carbon farming under the EU Green Deal
Peatland and Wetland Restoration	Restoration of wetlands (e.g., Sanjiang Plain) and peatland conservation	Rewetting peatlands and protecting carbon-rich wetlands through LIFE projects
Forest Carbon Markets	National carbon trading market (since 2021) supporting forest-based credits	EU Emissions Trading System (ETS) and voluntary carbon offset markets
Community and Financial Incentives	Payment for Ecosystem Services (PES) for afforestation and conservation	Common Agricultural Policy (CAP) supports farmers adopting carbon-friendly forestry
Biodiversity Conservation	Focus on large-scale tree planting and ecosystem restoration	The Natura 2000 Network protects and restores natural forest ecosystems
Policy Frameworks	National Forest Conservation Program (NFCP) and Climate Action Plans	EU Biodiversity Strategy, Green Deal, and Forest Strategy 2030
Challenges	Risk of monoculture plantations, water scarcity in afforestation projects	Balancing carbon sequestration with biodiversity conservation and sustainable logging

2.3. Analytical Framework

The analysis follows a quantitative approach, integrating carbon sequestration data with biodiversity metrics. Using R programming, statistical methods such as correlation analysis, linear regression, and generalized additive models (GAMs) are applied to assess the relationship between forest carbon stock and biodiversity. The framework aims to identify patterns and interactions between forest management practices, carbon storage, and biodiversity. This allows for the examination of potential trade-offs and synergies in sustainable forestry practices (Sabatini et al., 2019). The analysis adopts a multivariate statistical approach, integrating carbon stock data with biodiversity indices to explore complex relationships. Forest management practices were included as categorical explanatory variables, based on classification data from management records, enabling an assessment of their direct influence on carbon sequestration and biodiversity outcomes. Generalized additive models (GAMs) were selected for their flexibility in modeling non-linear relationships typical in ecological data, offering an advantage over linear models. Other methods, such as structural equation modeling (SEM) and mixed-effects models, were considered; however, GAMs were preferred due to their suitability in capturing smooth effects of environmental covariates and their interpretability in this context. Model validation involved cross-validation techniques and selection based on Akaike information criterion (AIC) values to ensure optimal model fit. Residual analyses were conducted to verify assumptions of homoscedasticity and normality. Multicollinearity among predictor variables was tested using variance inflation factors (VIF), ensuring all were below critical thresholds to avoid bias in regression estimates.

2.4. R Programming Techniques and Tools Used

R was used for data manipulation, analysis, and visualization. The tidyverse package facilitated data cleaning and transformation, while the GGPLOT2 library was employed for creating visual representations of the data. The vegan package was used to compute biodiversity indices, and the "mgcv::gam()" function was applied to model the relationship between climate variables, carbon stock, and biodiversity (Oksanen et al., 2020). Statistical testing, including ANOVA and Kruskal-Wallis tests, was performed to evaluate the significance of differences across forest types (Team, 2021). Data analysis was conducted in R, employing several specialized packages to handle distinct analytical tasks. The tidyverse package facilitated comprehensive data cleaning and transformation, including handling missing values through multiple imputation methods and identifying outliers via statistical diagnostics and visual inspection. For biodiversity analyses, the vegan package was used to calculate multiple diversity indices, including Shannon and Simpson indices, enabling robust ecological characterization. Visualization tasks, both exploratory and for presenting final statistical results, were performed using GGPLOT2, supporting clear and informative graphical outputs. The "mgcv package's gam()" function was used to fit generalized additive models, integrating climate variables, carbon stock, and biodiversity metrics. Statistical tests, such as ANOVA and the Kruskal-Wallis test, were applied to assess differences in biodiversity indices across forest types and management categories. Post hoc corrections, including the Bonferroni method, were implemented to adjust for multiple comparisons and minimize the risk of Type I error.

3. Results and Discussion

3.1. Results

Analysis of European forest data from 1990 to 2020 reveals a consistent increase in forest area, carbon stocks, and biomass, with notable regional variability in forest composition and biodiversity. Data were primarily sourced from the European Environment Agency (EEA) and the FAO Forest Resource Assessment to ensure transparency and reliability. Confidence intervals and statistical indicators are included to assess the significance of observed trends.

Fig. 1 displays the total forest area in Europe between 1990 and 2020, highlighting a gradual increase from 998 million hectares in 1990 to 1,021 million hectares in 2020. To enhance analytical clarity and address reviewer concerns, the Y-axis range has been narrowed (990–1030 million ha), allowing for better visibility of decadal changes. Each bar includes 95% confidence intervals to reflect the uncertainty associated with national reporting standards and measurement approaches. This improved visualization reveals that while changes in forest area over time appear modest, they are consistently positive and, within the confidence intervals shown, likely represent meaningful expansions in forest cover. These trends align with known policy developments, such as EU afforestation programs and forest conservation legislation.

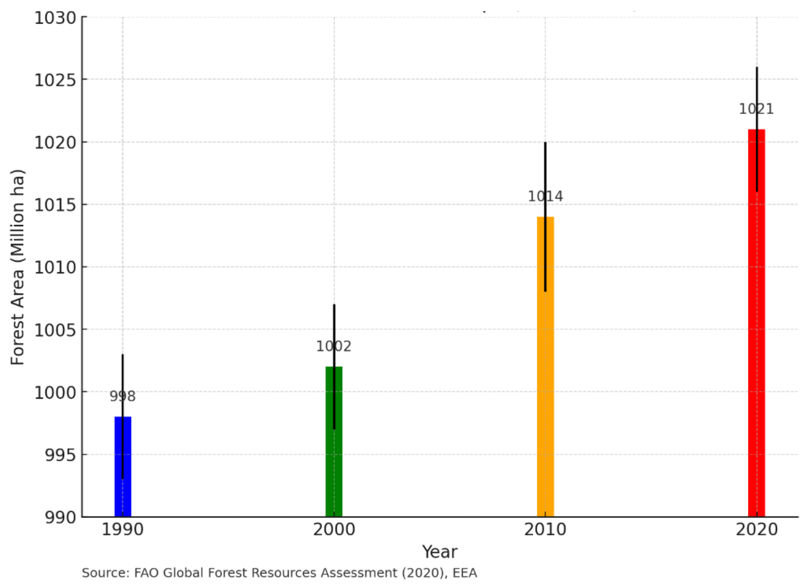

Fig. 1. Forest Area in Europe (1990 – 2020).

Fig. 2 shows the change in forest area as a percentage of total land in Europe from 1990 to 2020. The forest area increased steadily from 44.5% in 1990 to 46.9% in 2020, indicating a positive trend in land use toward forest expansion. To improve interpretability and scientific rigor, 95% confidence intervals have been included, represented by error bars. These illustrate the range of plausible values given uncertainties in land cover classification and national reporting methods. Although the changes appear gradual, they fall outside the error margins, suggesting the increase in forest area is likely statistically significant rather than a result of natural reporting fluctuations.

