frontiers
in Ecology and Evolution

ORIGINAL RESEARCH
published: 15 October 2020
doi: 10.3389/fevo.2020.547696

Forest Biodiversity, Carbon Sequestration, and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes Across Europe

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Europe's forests provide vital habitat for biodiversity and essential ecosystem services whose provision must be sustained or enhanced over the coming century. However, the potential to secure or increase forest ecosystem services, while securing the habitat requirements of taxa remains unclear, especially within the context of uncertain climate and socio-economic developments. To tease out the associated trade-offs and synergies, we used 10 case study landscapes within nine countries throughout Europe. Starting with the current status of the forests in the case study landscapes, we simulated forest development 100 years into the future. Simulations were embedded in three combined climate and socio-economic frame scenarios based on global and European policies which varied in their climate change mitigation efficiency. Scenarios were translated into country specific projections of climate variables, and resultant demands for wood products. Forest management regimes were projected to vary in response to these scenarios at local scales. The specific combinations of alternative forest management practices were based on parallel research and input from local forest stakeholders. For each case study, a specific forest growth simulator was used. In general, the climate scenarios applied did not cause fundamentally different ecosystem service outputs at the case study level. Our results revealed almost no reduction in

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Edited by:
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Specialty section:
This article was submitted to Biogeography and Macroecology, a section of the journal Frontiers in Ecology and Evolution

Received: *31 March 2020*
Accepted: *14 August 2020*
Published: *15 October 2020*

Citation:
Biber P, Felton A, Nieuwenhuis M, Lindbladh M, Black K, Bahýl' J, Bingöl Ö, Borges JG, Botequim B, Brukas V, Bugalho MN, Corradini G, Eriksson LO, Forsell N, Hengeveld GM, Hoogstra-Klein MA, Kadıoğulları Aİ, Karahalil U, Lodin I, Lundholm A, Makrickienė E, Masiero M, Mozgeris G, Pivoriūnas N, Poschenrieder W, Pretzsch H, Sedmák R and Tuček J (2020) Forest Biodiversity, Carbon Sequestration, and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes Across Europe. Front. Ecol. Evol. 8:547696. doi: 10.3389/fevo.2020.547696

outcomes for biodiversity indicators with an increase in wood production, and in some cases synergistic results occurred when diversity was actively promoted as part of the management concept. Net carbon uptake was not strongly correlated with biodiversity, indicating that biodiversity-friendly forest management doesn't need to curtail carbon sequestration. Notably, we obtained heterogeneous results for the relation between sustainable wood production and net carbon uptake. Most scenarios resulted in a more or less reduced net carbon uptake over the long term, often due to stand age class distribution shifts. Levels of sustainable wood production varied widely during the simulation period, from significant increases (Sweden, Lithuania) to minor changes (Slovakia, Turkey) and slight decreases (Ireland, Netherlands). We place our results within the larger context of European forest policy and the challenges of simulating and contrasting forest biodiversity and the ecosystem services that societies depend on.

Keywords: ecosystem services, biodiversity, wood production, carbon sequestration, forest management, sustainability, simulation, Europe

INTRODUCTION

Forests provide vital habitat for biodiversity and essential ecosystem services (Brockerhoff et al., 2017). Forest biodiversity, and the associated goods and services provided, must be sustained or enhanced over the coming century to meet the resource requirements of the global human population, and to halt the biodiversity crisis (IPBES, 2019). However, the potential to secure or increase forest ecosystem services, while simultaneously securing the habitat requirements of taxa remains unclear, especially within the context of uncertain climate and socio-economic developments (Plas et al., 2016; Felton et al., 2020). Whereas, the *wake theory* (cf. Knoke et al., 2017) suggested that desirable forest ecosystem services would be delivered "in the wake" of sustainable wood production, empirical studies have repeatedly challenged this assumption. Habitat loss and the depleted delivery of at least some ecosystem services is frequently associated with forests managed primarily for wood provision (Paillet et al., 2010; Gamfeldt et al., 2013; Felton et al., 2016b).

A recurring theme in assessing forest ecosystem services provision is the relation between a landscape's biodiversity and wood biomass production (Jucker et al., 2014; Bugalho et al., 2016; Felton et al., 2020). Possible conflicts, but also synergies have been discussed in relation to forest (Maes et al., 2012; Biber et al., 2015; Borges et al., 2017; Dieler et al., 2017) and agricultural natural resource management (Tscharntke et al., 2005; Whittingham, 2011; Harrison et al., 2014). Of growing and related importance is determining how best to optimize the carbon sequestration capacity of forest lands; in specific terms whether the intensive harvest or setting aside of forest land is best suited to mitigating climate change (Winjum et al., 1993; Leighty et al., 2006; Profft et al., 2009; Daigneault et al., 2010). Addressing these issues also requires deciphering to what extent forest biodiversity and forest carbon sequestration influence each other, and how forest management can be altered to achieve both biodiversity conservation and climate change mitigation goals (Boscolo and Vincent, 2003; Caparrós and Jacquemont, 2003; Bekessy and Wintle, 2008; Díaz et al., 2009; Felton et al., 2016a).

Few empirical or modeling studies address the trade-offs and synergies that can occur among forest biodiversity, biomass production, and carbon sequestration, at landscape scales. A key obstacle to such assessments is the need to contrast less readily quantifiable aspects like biodiversity, across a wide variety of forest types and biogeographical and socio-economic conditions. Although the tools used to do so are still in their infancy, in recent years promising new approaches have been developed for evaluating forest biodiversity despite such varying conditions, including those by Blattert et al. (2017, 2018) and Biber et al. (2020, submitted: "A Fuzzy-Logic Based Approach for Evaluating Ecosystem Service Provision Applied to a Case Study in Southern Germany"). The assessment of carbon sequestration likewise requires careful attention and unambiguous categorization if large scale or cross-national comparisons are to be made. This is because outcomes strongly depend on how the boundaries of the analysis are drawn and which aspects are incorporated, i.e., developments solely within the forest ecosystem itself, or inclusive of wood products and emission substitution effects (Peckham et al., 2012; Pukkala, 2014). In contrast, the quantification of wood production can seem relatively simple, largely because forest science has provided clear definitions of key variables since its earliest days. However, even wood production has traditionally been evaluated using a range of different variables, including periodic annual increment, mean annual increment, standing volume, and total volume production.

Under some circumstances, for example those in which evidence-based guidance for forest stakeholders is sought, clearer insights can be achieved by condensing the inevitably multidimensional outcomes for biodiversity, and selected ecosystem services, into a single robust indicator for each ecosystem service and overall biodiversity. With this in mind, here we use recently developed approaches to contrast and evaluate the outcomes of forest management decisions and developmental trajectories for carbon sequestration, wood production, and forest habitat availability for biodiversity. To do so, we assess—based on the methodological considerations made above-—10 case study landscapes across Europe, where future forest development scenarios have been simulated for 100 years. These scenarios are defined by detailed silvicultural measures which in turn are embedded in combined socio-economic and climate frame scenarios. We explore expected trade-offs and synergies between biodiversity, carbon sequestration and wood production and place our results within the context of forest management and policy formulation in Europe.

MATERIALS AND METHODS

Case Study Landscapes

Our research was based on case study areas (CSAs) in nine European countries (from North to South: Sweden, Lithuania, Ireland, Netherlands, Germany, Slovakia, Italy, Portugal, and Turkey). Except Germany, which hosted two CSAs, there was one CSA per country, resulting in a total of 10 CSAs (**Figure 1**, **Table 1**, **Supplementary Table 1**). CSAs were forest landscapes covering areas between several thousands and several hundred thousands of hectares (**Table 1**). They were selected to capture the most important issues relating to sustaining habitat for biodiversity, and the goods and services forests provide, operating at the interface of forest management and forest policy. Usually, the case studies' significance is not solely restricted to the country within which it is located, but extends to comparable biogeographic circumstances in their respective climate zone (cf. **Supplementary Table 1**). For example, the results of the Irish case study can be used to represent the vast peatland areas throughout Northern Europe. For all CSAs, state-of-the art simulation models and decision support systems (DSSs) were available (see **Table 1**). These had the advantage of being adapted to the circumstances within which they were applied. The drawback, however, is that the output variables were not *a priori* comparable across CSAs, due to e.g., different definitions and input variables. This has been a major obstacle for previous European-wide studies (Biber et al., 2015; Orazio et al., 2017). For this reason, a pre-condition for inclusion in this study was that all CSAs need to apply a common standard for output information that was defined and established across all simulation models and DSSs (Nordström et al., 2019).

Frame Scenarios

Three nation-level frame scenarios provided by the International Institute for Applied Systems Analysis (IIASA) provided the foundation for silviculturally detailed forest development scenarios for application within the CSAs. These scenarios represent different levels of climate change mitigation effort, and related wood demand for material and bioenergy purposes, which can directly impact on wood production, biodiversity and carbon sequestration in the forest landscape. The three scenarios combined the RCP (Representative Concentration Pathways)-SSP (Shared Socioeconomic Pathway) scenarios developed for the International Panel for Climate Change (IPCC) (Fricko et al., 2017) with policy targets for the European Union (Forsell et al., 2016), and are defined as follows (see Forsell and Korosuo, 2016 for details):

- The *Reference scenario* projects future development pathways based on historical development trajectories. This scenario takes into account EU policies and targets until 2020 in current legislation, and thereafter continues with development toward climate outcomes that follow pathways experienced in the past. In addition, the global economic growth and population development are assumed to be consistent with pathways experienced in the past. Climate change is somewhat mitigated via additional policies on greenhouse gas emission mitigation and through the development of carbon capture technologies. Global temperatures will significantly increase, and reach 3.7°C above the pre-industrial level by 2,100.
- The *EU Bioenergy scenario* projects rapid development of the EU bioenergy sector. This scenario takes into account EU policies aiming at an 80% reduction in carbon emissions by 2050, with some global climate policies also in place. In this scenario, the emission reduction targets in the EU for 2030 and 2050 are assumed to be fulfilled. The biomass demand for energy is assumed to remain stable thereafter in the EU. However, the importance of woody biomass as feedstock for building materials is projected to increase. Outside of the EU, it is assumed that additional climate change mitigation policies are in effect, so that global temperatures at 2,100 will increase by 2.5°C above the pre-industrial level.
- The *Global Bioenergy scenario* projects global development toward climate targets. It is assumed that climate policies are enacted globally, with both stringent EU policies and strong global climate mitigation. In the EU, the same targets until 2050 are in place as in the previous scenario (EU Bioenergy). Additionally, strong global mitigation actions are expected to be taken in all sectors and the bioenergy demand is expected to increase due to the investments in renewable heat and power. This leads to a temperature increase of 1.5–2.0°C by 2,100, compared to pre-industrial level.