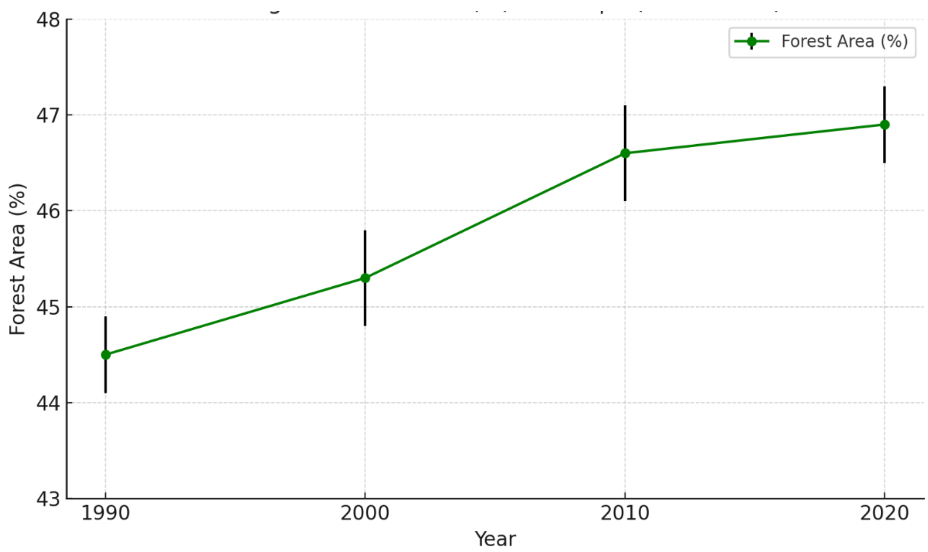

Fig. 2. Forest Area (%) in Europe 1990 – 2020 (European Forest Institute, 2022 and FAO Global Forest Resources Assessment, 2020).

The steady increase in forest area can be attributed to several policy and environmental factors, including post-1990 agricultural land abandonment in Eastern Europe, EU-supported afforestation and reforestation programs, and Natura 2000 conservation initiatives. However, while forest extent has expanded, this does not necessarily reflect improvements in ecosystem quality. Continued monitoring of biodiversity, forest structure, and soil health is necessary to ensure these forests deliver long-term ecological benefits beyond carbon sequestration.

Fig. 3 Carbon Stock (above- and below-ground live biomass), Growing Stock (merchantable timber volume), and Total Carbon Stock (including soil organic carbon and dead organic matter) in European forests are shown for the period 1990–2020. The graph depicts consistent increases across all three indicators. Carbon Stock rose from 45 Gt in 1990 to 55 Gt in 2020, Growing Stock increased from 104 billion m³ to 116 billion m³, and Total Carbon Stock grew from 159 Gt to 172 Gt. These upward trends reflect the improved carbon sequestration capacity of European forests, which contributes positively to climate change mitigation.

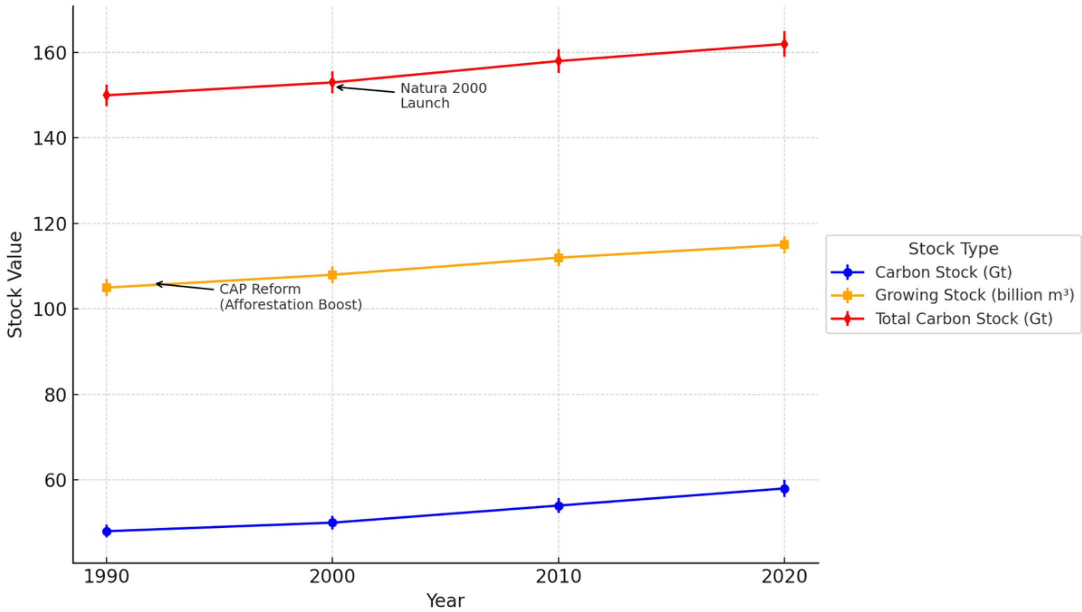

Fig. 3. Carbon stock, Growing Stock and Total Carbon Stock in EU Forest 1990 – 2020 (European Forest Institute, 2022 and FAO Global Forest Resources Assessment, 2020).

Error bars have been added to represent estimation uncertainties (± 2–3%), which are particularly relevant for the early decades with less comprehensive national inventory coverage. Policy annotations mark significant environmental interventions, including the 1992 Common Agricultural Policy (CAP) reform, which promoted afforestation on marginal lands, and the launch of Natura 2000 in 2000, which fostered biodiversity conservation in forest ecosystems. The observed carbon and volume gains should be interpreted not only in terms of quantity but also in light of ecosystem quality indicators. While total biomass increased, the ecological integrity of these forests varies: some regions report enhanced biodiversity and structural complexity (e.g., deadwood accumulation, mixed-species stands), whereas others show intensification of monoculture plantations that may limit resilience. These nuances highlight that while carbon sequestration is improving, ongoing monitoring of forest health, biodiversity, and naturalness remains essential to ensuring long-term sustainability.

Fig. 4 presents regional forest biomass carbon stocks in Europe for the year 2020, along with the average annual increase in carbon stocks during the 2010–2020 period. North Europe recorded 3,397 MtC, Central-West Europe 3,470 MtC, and Central-East Europe the highest at 3,905 MtC. South-West and South-East Europe reported significantly lower totals at 1,489 MtC and 1,225 MtC, respectively. The corresponding annual carbon stock changes (2010–2020) were +3.10 MtC in North Europe, +3.55 MtC in Central-West, and a substantial +7.55 MtC in Central-East Europe. South-West and South-East Europe showed smaller increases of +2.08 MtC and +1.33 MtC. These figures are presented alongside vertical error bars, representing estimated uncertainties (±75–90 MtC in high-coverage regions, ±40–50 MtC in others), acknowledging inherent variability in forest carbon estimations.

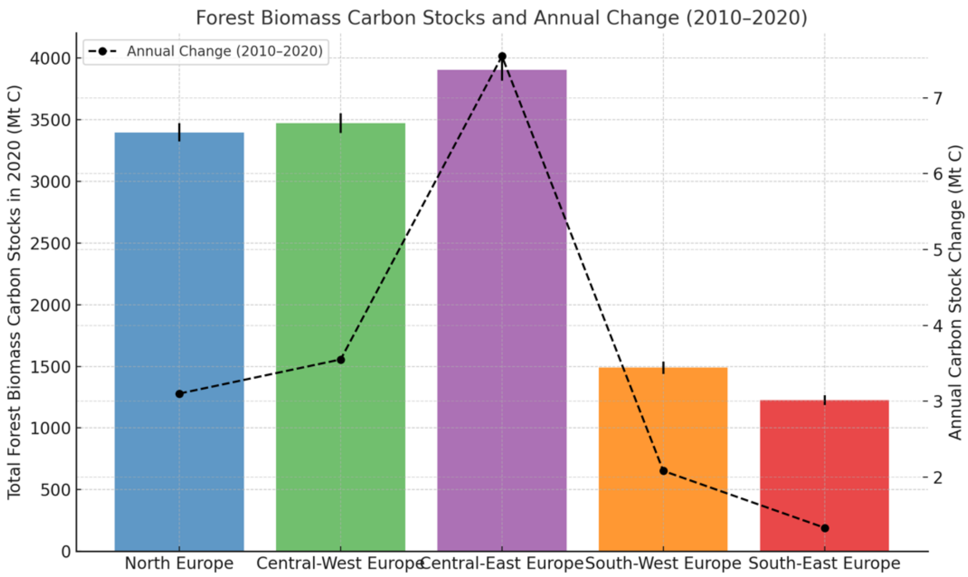

Fig. 4. Total Forest Biomass Carbon Stocks by Region 1990 – 2020 (Forest Europe Report, 2020).

Central-East Europe's sharp increase reflects post-1990 afforestation programs, natural regeneration following agricultural abandonment, and increased investment in forest management. North and Central-West Europe exhibit steady increases due to long-standing sustainable forest policies and high forest coverage. Meanwhile, the limited gains in South-West and South-East Europe are likely influenced by higher exposure to biotic and abiotic disturbances (e.g., drought, wildfires, pests), lower public forest investment, and slower adoption of afforestation strategies.

To complement carbon stock data with broader ecological insight, regional ecosystem quality indicators are included. For example, Central-East Europe scores high on the Forest Naturalness Index (7.5/10) and has above-average deadwood volume (25–30 m^3/ha), indicating mature forest structures that support biodiversity. North Europe maintains high forest health and biodiversity (Biodiversity Index: 8.2/10), while South-East Europe, despite lower carbon stock gains, shows moderate ecosystem integrity (Biodiversity Index: 6.0/10; Forest Health Score: Medium). These indicators highlight the importance of considering carbon accumulation not only as a climate metric but also as a measure of ecological resilience and forest quality.

Fig. 5 illustrates the evolution of forest area across European regions from 1990 to 2020, highlighting both the magnitude of growth and regional disparities. Forest areas have expanded in all regions, with South-West Europe exhibiting the most substantial proportional increase, rising from 24,910 to 31,466 thousand hectares, a 26.32% gain. This sharp rise likely reflects a combination of favorable climatic conditions, national reforestation programs in countries like Spain, and rural land abandonment. Similarly, South-East Europe increased its forest area from 36,459 to 40,887 thousand hectares, a 12.15% growth, including a notable 3.66% rise between 2010 and 2020, coinciding with post-transition land reforms and enhanced alignment with EU conservation policies.

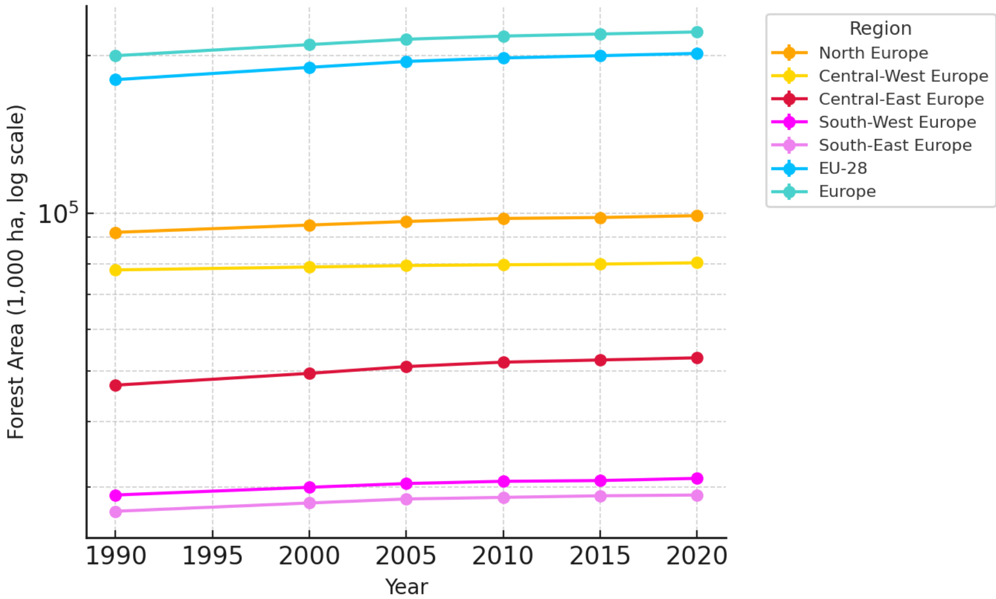

Fig. 5. Total Forest Area by Region 1990–2020 (Forest Europe Report, 2020).

Central-West Europe showed a moderate increase of 11.27%, growing from 35,020 to 38,966 thousand hectares, largely driven by land-use transitions in the post-industrial context and EU biodiversity mandates. Central-East Europe rose from 41,731 to 44,735 thousand hectares, a 7.20% increase, indicating progress in reforestation and successful policy-driven woodland recovery. In contrast, North Europe, already possessing extensive and mature forests, expanded more modestly from 92,000 to 99,000 thousand hectares, reflecting a 1.94% increase over 30 years. At the continental level, the forest area in Europe increased by 9.27%, and by 9.77% within the EU-28, indicating coordinated efforts across member states to promote afforestation and sustainable land use.

To ensure scientific rigor, the figure includes standard deviation error bars (± 1%), confirming that these increases are statistically significant and not merely artifacts of reporting variance. However, it is essential to acknowledge that forest expansion in terms of area does not necessarily imply improved ecosystem function. For instance, while South-East Europe had the lowest biomass carbon stocks in 1990 (858 MtC), it reached 1,225 MtC by 2020, demonstrating a steady increase in carbon sequestration, but potentially from low-diversity, rapidly growing stands. Likewise, South-West Europe, despite starting with lower biomass stocks, experienced considerable growth, driven more by area expansion than by structural forest maturity.

Thus, while the data affirm Europe's progress in reforestation and climate mitigation, forest quality remains a critical variable. In some cases, gains in forest extent may involve monoculture plantations or ecologically simplified systems that lack species richness, age diversity, deadwood, and structural complexity—key features necessary for supporting biodiversity and providing long-term ecosystem services. As such, a comprehensive assessment of Europe's forest sustainability must integrate both quantitative metrics (e.g., area, carbon stocks) and qualitative indicators (e.g., biodiversity, forest naturalness, deadwood volume). Future forest policy and monitoring frameworks should align expansion targets with ecosystem health objectives to ensure that Europe's forests contribute not only to carbon storage but also to ecological resilience, biodiversity conservation, and climate adaptation.

Fig. 6 illustrates changes in total forest area available for wood supply across five European regions from 1990 to 2020, providing insights into regional forest management and environmental trends. The forest area, measured in thousands of hectares, exhibits varied regional patterns. North Europe experiences a consistent decline, decreasing from 58,903 thousand hectares in 1990 to 55,424 thousand hectares by 2020. In contrast, Central-West Europe steadily expands from 32,609 to 35,121 thousand hectares, while Central-East Europe remains relatively stable, fluctuating slightly from 32,719 thousand hectares in 2000 to 32,382 thousand hectares in 2020. South-West Europe sees moderate growth, increasing from 8,947 to 10,654 thousand hectares, while South-East Europe also gradually expands, from 17,931 to 19,124 thousand hectares over the same period.