Forest Management Scenarios

Forest management scenarios were developed for each CSA, for which detailed silvicultural actions were applied to the forest as guided by surveys of important stakeholders in each CSA (Marques et al., 2020; Trinh et al., 2020). As can be taken from **Table 1**, these stakeholders cover a wide range of interests, from commercial private forest owners to environmental NGOs. The management alternatives implemented in the different scenarios considered the interests and opinions of the stakeholders in the CSA. The heterogeneity of stakeholder constellations led to different solutions among the case studies. For example, in Portugal and Turkey, one forest management scenario was applied under all frame scenarios. Some case studies decided to define different forest management scenarios that were directly linked to the frame scenarios (Sweden, Netherlands), whereas others applied different management scenarios inside each frame scenario (Italy, Slovakia, Germany, Ireland, Lithuania). Note that if a forest management scenario was applied to more than one frame scenario, it had to be adapted in order to take account of the different market and climate developments associated with the frame scenarios. For example, increased bioenergy demand in the EU Bioenergy or Global Bioenergy frame scenario might

FIGURE 1 | Locations of the case study landscapes.

require more harvesting compared to Reference conditions, even within the same forest management scenario. This occurred in Sweden, Ireland, the Netherlands, Slovakia, Italy and the German case study AWF (cf. **Supplementary Table 3**). While these forest management scenarios were designed to achieve goals at the landscape level, this often was achieved using a variety of silvicultural treatments at the level of individual stands.

Despite heterogeneity in forest management scenarios (**Table 2**), they can be usefully categorized into four different types. Often, a CSA covers more than one of these scenario types. There are scenarios striving to maximize the economic profit (type 1, found for Sweden, Lithuania, Netherlands, Germany, Slovakia). Related scenarios also involved a focus on production and profit, however with the addition of environmental restrictions, or efforts to mitigate production risk by e.g., increasing the share of deciduous species (type 2, found for Ireland, Lithuania, Netherlands, Slovakia, Sweden). Other scenarios did not prioritize wood production above other ecosystem services, and strived to achieve a variety of goals at the same time (type 3, found for Portugal, Turkey, Germany, Italy, Slovakia, Netherlands). The fourth category of scenarios prioritized ecosystem services other than wood production, including nature protection and recreation (found for Germany, Italy).

Simulation Tools

The simulation tools used for this study (**Table 1**, **Supplementary Table 2**) are among the leading instruments available in the field of management-oriented forest modeling. Their construction, validation, and utilization has been documented in a large body of publications, the most recent of which are listed at the bottom of **Table 1**. All of the models were adapted to the information supply and demand of the specific case studies they were applied to.

TABLE 1 | Case study landscapes used in this study [taken from Biber et al. (2019), modified].

(Country code) Name(s)	Area, 1000 ha (% forest)	Forest ownership (%)	Main stakeholders	Main ecosystem services	Available simulation models or DSS
(SWE) Kronoberg county	847 (77)	83 Private 17 Public	Forest owners' association, environmental organizations, forest industry, Swedish Forest Agency, public	Timber, biodiversity, water, recreation, carbon sequestration	Heureka[a]
(LTU) Telšiai	254 (34)	63 Private 37 Public	State forest managers, private forest owners, environmental organizations, regional park	Timber, biodiversity, water, recreation, carbon sequestration	Kupolis[b]
(SVK) Podpolanie	34 (57)	7 Private 93 Public	State forest managers, private forest owners, environmental organizations, general public	Timber, biodiversity, water, recreation, carbon sequestration	Sibyla[c]
(IRL) Barony of Moycullen	81 (16)	22 Private 78 Public	Forest service, advisory services, private forest owners, environmental organizations, industries, public, fisheries, investment bodies	Timber, biodiversity, water, recreation, carbon sequestration	Growfor[d] Remsoft[e]
(ITA) Veneto	76 (100)	74 Private 26 Public	Forest owners' association, logging enterprises, municipalities, regional forest administration, environmental organizations	Timber, biodiversity, water, erosion control, carbon sequestration	InVEST[f] VALE
(PRT) Sousa Valley	15 (10)	90 Private 10 Public	Forest owners' association, forest owner federation, forest industry, forest service, local municipality, other non-governmental organizations	Timber, regulatory services (related to wildfire risk), soil erosion, recreation, carbon sequestration	StandSim[g] SADfLOR[h]
(GER) Augsburg Western Forests (AWF)	150 (33)	50 Private 50 Public	Private forest owners, environmental organizations, forest service, forest industry, general public (stable ownership structure for decades)	Timber, biodiversity, recreation, water, soil protection, carbon sequestration	SILVA[i]
(GER) Lieberose –Schlaubetal, Neuzelle (LSN)	90 (37)	44 Private 56 Public	Private forest owners (their share steadily increasing), forest service, environmental organizations, forest industry, general public	Timber, biodiversity, recreation, soil protection, carbon sequestration	SILVA[i]
(NLD) Netherlands	3,734 (11)	52 Private 48 Public	Government: National, Regional and Owners: Owner association, State forestry, National Trust, private non industrial forest owners, general public	Timber, recreation, biodiversity, carbon sequestration	EFISCEN-space[j]
(TUR) Gölcük	81 (49)	9 Private 91 Public	Gölcük state forest enterprise, timber processing companies, nature protection agency, forest cooperatives and contractors, forest villagers	Timber, biodiversity, soil conservation, recreation, water, carbon sequestration,	ETFOP[k]

[a] Wikström et al. (2011).
[b] Petrauskas and Kuliešis (2004).
[c] Fabrika (2005) and Fabrika and Durský (2006).
[d] Purser and Lynch (2012).
[e] Walters (1993).
[f] Kareiva et al. (2011).
[g] Barreiro et al. (2016).
[h] Marto et al. (2019).
[i] Pretzsch (2009, p. 515 ff.) and Pretzsch et al. (2002).
[j] Schelhaas M. et al. (2018) and Schelhaas M.-J. et al. (2018).
[k] Kadıoğulları et al. (2018).

However, the simulation tools used by CSAs differed extensively from each other due to differences in the available input data (e.g., remote sensing data sources vs. terrestrial grid inventories), their fields of application (e.g., commercial forestry vs. multifunctional management, which implies a different focus in the set of output variables), model conception (e.g., empirical vs. theory-based), and DSS capabilities (e.g. automatic optimization procedures available or not). See **Supplementary Table 2** and Nordström et al. (2019) for more details; see **Table 1** for model names and key references. To overcome some methodological differences, all models had to adequately take into account the climate and wood demand developments predicted in the global frame scenarios (Nordström et al., 2019), with outputs provided as a standard set of variables. Due to the structure of their DSS, the Italian case study could not provide the full set of standard variables.

Evaluation Methods

We assess the value of the simulated development of forests for biodiversity, sustainable wood production and carbon sequestration. As stated above, each of these categories is considered to be a complex and multi-dimensional construct

TABLE 2 | Overview of the forest management scenarios used in this study [after Biber et al. (2019), modified].

Country	Forest management scenario name	Concept	Used with global frame scenarios
Sweden	High wood production	Better regeneration and more pre-commercial thinnings, shorter rotations, more Scots pine, hybrid larch, fertilization in pine forests, Norway spruce clones	Global Bioenergy
	More diverse forest management (EU version)	More diverse forest management. More Scots pine, more oak for wood production, include border zones without management, spruce-birch admixtures, continuous cover forestry	EU Bioenergy
	More diverse forest management (Reference version)	More diverse forest management. More Scots pine, more oak for wood production (compared to EU Bioenergy), more spruce-birch admixtures (compared to EU Bioenergy), include border zones without management, Douglas fir, continuous cover forestry	Reference
Lithuania	Adaptive rotation ages	Maximize forest rent/present net value, applying rotation ages depending on soil types	All
	Care for deciduous	Adjust silvicultural priorities toward deciduous species, while conifers still remain important	All
Ireland	Environmentally constrained profit maximization	Increase profit of blanket peat forests while having low environmental impact. Low stocked planting of lodgepole pine, create good conditions for native broadleaf species, Sitka spruce under birch nurse, include zones for bog restoration	All
Netherlands	Reference gfdl	Slightly adapted management based on current developments (gfdl 8.5 climate)	Reference
	Reference hadgem	Slightly adapted management based on current developments (hadgem 8.5 climate)	Reference
	Wood	Focus on timber production (hadgem 4.5 climate)	EU Bioenergy
	Bioenergy gfdl	Focus on local sustainability and bioenergy (gfdl 2.6 climate)	Global Bioenergy
	Bioenergy hadgem	Focus on local sustainability and bioenergy (hadgem 2.6 climate)	Global Bioenergy
Germany (both case studies)	Multifunctional	Establish and maintain (uneven-aged) mixed stands in order to provide a broad range of ESs	All
	Production	Maximize wood production with monospecific even-aged conifer forests, reduce share of other forest types	All
	Setaside	Landscape is treated as a strictly protected area; no active silviculture	All
Slovakia	Conservative	Management goals determined by natural conditions and species composition	All
	Liberalized	Management goals determined by the forest owner	All
Italy	Recreation and habitat selectivity	Close to nature, improve recreational and cultural forest functions, maintain biodiversity	All
	Uniform shelterwood and coppice	Uniform shelterwood in oak-hornbeam forests, transform coastal forests into holm oak coppice with standards	All
Portugal	Combination of eucalypt, pine, broadleaf, cork oak and riparian forest management	Address challenges related to the management of eucalypt plantations, risk of fire, fragmented land ownership, lack of management and abandonment; develop a landscape mosaic that provides the full range of ecosystem services (e.g., wood and non-wood products, resistance to wildfire, biodiversity, carbon, soil erosion protection, and cultural values)	Reference[a], EU Bioenergy[a]
Turkey	Continuous Cover Forestry	Provide a multitude of ESs by creating and maintaining uneven aged mixed stands	All

***Supplementary Table 3** provides complementary information about the mean annual harvest amounts and areas modeled for the scenarios.*

[a] *These are local scenarios provided by the Clipick tool (Palma, 2017)—Global Bioenergy is not considered due to lack of precipitation data.*

that cannot be measured directly and/or objectively. Based on earlier work, we constructed indicators for each of these services that integrate along these different dimensions. For biodiversity and sustainable wood production we used a fuzzy logic approach (Biber et al., submitted) to qualitatively indicate the interaction effect between the dimensions, whereas for carbon sequestration we assumed its different dimensions were quantitatively additive (Biber et al., 2018). The methods we used to evaluate biodiversity, sustainable wood production, and carbon sequestration at forest landscape levels were possible due to the standardization of CSA model outputs outlined above. Standardization allowed us to collate comparable estimates for outcome variables from all CSAs.

Biodiversity

Our primary aim was to provide a means of contrasting important forest features for biodiversity across biogeographical regions in a way that was readily interpretable, and considered fair, by all those involved. Thus, for assessing forest biodiversity, we used a rule-based approach modified from Biber et al. (submitted). This method estimates a forest landscape's biodiversity based on a range of forest compositional and structural variables of demonstrated importance to forest biodiversity (Felton et al., 2016b). These variables, calculated as area-weighted mean stand values at the landscape scale were (i) the amount of coarse deadwood, (ii) tree species diversity, and (iii) the abundance of big trees. Coarse deadwood was measured in m^3/ha, and the abundance of big trees was expressed as the volume (m^3/ha) of trees with a diameter at breast height of 60 cm or more. The importance of deadwood (Müller and Bütler, 2010; Ranius et al., 2018) tree species diversity (Gamfeldt et al., 2013; Ampoorter et al., 2020) and large trees (Lindenmayer and Laurance, 2017) to the conservation of forest biodiversity is supported by reviews of the available empirical data.