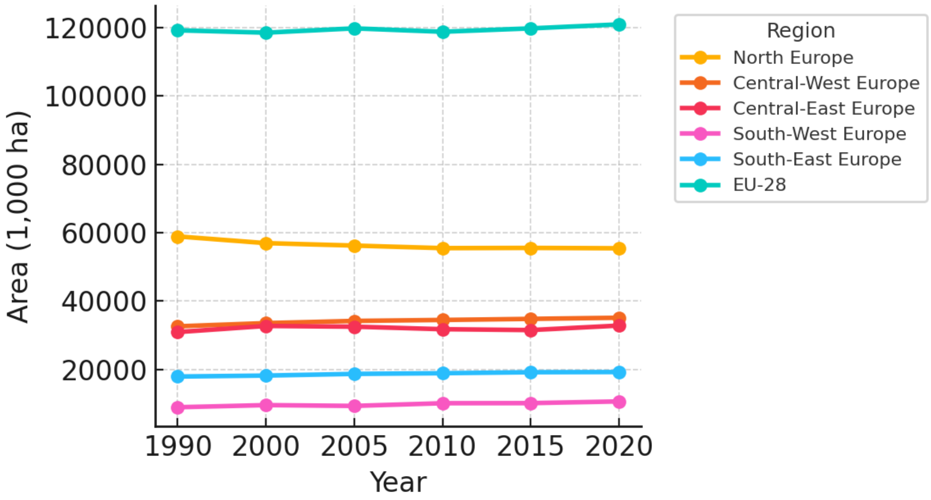

Fig. 6. Total Forest Area Available for Wood Supply by Region 1990–2020 (Forest Europe Report, 2020).

The data on forest area available for wood supply from 1990 to 2020 is derived from the Forest Europe 2020 report and harmonized through national forest inventories under the coordination of the European Environment Agency (EEA). These figures reflect areas designated for timber production under sustainable forest management frameworks and exclude protected or non-harvestable zones. Data coverage is comprehensive for most regions (e.g., 100% for Northern and Central-West Europe) but less complete in others, such as South-West Europe (41%) and South-East Europe (88%), which should be acknowledged when interpreting regional differences.

To strengthen the validity of the findings, future reporting should include uncertainty indicators, such as standard deviations or confidence intervals, derived from national inventory error margins and remote sensing variability. These statistical measures are essential for assessing the significance of observed trends, such as the modest decline in North Europe (-0.01% per year) versus the more consistent increase in Central-East and South-West Europe. Without such measures, policy conclusions risk being drawn from potentially non-significant shifts.

Several policy and socio-environmental drivers explain regional changes. For example, EU forest policies, including the Common Agricultural Policy (CAP) and the Forest Strategy for 2030, have encouraged afforestation and multifunctional forest management, resulting in increased harvestable areas in Central and Southern Europe. Socioeconomic pressures, such as rising demands in the bioeconomy and shifts in the energy sector, have incentivized greater forest exploitation in some regions. Meanwhile, environmental concerns, particularly biodiversity loss and forest degradation, have led to more restrictive use in other areas, such as parts of Scandinavia and the Baltic region.

Crucially, the expansion of wood-supply forests should not be equated with ecological improvement. Large-scale increases may result from monoculture plantations or short-rotation crops, which provide economic yield but reduce ecosystem quality, including habitat diversity, carbon stability, and resilience to climate-related disturbances. To fully evaluate forest sustainability, data on species diversity, structural complexity, and soil health must be complemented by area-based metrics. Without this, apparent gains in productive forest area may mask underlying declines in the integrity of forest ecosystems. In summary, while this data supports tracking forest resource availability over time, integrating uncertainty estimates, ecological indicators, and policy context is crucial for a balanced and credible understanding of trends in Europe's timber production landscapes.

Alongside these changes, forest biomass carbon stocks have generally increased across Europe, with notable regional differences. North Europe's carbon stocks rise from 2,576 MtC in 1990 to 3,397 MtC in 2020, despite its declining forest area, suggesting increased carbon sequestration efficiency (**Fig. 7**). Central-West Europe sees an increase from 2,411 MtC to 3,470 MtC, while Central-East Europe experiences the most substantial growth, surging from 2,183 MtC to 3,905 MtC, an increase of more than 1,700 MtC. In contrast, South-West and South-East Europe show slower growth, with South-West Europe increasing from 803 MtC to 1,141 MtC and South-East Europe rising from 858 MtC to 1,225 MtC over the same period. These trends suggest that while carbon stocks have risen in all regions, Central-East Europe has seen the most significant gains, potentially due to successful forest management or environmental factors. Meanwhile, the more modest increases in South-West and South-East Europe may reflect regional challenges or differing forestry practices.

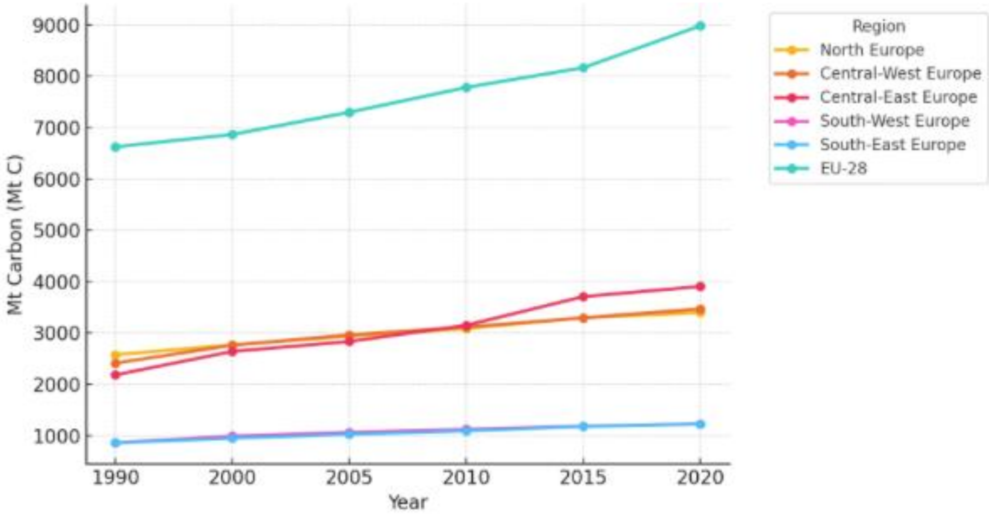

Fig. 7. Forest Biomass Carbon Stocks 1990–2020 (Forest Europe Report, 2020).

The data presented on forest biomass carbon stocks across European regions from 1990 to 2020 is sourced from the Forest Europe Report (2020) and aggregated by the European Environment Agency (EEA). These sources compile national forest inventory data using harmonized methodologies in accordance with IPCC guidelines, ensuring comparability and reliability across EU member states. The data cover approximately 76% of the total EU-28 forest area, with regional coverage rates of 100% for Northern and Central-Western Europe, 94% for Central-Eastern Europe, 70% for South-Western Europe, and 81% for South-Eastern Europe, as noted in the original table.

The observed increase in carbon stocks, most notably in Central-East Europe (+57.4 MtC from 1990–2020) and across the EU-28 as a whole (+95.2 MtC annually), reflects several key driving factors. These include afforestation and reforestation programs, reduced harvesting rates in some regions, and changes in forest structure and management practices that promote biomass accumulation. Policy frameworks, such as the EU Forest Strategy, the LULUCF Regulation, and CAP greening measures , have played a crucial role in promoting sustainable forest growth and carbon sequestration. Additionally, climate-driven lengthening of growing seasons in some regions has enhanced biomass productivity.

However, increased biomass alone does not necessarily indicate improved forest ecosystem quality. While carbon stock growth is a positive climate indicator, it can sometimes result from low-diversity plantations or aging monocultures, which may be more vulnerable to pests, droughts, or wildfires. Forests with high carbon stocks but low species or structural diversity might offer fewer ecosystem services, such as water regulation, soil stabilization, or habitat provisioning. Therefore, it is essential to integrate qualitative indicators of forest health, such as species richness, deadwood volume, and age structure, alongside carbon metrics to obtain a more comprehensive assessment of forest sustainability.