Defining what constitutes a "big" tree is challenging because it is an ecosystem- and tree species-dependent concept, for which definitions vary even among researchers working within the same region, and depending on whether scientific or legal requirements are considered (Lindenmayer and Laurance, 2017). So for our purposes, we erred on the side of caution and consistency across CSAs, and chose a threshold size limit that was securely within a tree size range demonstrably beneficial for biodiversity regardless of which biogeographical region was under consideration (Lindenmayer et al., 2012; Felton et al., 2017). Concurrently, this threshold was below that commonly used in Europe for maximum target diameter cutting [i.e., 70–80 cm dbh (Vandekerkhove et al., 2018)], to allow for the potential presence of such trees even in commercially harvested forests. Whereas, some tree species may be sufficiently old to begin producing key features of importance to biodiversity (tree hollows, large crowns, large branches, deep bark fissures) at smaller diameters and within some regions, e.g., northern Europe (Felton et al., 2010), varying the size threshold by tree species and region to capture this lower limit was considered to potentially add bias and limit the comparative interpretation of outcomes.

In contrast to Biber et al. (submitted), we used the Shannon Evenness (Pretzsch, 2009, p. 280) to measure tree species diversity. We calculated it as

$$E = \begin{cases} \frac{-\sum_{i=1}^{s} p_i \cdot \ln(p_i)}{\ln(s_{\max})} & if\ s > 1 \\ 0 & if\ s = 1 \end{cases} \tag{1}$$

with s being the number of tree species and p_i the volume share of species i. The numerator of the equation for $s > 1$ is the usual unstandardized Shannon diversity index (Shannon, 1948; see also Pretzsch, 2009, p. 279). By dividing it by the natural logarithm of the number of species, which is the maximum Shannon index for the given number of species, we obtained the Evenness. The Evenness is standardized to the interval $[0, 1]$, whereby 1 indicates the maximum diversity that can be obtained from the tree species pool available. This was advantageous because it acknowledges that the potential maximum number of tree species differs considerably among the regions included in this study (e.g., a number of tree species considered "rich" in Northern European landscapes, could still be considered "poor" in some Southern European landscapes). We also took into consideration that different combinations of frame scenarios and forest management scenarios can result in different numbers of tree species within the same CSA. This means that for different scenarios in the same case study the maximum number of species obtained across all scenarios was used for standardization. Thus, to standardize the Shannon index to the Evenness in Equation (1), we used $\ln(s_{\max})$, with $s_{\max}$ as the maximum number of tree species occurring in any simulation run for a given CSA.

Using the species' volume shares p_i, instead of tree number shares, added another advantage: if in a scenario e.g., old monospecific conifer stands are transformed into multispecies forests, the tree number shares of the new species will increase very quickly due to the high number of small trees per unit area. However, as the volume of these small trees is negligible compared to the older trees, tree number shares can overemphasize the actual presence of the newly introduced tree species.

To translate the three input variables into a single biodiversity assessment, we applied the fuzzy logic rule system developed by Biber et al. (submitted). The full rule system is graphically shown in **Table 3**. To illustrate, one rule from **Table 3** reads as follows: "*IF the coarse deadwood amount is low AND the volume of big trees is low AND the Evenness is high, THEN the biodiversity is medium.*"

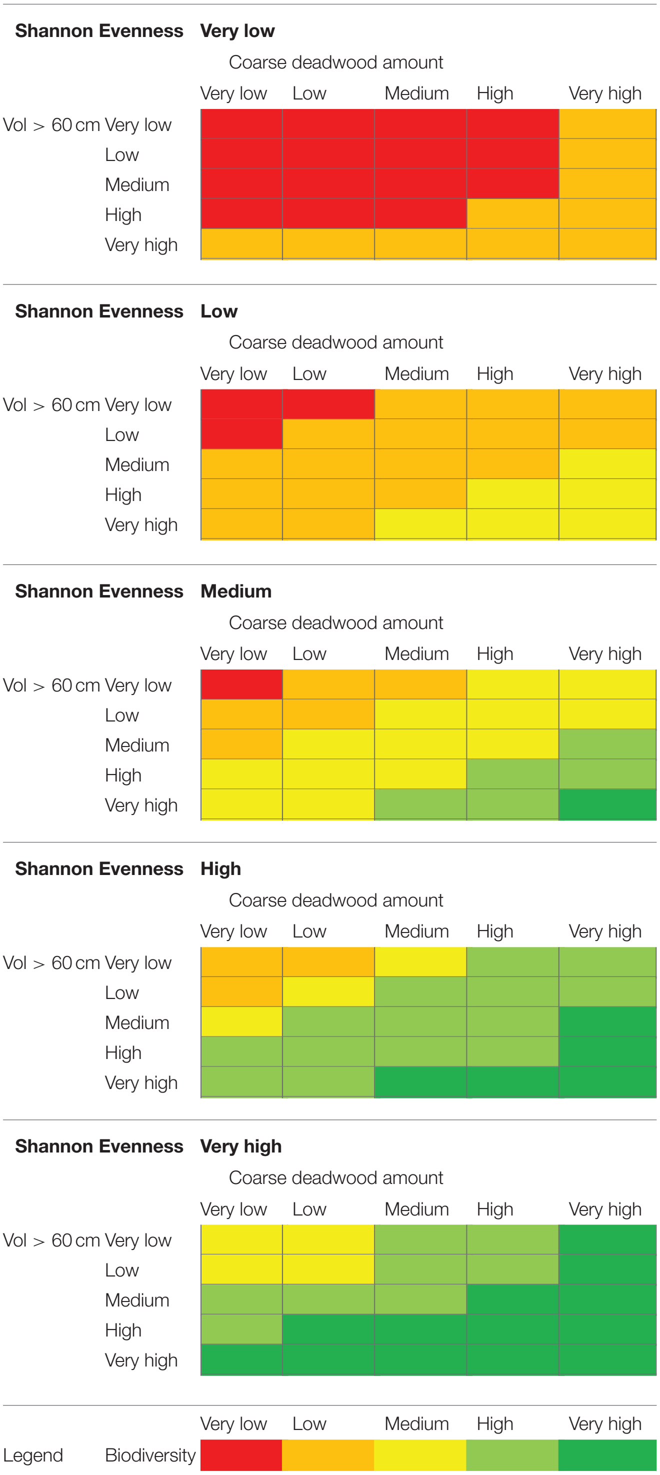
All input variables are mapped to the categories *very low*, *low*, *medium*, *high*, and *very high* by way of equally spaced overlapping triangular fuzzy sets, and the output—the assessed biodiversity–is mapped to the range $[0, 1]$, with 0 being *very low* and 1 representing *very high* [see Biber et al. (submitted) for details]. For coarse deadwood, the typical values for very low and very high were 0 and 50 m^3/ha, respectively [taking into account evidence based recommendations for Europe by Müller and Bütler (2010)]; the same range for the volume of big trees was 0 and 50 m^3/ha (adjusting downwards the levels assumed by Biber et al. (submitted), which were made specifically for highly productive forest sites), and for the Evenness these extremes were given by their natural range [0, 1].

While the use of fuzzy logic for assessing the provision of ecosystem services is discussed in detail by Biber et al. (submitted), we should mention here that fuzzy logic has already demonstrated its usefulness in numerous fields where human evaluation and assessment processes are to be mimicked (Reynolds et al., 2014; Marto et al., 2018). As such, it is highly useful in situations where expert knowledge is used for assessment purposes. The rule system laid down in **Table 3** is based on expert knowledge provided by contributing authors who are forest biodiversity specialists.

Sustainable Wood Production

To assess sustainable wood production, another fuzzy logic evaluation system developed by Biber et al. (submitted) was

TABLE 3 | Fuzzy rule set for biodiversity assessment (modified after Biber et al., submitted).



Shannon Evenness **Very low**

Vol > 60 cm	Coarse deadwood amount: Very low	Low	Medium	High	Very high
Very low	🟥	🟥	🟥	🟥	🟧
Low	🟥	🟥	🟥	🟥	🟧
Medium	🟥	🟥	🟥	🟥	🟧
High	🟥	🟥	🟥	🟧	🟧
Very high	🟧	🟧	🟧	🟧	🟧

Shannon Evenness **Low**

Vol > 60 cm	Coarse deadwood amount: Very low	Low	Medium	High	Very high
Very low	🟥	🟥	🟧	🟧	🟧
Low	🟥	🟧	🟧	🟧	🟧
Medium	🟧	🟧	🟧	🟧	🟨
High	🟧	🟧	🟧	🟨	🟨
Very high	🟧	🟧	🟨	🟨	🟨

Shannon Evenness **Medium**

Vol > 60 cm	Coarse deadwood amount: Very low	Low	Medium	High	Very high
Very low	🟥	🟧	🟧	🟨	🟨
Low	🟧	🟧	🟨	🟨	🟨
Medium	🟧	🟨	🟨	🟨	🟩
High	🟨	🟨	🟨	🟩	🟩
Very high	🟨	🟨	🟩	🟩	🟢

Shannon Evenness **High**

Vol > 60 cm	Coarse deadwood amount: Very low	Low	Medium	High	Very high
Very low	🟧	🟧	🟨	🟩	🟩
Low	🟧	🟨	🟩	🟩	🟩
Medium	🟨	🟩	🟩	🟩	🟢
High	🟩	🟩	🟩	🟩	🟢
Very high	🟩	🟩	🟢	🟢	🟢

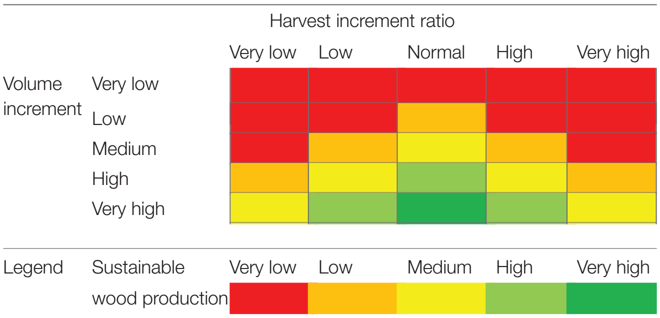
Shannon Evenness **Very high**

Vol > 60 cm	Coarse deadwood amount: Very low	Low	Medium	High	Very high
Very low	🟨	🟨	🟩	🟩	🟢
Low	🟨	🟨	🟩	🟩	🟢
Medium	🟩	🟩	🟩	🟢	🟢
High	🟩	🟢	🟢	🟢	🟢
Very high	🟢	🟢	🟢	🟢	🟢

Legend	Very low	Low	Medium	High	Very high
Biodiversity	🟥	🟧	🟨	🟩	🟢

The rule set consists of five matrices, each one for a fuzzy value of the Shannon Evenness (very low, low, medium, high, very high). Each matrix combines the volume of trees with dbh > 60 cm with the coarse deadwood amount (using the AND operator). The color codes "red", "orange", "yellow", "green", "dark green" represent the biodiversity assessments "very low", "low", "medium", "high", and "very high", respectively". More explanations in the text.

TABLE 4 | Fuzzy rule set for the assessment of sustainable wood production (according to Biber et al., submitted).



Volume increment	Harvest increment ratio: Very low	Low	Normal	High	Very high
Very low	🟥	🟥	🟥	🟥	🟥
Low	🟥	🟥	🟧	🟥	🟥
Medium	🟥	🟧	🟨	🟧	🟥
High	🟧	🟨	🟩	🟨	🟧
Very high	🟨	🟩	🟢	🟩	🟨

Legend	Very low	Low	Medium	High	Very high
Sustainable wood production	🟥	🟧	🟨	🟩	🟢

The rule set consists of a matrix which combines the annual wood volume increment per unit area with the ratio of harvest and increment. In this rule system, all combinations use the AND operator. The color codes "red", "orange", "yellow", "green", "dark green" represent the sustainable wood production assessments "very low", "low", "medium", "high", and "very high", respectively".

applied. Here the periodic annual volume increment (of each 10 year simulation period) at landscape level was used to determine the amount of wood currently produced in the forest landscape, whereas the harvest increment ratio (i.e., the ratio of wood harvested and the volume increment from the same period) indicated the sustainability of wood production. The more this ratio deviates from 1, the less sustainable the situation is, either due to over- or underharvesting. While the non-sustainable aspect of overharvesting is self-evident, underharvesting also must be considered unsustainable, as it does not utilize the forest landscape's potential and leads to overly dense, instable, calamity-prone stands, which limits the choice of future silvicultural options for decades [see the extensive review provided by Cameron (2002)]. The concept of the evaluation is that the absolute increment defines the potential level of sustainable production, while an unsustainable harvest-increment ratio moves the forest landscape away from that level. The corresponding fuzzy rule system is shown in **Table 4**. Whereas, this follows the same approach as the biodiversity assessment (e.g. *IF volume increment is high AND harvest increment ratio is normal, THEN sustainable wood production is high*), in this case it is much shorter as only two input variables are taken into account (volume increment and harvest increment ratio). Just as with biodiversity, both input variables are mapped to the categories *very low*, *low*, *medium/normal*, *high*, and *very high* (typical very low, low, medium, high, and very high volume increments: 0, 4, 8, 12, and 16 m^3/ha/a; typical very low, low, normal, high, and very high harvest increment ratios: 0, 0.5, 1, 1.5, 2) by equally spaced overlapping triangular fuzzy sets, and the resulting assessment of sustainable wood production is mapped to the range $[0, 1]$, with 0 being *very low* and 1 representing *very high* [see Biber et al. (submitted) for details].

Carbon Sequestration

We used a generic tool for calculating carbon sequestration and carbon balancing, that was developed by P. Biber and K. Black (Biber et al., 2018). Its application is described in detail in

Schwaiger et al. (2019). This software tool can be applied *post hoc* to the output data of forest simulation models. The most important information required includes, timelines of growing stock, species shares, annual increments, harvest amounts and how these are split into main assortments and the amount of wood remaining in the forest. Dead wood and product stocks are dynamically calculated based on typical, and adjustable, half-life times. This software traces the most important carbon stocks in the forest (including above and below ground living tree biomass and deadwood), wood usage and wood products as well as carbon emission savings due to the usage of wood instead of other materials. This enables an encompassing approach to carbon balancing, which includes carbon found in the forest itself, the related wood products, and emission savings, while ensuring the avoidance of double counting.

While the framework provided by this carbon balancing tool is generic, it allowed numerous parameters to be adjusted to the requirements of a CSA. Most importantly (but not exclusively) such adjustments related to the shares of different harvested wood assortments being attributed to different kinds of use (energetic, pulp, wood-based-products, sawn wood), half-life times of wood products, and shares of harvest residuals that remain in the forest (see Schwaiger et al., 2019 for more details). For this study, we used the mean annual total carbon balances for each 10 year simulation period. "Total" meant that the balance included the whole system forest-wood products-emission savings. These annual balances were expressed in tC per ha forest area, which also included the wood product stocks related to that area. Positive values indicated a net carbon uptake, while negative values indicated net carbon release.

Compared to the carbon stocks mentioned above, the soil-bound carbon stocks and their balances are of less importance to modeling outcomes, especially in relation to the extensive effort required for their inclusion. However, soil-bound carbon could not be neglected for the Irish and the Lithuanian case study where the mineral soil is mostly covered by a thick organic layer. In the Irish case we subtracted 0.91 t/ha/a from all the annual balances obtained with our model, in order to represent the C emissions from organic soils. This value was derived from the UNFCCC greenhouse gas inventory (Duffy et al., 2020). For the Lithuanian case study we applied the IPCC guidelines' default soil carbon emission rate for this region of 0.68 t/ha/a for organic soils in cold wet temperate conditions, plus 0.31 t/ha/a for C runoff; amounting to soil carbon losses of 0.99 t/ha/a (Intergovernmental Panel on Climate Change (IPCC), 2006).

RESULTS

Here we present the results for the three target variables of this study, sustainable wood production, biodiversity, and carbon balance. Additional information beyond that presentable in this publication, including the simulated development of all input variables for each CSA, is freely available online (Biber et al., 2019).

Country Specific Results

We display the CSA results (roughly clockwise by cardinal direction, starting in the North) with a standard set of three "trade-off" diagrams. We explain this setup using the results from Sweden as an example (**Figure 2**). In order to visualize the four-dimensional relationship of biodiversity, sustainable wood production, carbon balance, and time in an interpretable way, we prepared three two-dimensional diagrams per CSA. Each diagram plots two of our three variables against each other, thus covering all possible combinations of two. Inside each diagram we plotted the time trajectory of the particular variable combination (a so-called "phase diagram"). We marked the starting point (initial time) with a • symbol and the endpoint (final time) with a ▲. This allowed the development of all variables to be followed in relation to each other over time, and possible trade-offs and synergies to become visible, even if they are only temporary. In these diagrams the variables "biodiversity" and "sustainable wood production" obtained from the fuzzy logic assessments were scaled over the range [0, 1], with the extremes "very low" at 0, "very high" at 1, and "medium" in the middle. In contrast, we scaled the carbon balance from −3 to +3 tC/ha, which was slightly wider than the most extreme range we obtained from the analyses. As a result, values near the center of a diagram showed either medium values (for the fuzzy based variables) or a neutral total carbon balance. Values in the upper right quadrant indicated above average values of both displayed variables, with the opposite indicated by values in the bottom left quadrant. The upper left quadrant indicated good values for the y-axis variable and less desirable ones for the x-axis variable, with the bottom right quadrant showing the opposite.

Sweden

For Sweden, the simulations started with sub-optimum biodiversity, and middle to low sustainable wood production (**Figure 2**, left). Sweden applied a different forest management scenario with each global frame scenario (**Table 2**), with the reference and the EU bioenergy scenarios aimed for more diversified forest management, and the global bioenergy scenario mainly focused on wood production. This was reflected by the Reference pathway, which ended with quite high biodiversity and with small increases in sustainable wood production (**Figure 2**, left). The EU bioenergy trajectory followed almost the same path but ended slightly less advanced. The global bioenergy scenario substantially increased sustainable wood production, as well as biodiversity. However, biodiversity increased significantly less than in the other two scenarios. As **Figure 2** (middle) shows, this comparably small gain in biodiversity in the global bioenergy scenario came with the steepest drop in carbon sequestration from about 1.5 down to 0.5 tC/ha/a. The other two scenarios showed only a slight decline in the C-balance with increasing biodiversity; in the reference scenario it fully recovered to the highest biodiversity level of all scenarios. When sustainable wood production and the carbon balance were plotted against each other (**Figure 2**, right), the intuitively expected correlation between both did not occur. The moderate increase in sustainable wood production in the reference and the EU bioenergy scenarios was achieved with no or only a

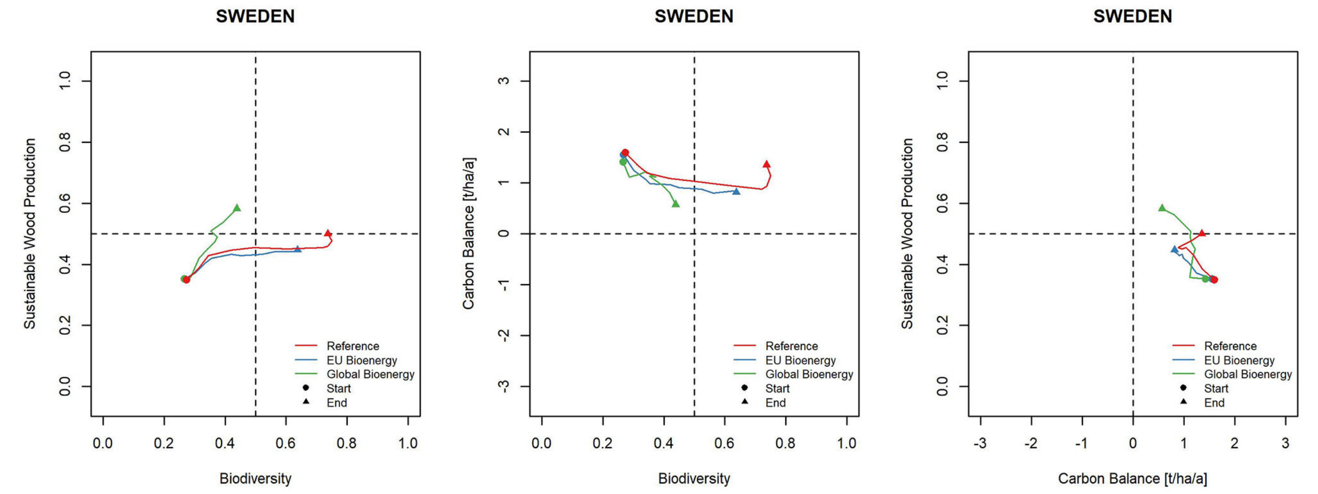


FIGURE 2 | Trade-off diagrams for Sweden.

slight loss in net carbon sequestration, while the carbon balance ended up lowest in combination with the highest sustainable wood production in the global bioenergy scenario. Increasing forest product stocks and C-emission avoidance effects could not compensate for lower C-stocks in the forest, due to lower average stand volumes.