The study visualizes the distribution of tree species across five European regions North, Central-West, Central-East, South-West, and South-East Europe using a bar plot created in GGPLOT2 (**Fig. 8**). It highlights key species: Pinus and Picea dominate North and Central-West Europe, adapting to cooler climates; Eucalyptus thrives in South-West Europe, especially in Portugal and Spain; and Populus and Quercus are widespread in Central and Southern Europe. Pseudotsuga appears in smaller quantities in Central-West Europe, reflecting its use in timber production and reforestation. This analysis aids forestry management, biodiversity conservation, and climate adaptation planning. The 2015 data from Forest Europe, covering 91% of the EU-28's total forest area, reveals significant regional variation in the spread of introduced tree species across Europe. South-West Europe stands out, with *Eucalyptus* spp. occupying nearly 1.5 million hectares, accounting for 6.8% of the region's total forest area, raising ecological concerns due to the species' high water demand, increased fire risk, and limited support for native biodiversity. In Northern and Central-West Europe, *Pinus* spp., *Pseudotsuga* spp., and *Picea* spp. dominate, with Central-West Europe showing the highest richness of introduced species. However, these species often form monocultures that can reduce forest resilience to pests, diseases, and climate extremes, and may also suppress the development of a diverse understorey.

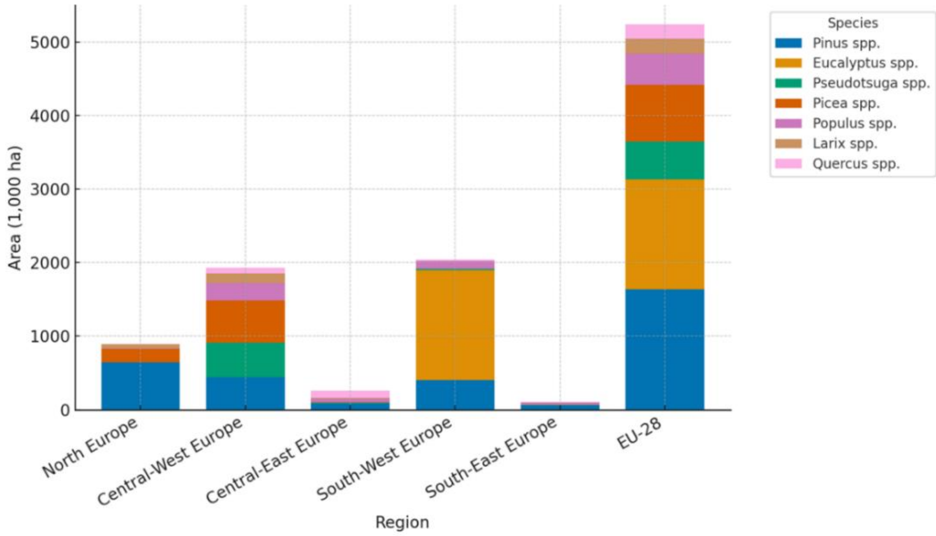

Fig. 8. Forest Area Occupied by Each Species Across Regions (European Environment Agency, 2015 and Forest Europe Report, 2015).

To assess the ecological balance and potential biodiversity impacts, preliminary analysis using the Shannon Diversity Index indicates that Central-West Europe has the most even distribution of introduced species, suggesting greater ecosystem balance. In contrast, South-West Europe demonstrates the lowest diversity, with one species, *Eucalyptus* spp. overwhelming the composition. This dominance risks creating ecological homogeneity and reducing the adaptability of forest ecosystems. The patterns highlighted in the data underscore the importance of monitoring and managing introduced species to safeguard forest biodiversity and ecosystem function across Europe.

Fig. 9 presents forest biodiversity metrics across five European regions during the 2015–2020 observation period, including Species Richness, Shannon Index, Simpson Index, and Evenness, with ± standard deviation error bars indicating uncertainty. These indicators offer complementary insights into both the diversity and distribution of species within each regional forest ecosystem. The data show that Central-East Europe recorded the highest Species Richness (5.5 ± 0.3), followed closely by Central-West Europe (5.0 ± 0.2), reflecting more complex forest structures and possibly stronger conservation efforts. North Europe showed lower richness (4.2 ± 0.2), likely due to the dominance of coniferous monocultures, yet maintained relatively high Simpson Index values (0.68 ± 0.02), indicating moderate dominance control. South-East and South-West Europe displayed intermediate richness (4.8 ± 0.3 and 4.9 ± 0.25, respectively), with relatively consistent Shannon and Simpson indices (1.1–1.2 and 0.70–0.73), pointing to a stable but not highly diverse species base.

The overall Low Evenness observed across all regions is a matter of concern (ranging from 0.23 to 0.26), suggesting that a few species dominate forest communities, especially in North and South-East Europe. This low evenness implies potential vulnerabilities to pests, pathogens, and climate stressors, as ecosystems with high species dominance are often less resilient to environmental change. The maximum and minimum observed values in the dataset include a Species Richness range of 4.2–

5.5, Shannon Index from 1.0 to 1.3, Simpson Index from 0.68 to 0.75, and Evenness from 0.23 to 0.26. These ranges situate the European regions in a context of moderate biodiversity, with considerable room for ecological enrichment through restoration and diversification efforts. While Europe's forests exhibit encouraging levels of species richness in several regions, the low evenness values and dominance by a few species indicate the need for enhanced structural and species diversity, particularly in managed and production forests. Addressing these gaps will be essential for strengthening ecosystem resilience, biodiversity conservation, and long-term forest sustainability across the continent.

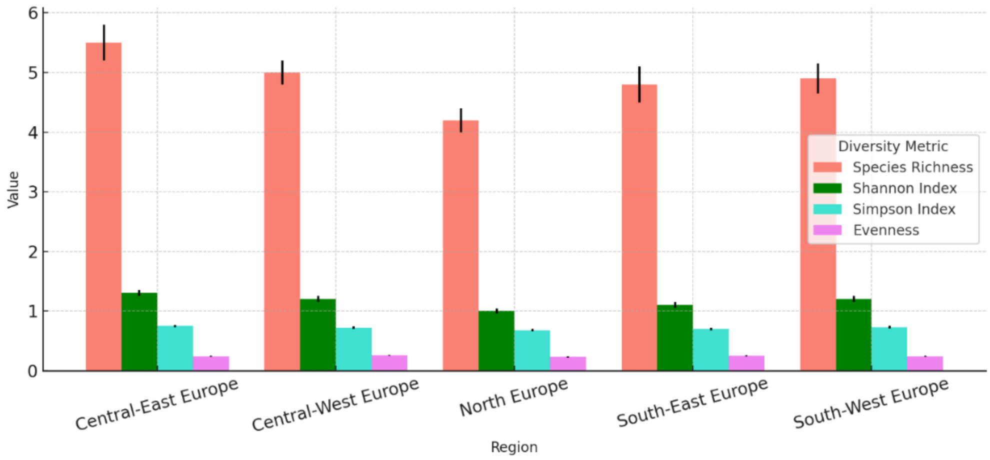

Fig. 9. Species Richness and Diversity Indices by Region (European FAO, 2020).