Lithuania

For the Lithuanian case study two different silvicultural concepts were applied under all three global frame scenarios (**Table 2**). One strived to maximize financial benefits from the forest, while the other one moderately increased the share of deciduous species, while the conifers remained important. As all diagrams in **Figure 3** show, there was almost no difference among the scenarios (i.e. close overlap in the trajectories), as all managed to substantially increase sustainable wood production from low values to intermediate ones (**Figure 3**, left). The runs which introduced more deciduous species ended up with slightly higher biodiversity scores, but the difference was negligible. Comparing the carbon balance and biodiversity (**Figure 3**, middle), the carbon balance increased from about −1 tC/ha/a, up to only slightly negative and neutral values, without impairing biodiversity, which remains low. The C-balance and sustainable wood production (**Figure 3**, right) were related in such a way that, for all scenarios, the substantial increase in the carbon balance occurred quite early, prior to the substantial increase in wood production. The latter was accompanied by a slight reduction in the C-balance.

Ireland

In the Irish case study, one silvicultural scenario was applied to all three global frame scenarios (**Table 2**). The goal was profit maximization with the caveat of certain environmental constraints that included bog restoration and increased native broadleaf species. Biodiversity under these conditions remained low, at the long-term expense of sustainable wood production which, after an intermediate maximum, drops down to low values (**Figure 4**, left). Differentiation among the global frame scenarios was hardly visible. As **Figure 4** (middle) shows, the carbon balance dropped steeply down from about 2 tC/ha/a, before stabilizing around −0.5 tC/ha/a; whereas biodiversity again remained constant. With respect to the trajectory of sustainable wood production vs. carbon balance, a spiraling pattern with initially high amplitudes but distinct stabilization was observed (**Figure 4**, right). An early increase in wood production came with a strong decrease in C-sequestration, which continued even as wood production decreased again. In the later phases of the simulation, both values oscillated around small negative carbon balances and low sustainable wood production.

The Netherlands

For the Dutch case study, five silvicultural scenarios were calculated, one fitting to the EU bioenergy frame scenario, and two each for the reference and the global bioenergy scenarios (**Table 2**). The reference frame scenario was covered with two analogous silvicultural scenarios (slightly adapted current management), under the gfdl (Geophysical Fluid Dynamics Laboratory) and hadgem (Hadley Centre Global Environmental Model) 8.5 climate scenarios. Global bioenergy was covered in a similar way but with a silvicultural focus on local sustainability and bioenergy, as combined with gfdl and hadgem 2.6 climate scenarios. For the EU bioenergy frame scenario, only one run was simulated. It had a silvicultural focus on wood production that was combined with the hadgem 4.5 climate scenario.

In contrast to the case studies shown before, the Dutch case study started and remained at a high level of biodiversity (**Figure 5**, left and middle). As also seen in previous case studies, differentiation among the global frame scenarios in the Dutch case study is not pronounced. Virtually unconnected to the biodiversity response, sustainable wood production started at a low to moderate level, rose to moderate, before falling back to below the initial value (**Figure 5**, left). When looking at the

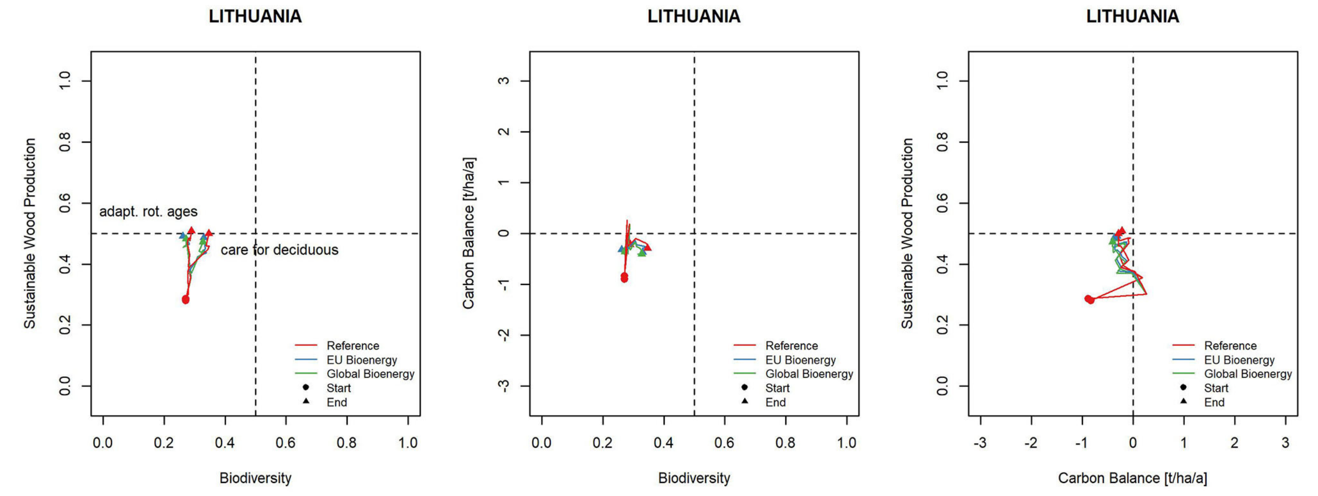


FIGURE 3 | Trade-off diagrams for Lithuania. The forest management scenarios "adaptive rotation ages" and "care for deciduous" are labeled in the left diagram.

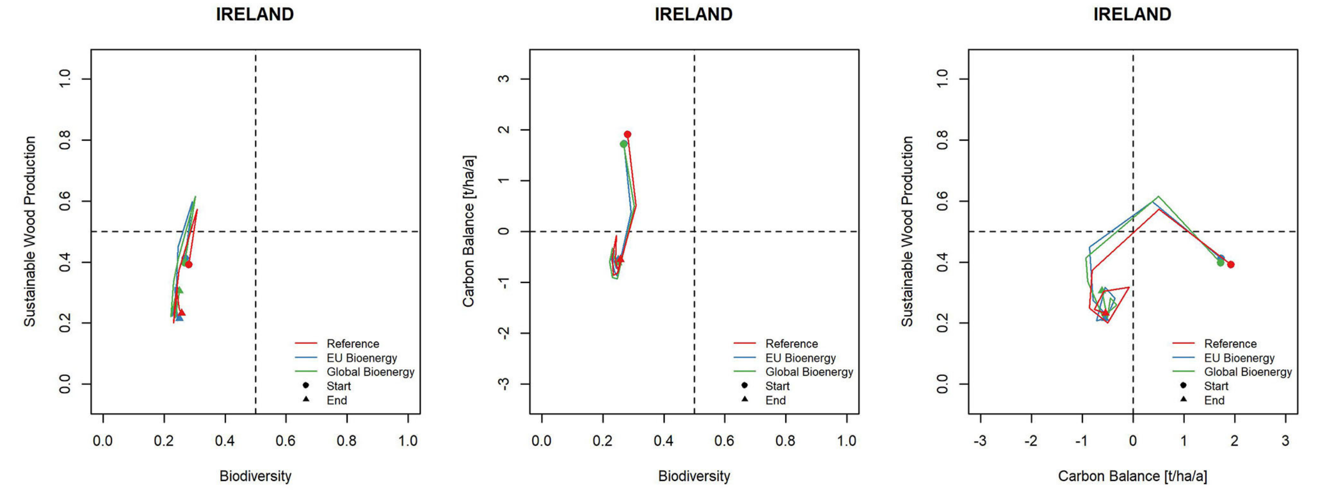


FIGURE 4 | Trade-off diagrams for Ireland.

carbon balance in relation to biodiversity (**Figure 5**, middle), all scenarios remained at high levels, even though there was a tendency to lower carbon balances at the end of the simulations. Relating the carbon balances to sustainable wood production (**Figure 5**, right), a positive correlation was visible, comprising the above-mentioned tendencies of both variables, with the global bioenergy related scenarios resulting in the smallest ranges.

Germany

In Germany, two case study areas were investigated, namely the north-eastern German case study "Lieberose-Schlaubetal, Neuzelle" (LSN), and the southern German region "Augsburg Western Forests" (AWF). The former was dominated by Scots pine (*Pinus sylvestris* L.) stands on low-growth sites, whereas the latter was dominated by Norway spruce (*Picea abies* (L.) H.KARST.) on productive sites. For the CSAs and global frame scenarios, three silvicultural scenarios were calculated, namely "Multifunctional", "Production", and "Set aside" (**Table 2**). Whereas, the "multifunctional" scenario involved establishing uneven-aged mixed stands, and the "production" scenario attempted to maximize wood production using conifer plantations, the "set aside" scenario simply maximized nature protection by stopping active forest management.

Considering the northeast case study (LSN) first (**Figure 6**, upper panel), differentiation among the frame scenarios was as low as for the previously shown case studies. In terms of the silvicultural scenarios, the set aside scenario stood out from the others. Considering biodiversity and sustainable wood production (**Figure 6**, upper panel, left), these started at very low and low values and remained as such for the whole simulation time span. The trajectories for the

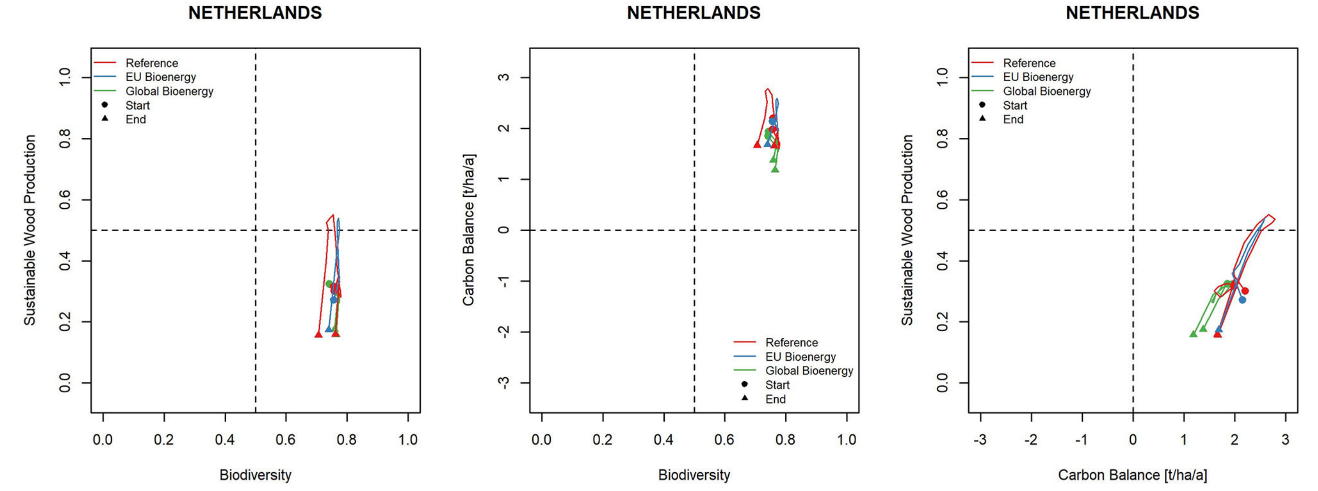


FIGURE 5 | Trade-off diagrams for the Netherlands.

multifunctional and the production-oriented scenarios were hard to tell apart. While almost no change in biodiversity occurred (remained at a low level), sustainable wood production fluctuated between low and medium, with the production scenario ending with higher production than the multifunctional forest scenario. Notably, the production forest scenario ended with very low biodiversity in the global bioenergy scenario. In all scenarios, carbon sequestration fell from values of >1 tC/ha/a, down to neutral or almost neutral values, while biodiversity remained virtually constant except for the global bioenergy effect mentioned above (**Figure 6**, upper panel, middle). When considering the carbon balance and sustainable wood production (**Figure 6**, upper panel, right), the set aside scenario resulted in very low sustainable wood production over the entire time span, while the carbon balance reduced with time. However, the net carbon uptake in the set aside scenarios remained higher over the long run than in all management scenarios. Despite no harvest taking place under the set aside conditions, sustainable wood production did not have a zero value. This reflected the fact that wood was produced within these "reserves," even though it was not harvested (categorized as not sustainable). While arriving and stabilizing at approximately neutral C-balances, the production forest scenarios managed to do so with an oscillating but on average increased sustainable wood production, while the wood production under multifunctional management remained at a relatively lower level.

The most pronounced differentiation among silvicultural scenarios inside any case study was evident for the southern German case study area "Augsburg Western Forests" (AWF, **Figure 6**, lower panel). Most noticeable were the strong oscillations of the production scenarios in all diagrams. These oscillations resulted from an uneven age-class distribution, which was not dampened by the silvicultural actions. Considering biodiversity and sustainable wood production (**Figure 6**, lower panel, left), the production scenario led—despite oscillations—to the lowest levels of biodiversity, especially in the global bioenergy scenario. Sustainable wood production was low to intermediate in phases of low harvest and high at times where high harvest volumes coincided with high volume increment. In the multifunctional forest, sustainable wood production remained stable at an intermediate to high level, with biodiversity consistently increasing from intermediate to high. The least movement was visible for the set aside scenarios where biodiversity remained at high levels, and sustainable wood production was low to intermediate. The latter resulted from high volume increments which were not harvested, and accumulated in the forest (categorized as a low degree of sustainability). Relating the carbon balance against biodiversity, similar patterns were obtained (**Figure 6**, lower panel, middle). At intermediate to low biomass levels, the carbon balance oscillated between almost −3 and 3 tC/ha/a. The most negative values occurred at times when a surplus of mature stands was harvested; the opposite was the case when high increment met low harvesting, leading to rapid C-accumulation in the forest. With increasing biodiversity, as mentioned before, the multifunctional scenarios showed a quick initial reduction in the C-balance, followed by a stabilization at about 1 tC/ha/a. Detailed analyses revealed that this was almost exclusively from substitution effects, due to the use of wood instead of other materials. A consistent decrease in the C-balance without any stabilization was evident for the set aside scenarios, accompanied by biodiversity remaining at a high level. Remarkably though, the multifunctional approach caught up with these biodiversity values in the long run. More than the other diagrams, **Figure 6** (lower panel, right) revealed a tendency toward higher sustainable wood production over the longer term in the production forest scenarios, while the C-balance oscillated without any clear tendency. The trajectories of the production scenarios formed a loop in the quadrant of high wood production and high carbon balances, which enclosed the entire trajectories obtained for multifunctional management. This indicated stability in multifunctional management at a high constant level. For the set aside scenario, wood

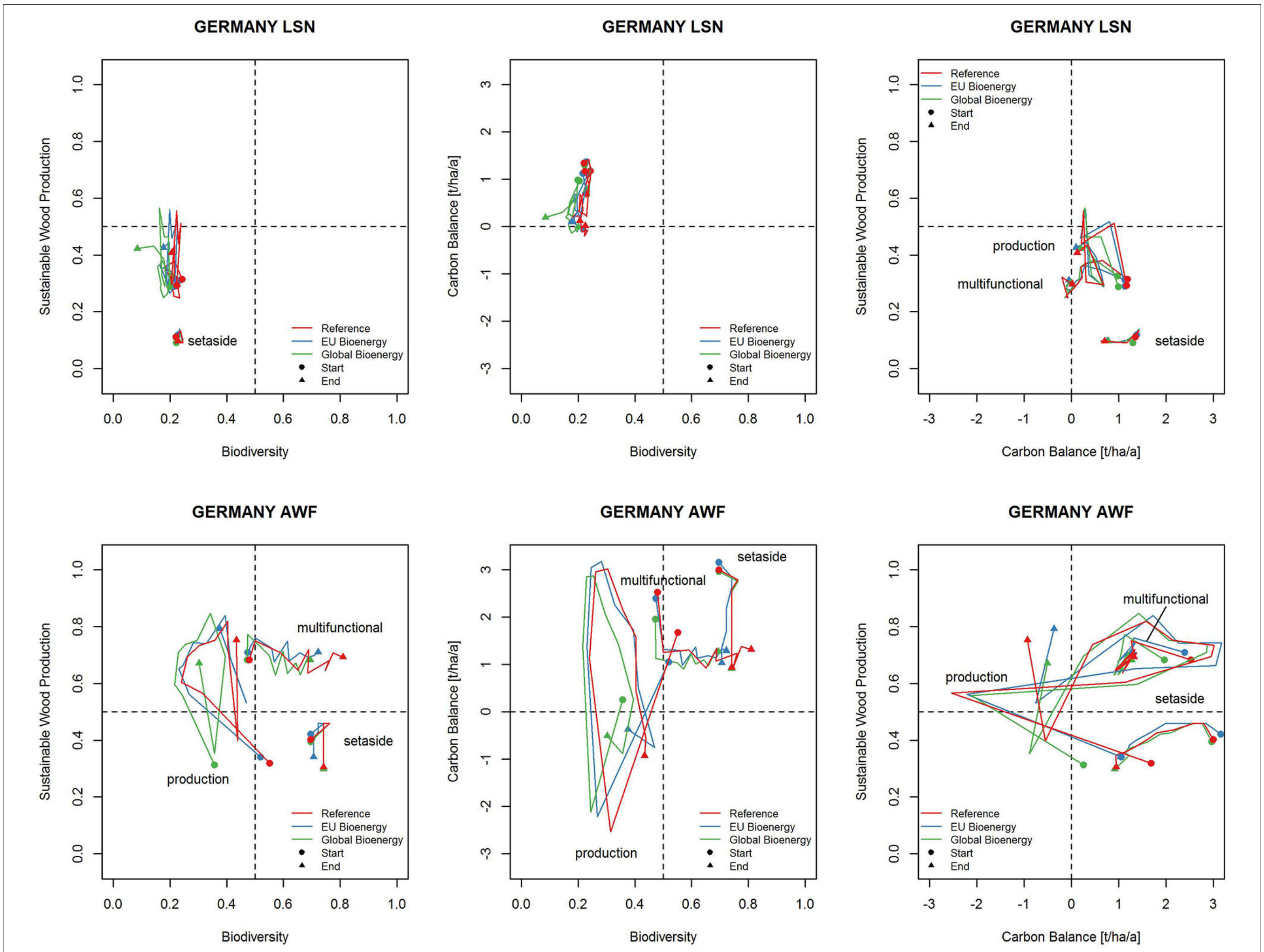


FIGURE 6 | Trade-off diagrams for the two German case studies. Upper panel: Northeast German case study "Lieberose-Schlaubetal, Neuzelle" (LSN). The trajectories of the "set aside" scenarios are labeled in the left and rightmost diagram. In the latter, also the multifunctional and production scenarios are marked. Lower panel: Southern German case study "Augsburg Western Forests" (AWF). The trajectories of all three silvicultural scenarios (multifunctional, production, and set aside) are labeled.

production fell down from medium to low levels along with a decreasing positive carbon balance. This indicated that high amounts of wood are produced "on reserve," storing high amounts of C in the forest. This happened, however, with a decreasing trend, as the stands approached their maximum standing volume.

Slovakia

For Slovakia, two silvicultural scenarios were available inside each frame scenario. The first ("conservative"), was based on business as usual approaches whereby management objectives were mainly determined by site conditions and the species composition of the forest. The other one ("liberalized"), was based on liberalized planning approaches whereby the management objectives depended mainly on the decisions of forest owners. The liberalized management scenario represented a very innovative management option in a former socialist country. In spite of the large conceptual differences in the management scenarios compared, a very small differentiation among the silvicultural scenarios was registered from the landscape perspective of the study (**Figure 7**). In addition, **Figure 7** showed certain reactions of the goal variables to the frame scenarios, but no clear distinct effects (careful consideration of the graphs shows a somewhat smaller distance of the end-points among the silviculture scenarios than among the frame scenarios. This was mainly caused by the outlying reference scenario). The average biodiversity remained low and almost invariable, while sustainable wood production varied slightly in the low/intermediate zone with a decrease in the Reference scenario and an increase in the others (**Figure 7**, left). Very similarly, the total carbon balance was stable, oscillating slightly around 0.5 tC/ha/a without any visible correlation with biodiversity (**Figure 7**, middle). The same stability occurred when the carbon balance was compared with sustainable wood

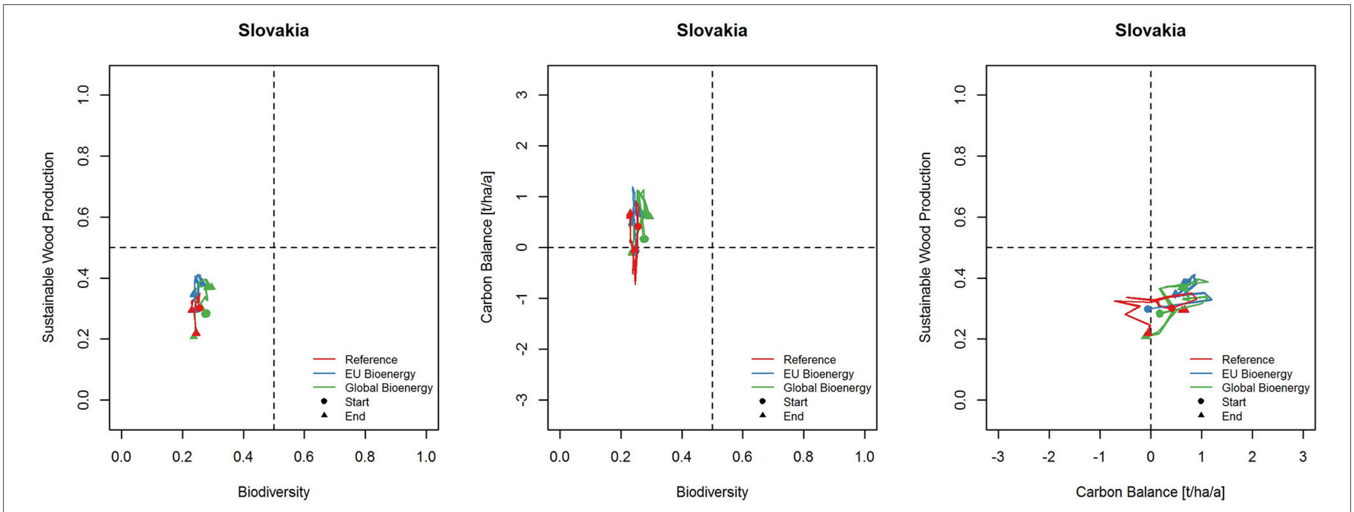


FIGURE 7 | Trade-off diagrams for Slovakia.

production (**Figure 7**, right). The amplitudes were so small that potential correlations would not play a decisive role.