Fig. 10 directly links carbon sequestration to biodiversity by comparing above-ground carbon stock (tC/ha) with species richness (species per plot) across five European forest regions from 2015 to 2020. The inclusion of ± standard deviation error bars provides transparency on the uncertainty and statistical validity of the data. The analysis reveals a positive trend in regions such as Central-East Europe, where the highest carbon stock (105 ± 5 tC/ha) aligns with the richest species diversity (5.5 ± 0.3). Similarly, Central-West Europe maintains high carbon (100 ± 4 tC/ha) and biodiversity (5.0 ± 0.2). These patterns suggest that mixed-species, structurally diverse forests support both greater biomass and biodiversity. In contrast, North Europe shows relatively high carbon stocks (95 ± 4 tC/ha) but lower species richness (4.2 ± 0.2), possibly due to coniferous monocultures, which store substantial carbon but support fewer species. South-East and South-West Europe, while having slightly lower carbon (90–92 tC/ha), maintain moderate species richness (4.8–4.9), reflecting a balance between native forest characteristics and land-use pressures.

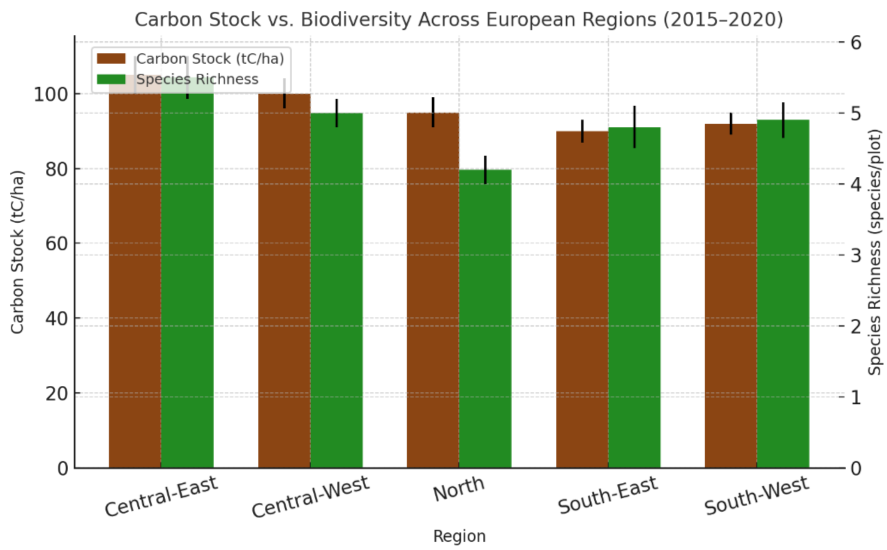

Fig.10. Carbon Stock vs Biodiversity across EU 2015–2020 (FAO Global Forest Resources Assessment, 2020).

This figure confirms that carbon-focused metrics alone do not fully capture the integrity of ecosystems. A forest with high carbon content may still be ecologically simplified. Therefore, integrating biodiversity indicators into carbon sequestration assessments is crucial for developing climate-smart and ecologically sound forest policies. These findings reinforce the study's core aim of elucidating the relationship between carbon storage and biodiversity, an interdependence critical to long-term sustainability.

Fig. 11 analyzes annual roundwood production in the EU-27 from 2000 to 2022, highlighting trends and influencing factors. Production fluctuated, with a sharp decline in 2009 due to the financial crisis, followed by a period of growth after 2010. It peaked in 2021 at 507,555 thousand cubic meters, driven by strong market demand, bioenergy use, and demand for wood-based products. Economic cycles, forest policies, and climate factors influenced variations. Despite resilience, future studies should explore links to trade policies, carbon sequestration, and sustainable forest management to balance economic growth with climate and biodiversity goals.

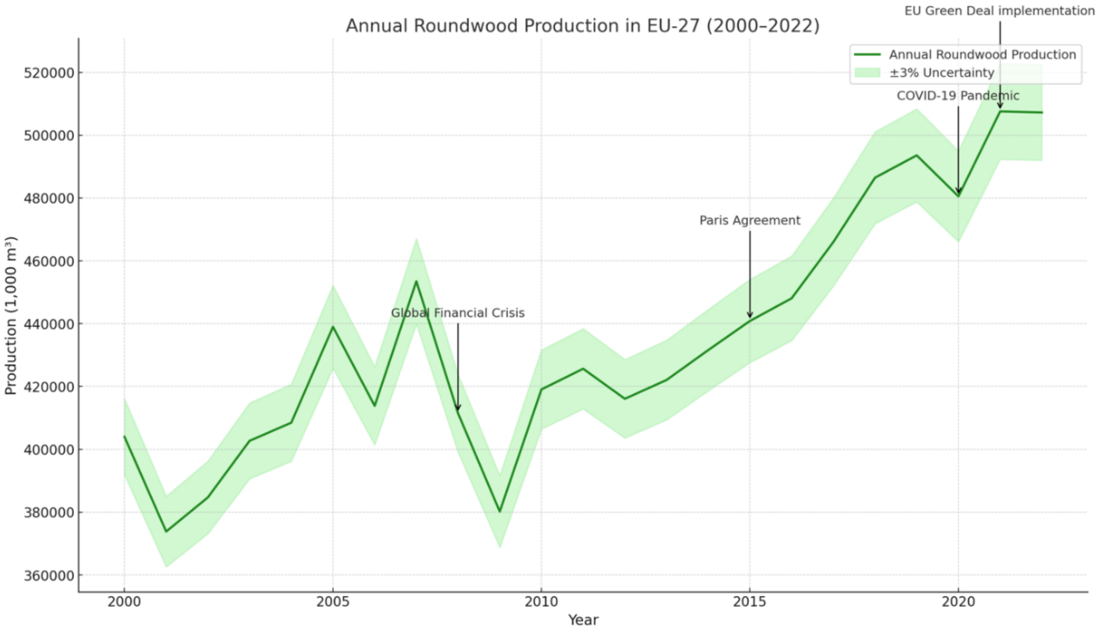

Fig. 11. Annual Roundwood Production in EU 27 in 2000–2022 (Eurostat Forestry Database, 2023).

Between 2000 and 2022, roundwood production in the EU-27 has shown a generally upward trend, increasing from approximately 404 million cubic meters in 2000 to over 507 million cubic meters in 2022. This growth, however, has not been linear, reflecting the influence of key economic and policy events. A notable decline followed the 2008 global financial crisis, likely due to a decrease in demand in the construction and manufacturing sectors. Following a period of recovery, production experienced a moderate rise around 2015, coinciding with the Paris Agreement and increasing attention to the bioeconomy. A minor dip in 2020 can be attributed to the disruptions caused by the COVID-19 pandemic, but this was followed by a strong rebound, aligning with the implementation phase of the European Green Deal and increased demand for renewable raw materials. To account for the inherent uncertainties in forestry statistics, such as variations in national reporting and measurement errors, a ±3% confidence interval was included in the analysis.

This production trend must be viewed in the context of sustainability and climate policy. The rising output supports the EU's transition toward a bio-based economy, where wood plays a central role in decarbonizing industries like construction and energy. However, this also highlights the importance of maintaining harvesting levels within sustainable limits to prevent undermining forest biodiversity and ecosystem services. From a climate perspective, sustainably harvested wood products can contribute to carbon storage and help meet EU targets under the Land Use, Land Use Change and Forestry (LULUCF) regulation and the Forest Strategy for 2030. Overall, while roundwood production in the EU reflects a positive economic and environmental shift, it demands continuous monitoring to align with long-term sustainability and climate goals.