Italy

As indicated in the methods section, the Italian case study was an exception insofar as no data were available that allowed us to evaluate biodiversity with the approach shown above. Therefore, only sustainable wood production and the carbon balance could be evaluated (**Figure 8**). There were two different silvicultural scenarios, each of which was applied in combination with all three frame scenarios (**Table 2**). The first silviculture scenario introduced close-to-nature forestry with the goal of maintaining biodiversity while improving recreational and cultural forest functions. The second scenario applied uniform shelterwood in important hardwood stand types, while transforming coastal forests into holm oak (*Quercus ilex* L.) coppice with standards. As **Figure 8** shows, the scenario differentiation was remarkably small. All trajectories moved around low to medium sustainable wood production with C-balances mostly between 0.5 and 1.0 tC/ha/a. The only exception was for the scenario with a constant high carbon balance and an increasing trend in wood production. This was the uniform shelterwood scenario in the Global Bioenergy frame scenario. The high wood demand in this frame scenario seemed to induce the strongest reaction from silviculture in terms of increased production.

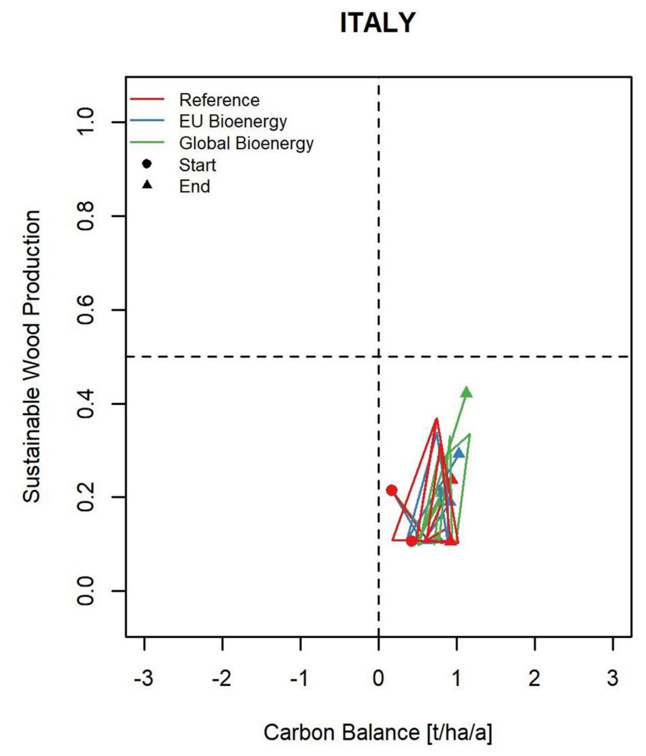


FIGURE 8 | Trade-off diagram for Italy. For the Italian case study, no data were available for the assessment of biodiversity based on this study's approach. Thus, only the trajectories for sustainable wood production and the carbon balance can be shown.

Portugal

In the Portuguese case study, a multifunctional silvicultural concept was applied (**Table 2**), which attempted to provide regulatory (wildfire resistance), cultural services, biodiversity, erosion control and wood production, within a spatially optimized approach (cf. Marto et al., 2019). Due to a lack of appropriate climate data for the Portuguese DSS, only the Reference and the EU Bioenergy frame scenarios were covered (**Figure 9**). While the frame scenarios did not make a large difference to outcomes, the silvicultural treatment resulted in interesting patterns. While for all three variable combinations the start and the endpoints did not vary extensively, there were wide fluctuations and clear correlations along the intervening path. As **Figure 9** (left) showed, sustainable wood production and biodiversity both co-fluctuated between low and intermediate levels. This happened with a clear linear-like correlation;

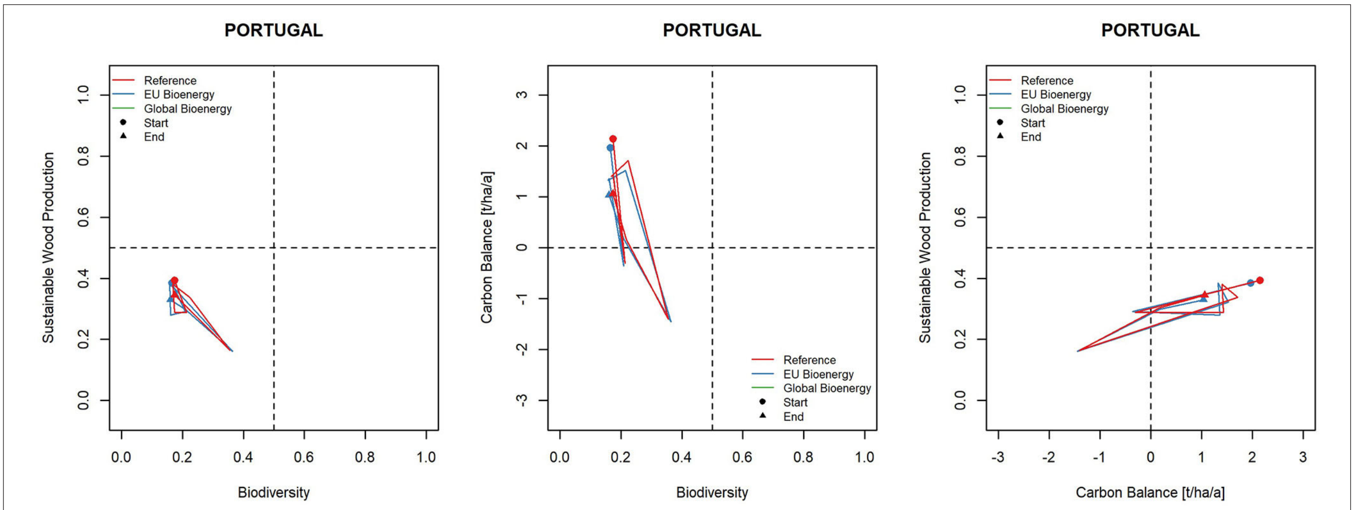


FIGURE 9 | Trade-off diagrams for Portugal.

intermediate biodiversity only occurred with low sustainable wood production and vice versa. The relatively low levels of assessed biodiversity resulted from the absence of large trees (>60 cm) as well as from the very small amounts of coarse dead wood, both resulting from silvicultural practices.

Stronger than that found in most other case studies, the total carbon balance correlated positively with sustainable wood production; the latter varying widely between −1 and +2 tC/ha/a, but mostly staying within the positive zone (**Figure 9**, right). Consequently, biodiversity correlated negatively with the total carbon balance (**Figure 9**, middle).

Turkey

In the Turkish case study, a multifunctional silviculture concept, which included continuous cover forestry as an alternative forest management scenario, was applied in all three global frame scenarios (**Table 2**). With no considerable frame scenario differentiation, we saw a slight increase in sustainable wood production (from very low to still low levels) along with a considerable increase in biodiversity (from low to intermediate, **Figure 10**, left). The main driving factor for the increased biodiversity in the Turkish case study was the increased abundance of big trees. This was due to an ongoing conversion from coppice to high forest while maintaining the existing set of production tree species.

This development, however, came with a decrease in the total C-balance, from about 1.5 down to 1.0 tC/ha/a, despite an increased sustainable wood production (**Figure 10**, middle). The decrease of the C-balance came in parallel with an age class shift toward younger stands at the end of the simulation period. Thus, whereas wood production and biodiversity were positively correlated, and the correlation between biodiversity and carbon sequestration was negative, a negative correlation between wood production and carbon sequestration was evident in **Figure 10** (right).

Synopsis

With **Table 5** we provided a synopsis of the results presented above, as visually interpreted correlations between our three target variables–sustainable wood production, biodiversity, and the carbon balance. In general, taking all case studies into consideration, correlations were not clear. Sustainable wood production did not show a clear correlation with biodiversity in either direction. In the case of Sweden and Turkey there seemed to be a positive relationship, while a negative correlation between both was evident in Portugal, as a consequence of the importance of eucalypt plantations to the sustainability of the overall timber supply. Additional correlations existed between sustainable wood production and the carbon balance. Positive correlations occurred in Ireland, the Netherlands, Portugal, Lithuania, where higher wood production meant more C-sequestration. However, there were also tendencies toward negative correlations in Sweden and Turkey. Correlations between carbon balance and biodiversity were also inconsistent. In six out of nine cases no correlation occurred, with the only identified correlations being negative (Portugal, Turkey, Sweden). Nevertheless, in the case of Portugal, this was explained by the importance of eucalypt plantations for both wood supply and C-sequestration, and its association with lower values of biodiversity.

DISCUSSION

Climate and Forest Management Sensitivity

Across all of the case studies, there were no fundamental differences in the outcomes from the climate scenarios. One could argue that this was due to a lack of sensitivity in the simulation models applied, which is possible, despite the standards demanded (Nordström et al., 2019). However, we deem this explanation unlikely to be the only one, as the models covered a broad range of conceptual types (from statistic

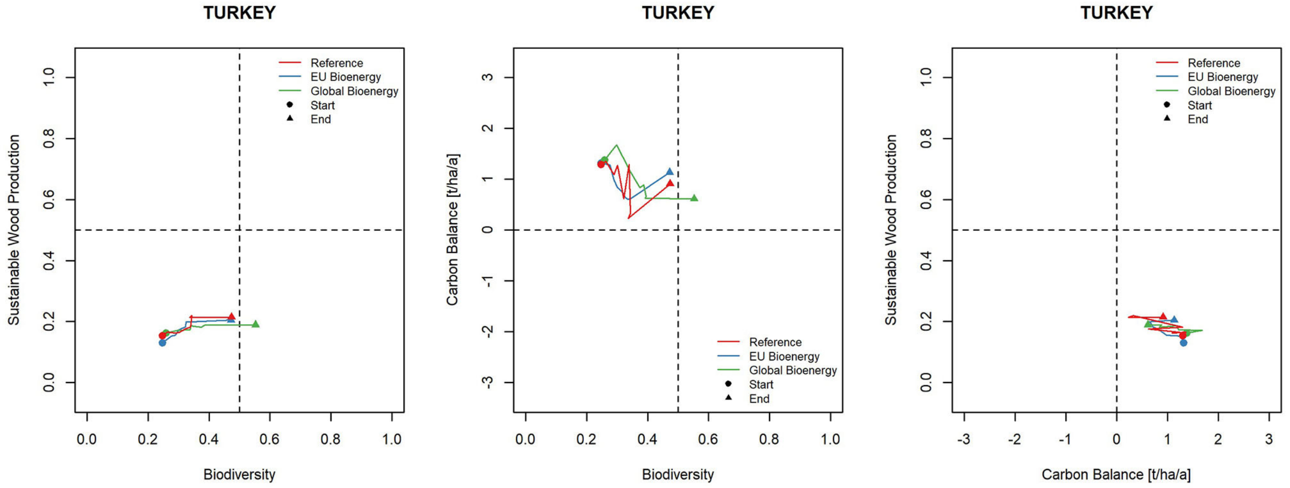


FIGURE 10 | Trade-off diagrams for Turkey.