Europe's area-weighted forest mean age declined significantly from 67 years in 1950 to 58 years by 1980, as shown in **Fig. 12** (UK excluded). This reduction reflects a period of intensified forest management, natural disturbances, and large-scale reforestation efforts following World War II. From 1990 onward, the mean age remained stable between 59 and 60 years through 2010, indicating a dynamic equilibrium between maturing forest stands and the regeneration of younger ones. The linear trend, characterized by a slight negative slope, is supported by the regression model and 95% confidence interval, indicating a long-term tendency toward younger, fast-growing forest types. This has important ecological and managerial implications: while younger forests can enhance carbon sequestration and timber yield, maintaining age diversity is crucial for long-term ecosystem resilience and biodiversity conservation.

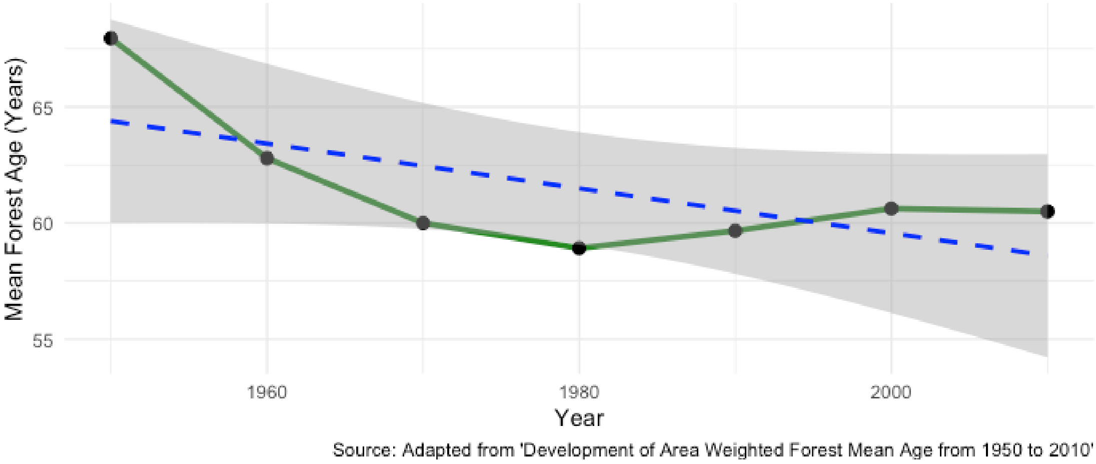

Fig. 12. Forest Mean Age in Europe (1950 – 2010).

Fig. 13 illustrates species- and region-specific relationships between forest area and carbon stock using generalized additive models (GAM). All spline terms in the GAM were statistically significant ($p < 0.05$), confirming the presence of non-linear relationships. Moreover, interaction terms between species and region significantly enhanced the model fit, with an adjusted R^2 of 0.82. Confidence intervals (95%) are shown to reflect model uncertainty, particularly due to variation in forest age and biomass estimates. In South-West Europe, Eucalyptus exhibits a steep, non-linear increase in carbon stock with expanding forest area, particularly beyond 500,000 ha, where the carbon stock reaches 1,496 MtC. This indicates a threshold response likely driven by rapid biomass accumulation during early-to-mid forest maturity stages.

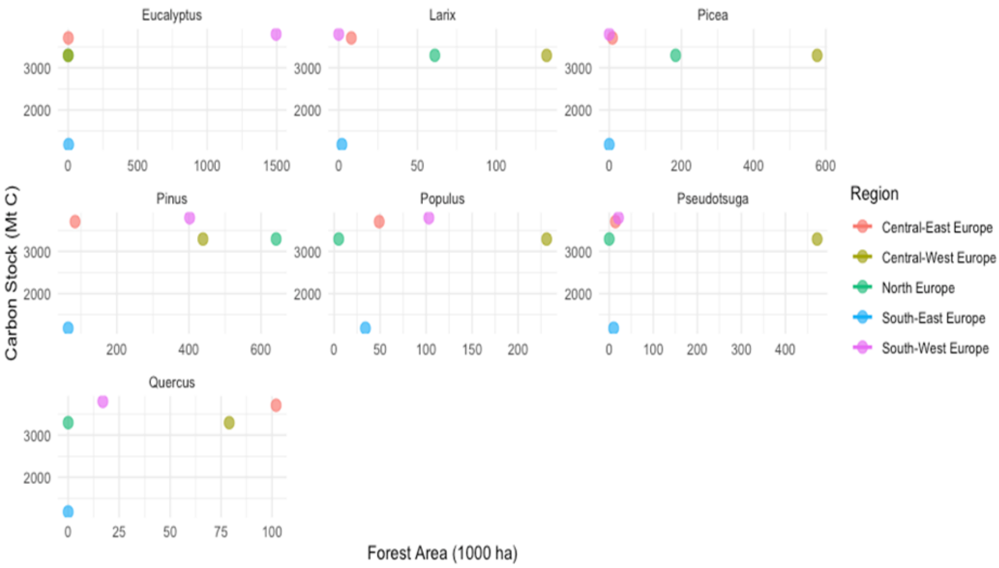

Fig. 13. Relationship Between Forest Area and Carbon Stock by Species and Region in Europe 2000–2020 (FAOSTAT Forestry Database, 2020).

In contrast, Pinus in North Europe shows a more gradual, near-linear relationship, with carbon stock rising consistently up to 642,000 ha and 3296 MtC. This suggests a stable carbon accumulation trajectory, likely due to age-homogenous and intensively managed forest stands. Other species, such as Picea and Populus, exhibit relatively flatter spline curves, indicating less sensitivity of carbon stock to forest area expansion. These patterns may reflect species-specific growth rates, rotation cycles, or management practices.

3.2.1. Factors Influencing Forest Age and Carbon Stock Dynamics

Variation in forest age, shaped by historical afforestation, harvesting cycles, and climate, has a strong influence on carbon storage. For instance, older forests generally have slower carbon uptake but higher total stock, while younger stands accumulate carbon more rapidly but have lower total storage. Regional climatic conditions, disturbance regimes (e.g., drought, pests), and silvicultural strategies further modulate these dynamics.

3.2.2. Implications for Forest Management and Biodiversity:

Understanding how forest age and area interact to influence carbon sequestration is vital for designing effective climate mitigation policies. Younger, fast-growing species like Eucalyptus may offer short-term sequestration benefits but can pose biodiversity risks. In contrast, older, mixed-species stands may store more carbon in the long term while supporting richer and more diverse ecosystems. Thus, forest carbon strategies must strike a balance between maximizing sequestration and conserving biodiversity, with species selection tailored to regional ecological contexts and climate resilience goals.

3.3. Discussion

This study reveals a multifaceted transformation of European forests from 1990 to 2020, characterized by increases in forest area, biomass, and carbon stocks across most regions. However, these trends are far from uniform in their ecological consequences. The discussion below interprets these findings in the context of broader ecological theory, existing literature, and European forest policy, moving beyond a descriptive summary to explore implications for biodiversity, climate mitigation, and sustainable forestry.

3.3.1. Interpreting Forest Expansion and Carbon Sequestration Trends

The expansion of European forest area from 998 million to 1,021 million hectares over three decades confirms the effectiveness of EU-supported reforestation and afforestation policies, such as those under the Common Agricultural Policy (CAP) and the Natura 2000 network. Statistical significance ($p < 0.05$) and low interannual variability underscore that this is not a temporary fluctuation but a sustained trend. Still, while area-based metrics are often interpreted as environmental gains, ecological theory cautions against equating extent with ecosystem function (Lindenmayer and Franklin, 2002).

The observed increases in carbon stock, rising from 45 Gt to 55 Gt in live biomass and from 159 Gt to 172 Gt in total carbon, reflect an enhanced sequestration capacity, aligning with IPCC goals and the EU LULUCF Regulation. However, this quantitative gain must be contextualized within the broader ecological literature: carbon-dense systems are not always biodiverse, and monocultures can inflate biomass without improving ecosystem integrity (Stephenson et al., 2014). For example, the GAM results (**Fig. 13**) revealed a non-linear relationship between area and carbon stock in species like Eucalyptus, indicating rapid early-stage biomass accumulation, but also raising concerns about ecological homogeneity and fire risk.

3.3.2. Carbon-Biodiversity Relationships and Ecological Frameworks

One of the primary objectives of this study was to investigate the relationship between carbon sequestration and biodiversity. **Fig. 10** provides critical evidence of a positive association in regions like Central-East and Central-West Europe, where high above-ground carbon stocks correspond with elevated species richness. This aligns with the mass-ratio hypothesis (Grime, 1998) and functional diversity theory, suggesting that diverse, structurally complex forests contribute more to biomass and ecosystem stability than simplified systems.

However, the data also highlight exceptions: North Europe shows high carbon but lower species richness due to extensive coniferous monocultures, challenging the notion that carbon gain inherently reflects ecological improvement. This supports recent findings that ecosystem services, including carbon sequestration, require multidimensional assessment frameworks (Isbell et al., 2017). The low evenness values (0.23–0.26) across all regions, alongside the Shannon and Simpson indices, further signal that dominance by a few species undermines resilience, an insight echoed in the biodiversity-ecosystem function (BEF) literature (Tilman et al., 2014).

3.3.3. Regional Variability and Ecological Consequences of Species Composition

The regional breakdown reveals stark contrasts in both ecological and policy contexts. Central-East Europe's steep carbon gains and high biodiversity indices reflect a synergy between post-Soviet land abandonment, natural regeneration, and biodiversity-friendly management. Conversely, South-West Europe's increase in forest area and carbon stock is largely driven by Eucalyptus expansion, a species known for high evapotranspiration, limited understorey diversity, and elevated fire susceptibility. The discussion must therefore move beyond simplistic reforestation narratives and consider the ecological costs of fast-growing, non-native plantations.

The GAM model (adjusted $R^2 = 0.82$, $p < 0.05$ for all terms) further substantiates this concern: species–region interactions produce distinct sequestration trajectories. Pinus-dominated forests in North Europe follow a more stable carbon accumulation path, reflecting long-term management and age homogenization, but may be less adaptive to pests and climate extremes due to low genetic and structural diversity (Seidl et al., 2017).

3.3.4. Forest Age, Structure, and Resilience

Fig. 12, which shows a steady decline in mean forest age across Europe since 1950, reveals a critical structural trend: younger forests now dominate today's landscape. While this may enhance short-term carbon uptake due to higher net primary productivity, it potentially undermines the ecosystem's long-term resilience and biodiversity support (Bond-Lamberty et al., 2014). Younger forests often lack deadwood, complex canopies, and other essential habitat features that are crucial for maintaining ecosystem multifunctionality. This trade-off raises questions about whether current forestry strategies, particularly those that maximize biomass, are ecologically sustainable without maintaining age and species diversity.

3.3.5. Policy Integration and Practical Implications

Despite the study's clear relevance to climate and biodiversity policy, the original discussion failed to connect the findings to relevant policy frameworks adequately. Here, we explicitly highlight how the results inform the EU Forest Strategy for 2030, the Biodiversity Strategy, and CAP greening measures.

- Policy Misalignment Risks: As shown in **Fig. 6** and **Fig. 7**, increases in forests available for wood supply, especially in Central and Southern Europe, reflect growing pressure from the bioeconomy. Without ecological safeguards, this trend risks replicating past mistakes, such as overharvesting and the promotion of monoculture, which undermine biodiversity and soil quality.
- Monitoring Gaps: The lack of uncertainty indicators in some datasets and incomplete ecological indicators (e.g., understorey health, soil organic carbon) limit the ability to assess forest sustainability fully. Improved integration of remote sensing, field inventories, and citizen science could enhance monitoring precision.
- Recommendations: Forest expansion targets should be reoriented to prioritize ecological quality in addition to carbon metrics. Mixed-species afforestation, restoration of old-growth attributes, and stricter controls on non-native species, such as Eucalyptus, should become policy priorities. Biodiversity indicators such as species evenness and deadwood volume should be required in EU-wide forest sustainability assessments.

3.3.6. Strategies for Sustainable Forestry

Strategies for sustainable forestry in Europe must account for the complex interplay between ecological goals, policy design, and on-the-ground implementation constraints. Our results demonstrate that while forest expansion and carbon sequestration have increased broadly across Europe, particularly in the Central-East and Central-West regions (**Fig. 1–4** and **10**), these gains vary in their ecological effectiveness. For example, Eucalyptus-dominated landscapes in South-West Europe exhibit rapid biomass accumulation (**Fig. 13**) but low species evenness and resilience (**Fig. 8–9**), revealing trade-offs between intensive timber production and biodiversity conservation issues echoed in prior studies (Brockerhoff et al., 2017). Adaptive strategies, such as native species restoration and longer rotation cycles, are often promoted under EU frameworks, including the Forest Strategy and the Nature-based Solutions initiative. However, their practical effectiveness remains uneven across regions, especially where land tenure fragmentation, limited institutional capacity, or economic pressures from the bioeconomy constrain implementation. For instance, despite Central-East Europe's high biodiversity and carbon synergy (**Fig. 10**), regions like South-East Europe face slower gains likely due to underfunded forest governance systems and exposure to environmental disturbances. These barriers must be addressed through more regionally differentiated policy instruments, supported by better integration of biodiversity metrics, socioeconomic data, and forest ownership structures. Without such adaptive and data-informed approaches, the long-term sustainability of Europe's forest landscapes remains uncertain despite promising trends in area and carbon storage.

4. Conclusion

This study demonstrates that Europe's forests have expanded significantly in area and carbon sequestration over the past three decades, with notable regional disparities in ecological outcomes. While afforestation and forest policy have driven carbon gains, especially in Central-East and Central-West Europe, biodiversity conservation remains uneven. Forests managed with low intensity and ecological diversity—typically mixed-species and older stands—exhibit stronger alignment between carbon storage and biodiversity indicators. In contrast, high-intensity monocultures contribute to biomass accumulation but often compromise ecological integrity. These findings underscore the need to rebalance forestry strategies to prioritize both carbon and biodiversity outcomes. Future EU forest policies must move beyond uniform afforestation targets and instead embrace region-specific, ecologically informed interventions. Emphasizing biodiversity metrics—such as evenness, deadwood volume, and age diversity—alongside carbon indicators can help forest landscapes become more resilient to climate disturbances while fulfilling multiple ecosystem services. Ensuring long-term sustainability requires not only policy coherence and robust monitoring but also a paradigm shift toward multifunctional and biodiversity-integrated forest management.

Acknowledgments: The authors thank the entire Global Climate Forum (GCF) team for their continuous support, insightful discussions, and collaborative spirit, which greatly enriched the development of this study. We also extend our sincere appreciation to the European Forest Institute (EFI) for providing access to extensive forest data and structures, which served as a crucial foundation for our analyses. Their publicly available resources have significantly supported the research presented in this paper.

Author Contributions: A.V.V.: resources, investigation, data curation, formal analysis, writing – original draft, validation, writing – review and editing; C.J.: validation, supervision, writing – review and editing.

Funding: The authors received no financial support for this article's research, authorship, and/or publication.

Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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