TABLE 5 | Country-wise correlations between the goal variables of this study, by visual interpretation of the trade-off diagrams (**Figures 2–10**).

Country	Wood vs. Biodiversity	Carbon balance vs. Biodiversity	Wood vs. Carbon balance
Sweden	+	−/0	−/0
Lithuania	0	0	0/+
Ireland	0	0	+
The Netherlands	0	0	+
Germany (LSN)	0	0	0
Germany (AWF)	0	0	0
Slovakia	0	0	0
Italy	n.a.	n.a.	0
Portugal	−	−	+
Turkey	+	−	−

The symbols "+", "−", "0" indicate correlations we interpret as considerably positive, negative, or not existing, respectively. Two symbols separated by a "/" means that both correlation types are observed in different scenarios of the related case study.

and hybrid, to mechanistic models, and from simulation to optimisation). Certainly, this result was also caused by the gradual nature of the temperature increase underlying the frame scenarios, and it can be contrasted with those provided by distinct forest management scenarios. In those case study areas for which several forest management scenarios were developed, the differences among these in biodiversity and ecosystem service outcomes were generally more pronounced than those driven by climate and market differences, as long as the management scenarios were sufficiently different (see below). An exception was Slovakia, where case study specific frame conditions prevented a significant differentiation of management outcomes. But even in the case of Portugal, which reported an optimized version of its generic management concept for both climate scenarios, the contrast between optimal and non-optimal solutions under each climate scenario was greater than the contrast between solutions, i.e., management scenarios across climate scenarios. There was, however, another significant caveat regarding this conclusion. While our models addressed the effects of mean annual climate on forest dynamics, they did not include any changes to the probability of extreme events and disturbances such as wildfires, storms and droughts (Lindner et al., 2010; Clark et al., 2016; Reyer et al., 2017). The combination of both facts in reality is the reason for the seemingly paradoxical situation that we observe accelerated forest growth in large parts of Europe, despite accumulating evidence for increased damage to these forests associated with climate change (Allen et al., 2010; Carnicer et al., 2011; Milad et al., 2011; Lindner et al., 2014; Seidl et al., 2014). The need to address disturbances and extreme events by forest simulation models and DSS is clearly an issue which requires attention in future studies (Reyer et al., 2017). For interested readers, we note that all of the scenarios presented in this study were also evaluated for the provision of regulatory services, i.e., resistance against typical disturbances. However, this information was not available at a generic enough level to be included in this study (see Biber et al., 2019 for these results).

In contrast to the generally small effects of climate, our results suggested, at least in principle, the considerable potential to alter biodiversity and ecosystem service outcomes by varying the silvicultural approach applied. However, this did require substantial differences in the silvicultural approaches used, such as those applied in the southern German case study AWF, to achieve large differences over relatively short time periods. This is due to the pronounced inertia of forest systems, even to altered management regimes; it is not, as could be conjectured, an inherent inertia of our evaluation methods. Notably, the application of the same silvicultural scenarios made much less of a difference when applied to the low-growth region LSN in northeast Germany. If the silvicultural scenarios were relatively similar, or if the area shares of different approaches did not change fundamentally, the inertia of forest landscapes appeared difficult to overcome over the time period considered. Examples of this were the case studies of Italy, Slovakia and Lithuania, for which even seemingly diverse forest management concepts did not substantially alter the provision of the ecosystem services evaluated.

Evaluating Ecosystem Service Provision

While our carbon balancing followed a strictly quantitative approach, the assessment of biodiversity and sustainable wood production was based on expert rules which introduced a subjective element to the evaluations. Whereas the authors tried to incorporate the best scientific knowledge and expert experience available [see also Biber et al. (submitted)], some level of conjecture was unavoidable. In such a context, the transparency of the rule system used is crucial, and this is certainly an advantage of a fuzzy logic approach due to the intuitive formulation of the rule systems (Reynolds et al., 2014).

In addition, due to the standardized requirements of the case studies, our evaluations were limited to a few cornerstone input variables that were only available as landscape level averages. While this provided the overview picture required for this study, it had the potential to obscure more fine-grained results that are of interest to decision makers at the case study and finer level. For example, detailed analyses of the Slovakian case study showed effects of biodiversity-friendly management practices which were not distinguished from the perspective of this study. Likewise, in the Portuguese case study, the inclusion of additional taxa in the biodiversity assessments, such as shrubs and herbaceous plants, was advocated by local experts as a means to improve result outcomes. The reader is encouraged to see the case study specific reports in Biber et al. (2019) for related information.

Another methodological issue were the estimates of tree species diversity, which were of direct relevance to biodiversity assessments. Our approach did not distinguish between the "ecological quality" of the tree species, i.e., species are weighted the same without distinguishing whether they are indigenous, exotic species or even cultured clones. This might bring about over-optimistic biodiversity assessments in silvicultural scenarios which rely on increasing production by introducing non-native and industrially bred species, as was the case in Sweden's global biodiversity scenario. Another point which is beyond our approach are climate-change related shifts in species distributions, and the potential losses to forest biodiversity in this century induced by more extreme greenhouse gas emission scenarios and associated disturbances (Felton et al., 2014; IPBES, 2019). Our study, in its simulation and evaluation methods, is limited to using variables that are available from forest inventories. Tackling this problem, in contrast, required (meta-) population modeling of key plant and animal species in a dynamically changing forest landscape (Wintle et al., 2005).

A Closer Look at the Outcomes

Our outcomes were constructed from two primary components: (i) the static component, i.e., the initial situation (in terms of our target variables) in each case study, including the existing trade-offs and synergies, and (ii) the dynamic component, i.e., the changes observed with simulated forest development. With regard to the static component, virtually all case study areas started at low to moderate biodiversity, combined with low to moderate sustainable wood production. In this regard, low to moderate biodiversity and wood production was associated with high levels of net carbon uptake. Regarding the dynamic component, our results suggested that in most case studies there was not a trade-off between biodiversity and sustainable wood production. This result is supported by recent studies Dieler et al. (2017) and Schulze (2018). We observed almost no reduction in biodiversity indicators associated with an increase in wood production, except in the Portuguese case study. The importance of the eucalypt pulpwood in the overall wood supply explained the trade-off observed in Portugal. Whilst the presence of eucalyptus may be instrumental to generating financial resources which can be used to support set-aside conservation areas, introduced eucalypt stands generally have low inherent biodiversity value (Deus et al., 2018).

In some cases (Sweden, Turkey) synergistic results occurred when diversity was actively promoted as part of the management concept [similar results were obtained by Biber et al. (2015)]. However, due to unbalanced forest age class distributions, we observed relatively large oscillations in ecosystem service provision in some case study areas (Ireland, Portugal, Germany AWF). In most cases, the net carbon uptake was not correlated with biodiversity, indicating that biodiversity-friendly forest management did not necessarily restrict carbon sequestration. However, conflict between biodiversity and carbon sequestration was projected in some case studies (Portugal, Turkey, partly Sweden). We feel these results are supported by a wide-scale review by Huston and Marland (2003), who argue that even win-win situations for C sequestration and biodiversity were possible given careful (spatial) planning.

Notably, we obtained heterogeneous results with respect to the relations between sustainable wood production and net carbon uptake. This was due to several issues: low-intensity forest management with low harvest volumes led to rapidly increasing forest-bound carbon stocks and thus resulted in a high net C-uptake. On the other hand, intensive management with high sustainable harvest levels could also increase carbon stocks in wood products and, even more important in the long run, maintained a high level of C-emission savings due to substitution effects. In addition, the effect of harvest volumes on the net carbon uptake of the whole system (forest, wood products, C-emission savings) depended to a large extent on what wood assortments (pulpwood, roundwood) were harvested, and how they were used (energy, pulp and paper, wood-based products, sawn wood), see Pingoud et al. (2010). Both harvested wood assortment shares and wood usage shares differed among the case study landscapes and management scenarios (Biber et al., 2019). If C-balancing is only considered in relation to the forest-bound C-stocks, a reduction in management intensity will always leads to an increase in the net uptake of C (assuming–forest carbon sinks are not yet saturated). However, we also took into account wood products and emission savings in our modeling. By so doing we see our work as helping to close a gap pointed out by Peckham et al. (2012), in the lack of whole forest system analyses with respect to C-balancing.

When we compared the outcomes for wood production to the wood demand described in the frame scenarios, we found that in almost all case studies production was considerably lower than the demand. Even though a statistical upscaling of the case studies to the EU level was not feasible, this could indicate that achieving the stringent renewable energy goals of the Global Bioenergy scenario is not realistic, or that the actual production potential was not fully utilized even in the production-focused silvicultural scenarios.

Implications

We believe that our study results are relevant to forest management and policy in Europe. Although our case studies were not selected for representativeness in a statistical sense, attention was payed to include circumstances with key properties of relevance at the European level. As the silvicultural scenarios were designed in consultation with the views of powerful stakeholders, they are not just utopian assumptions, but some aspects of them have a considerable chance of being implemented—as indeed, some already are. For practical forest management our results suggest that, at least with regard to wood production, biodiversity, and carbon sequestration, there are more degrees of freedom than may intuitively be assumed. This is certainly an advantage, because it indicates a considerable range of forest management options that do not automatically trade off one of the three ecosystem services against the others. On the other hand, this result highlights the necessity of forest management planning and assessment down to the regional and landscape scale in order to avoid improper generalizations with resulting suboptimal outcomes. Furthermore, this study shows that state-of-the-art optimisation and simulation models and DSSs are available throughout Europe which, however, require enhancement. As mentioned above, a necessary extension that these tools require in the future is to include the effects of extreme events like droughts or storms. Seen across all case studies, our results form a very heterogeneous picture, which indicates the diversity of forest management in Europe and the diversity of pathways along which it is expected to develop in the future. For European forest policy this suggests that strict top down regulations might not be the best approach to optimize ecosystem services provision. As far as forest management is concerned, a policy sometimes called "Europe of the Regions" (Luedtke, 2005) may be advisable.

CONCLUSIONS

We conclude that the potential exists to steer the provision of biodiversity, sustainable wood production, and carbon sequestration from European forests, but this should not be overestimated. If no fundamental changes in silviculture are applied, changes in the provision of these ecosystem services will mostly take decades. Specifically, our results are likely to be optimistic, with respect to climate change associated disturbances, such as storms and extended drought periods, which were not taken into account in our analyses. In relation to European forest policy development, we conclude that subsidiary approaches, that allow regionally tailored solutions, were the most appropriate to optimize ecosystem services provision throughout Europe.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors on reasonable request, without undue reservation.

AUTHOR CONTRIBUTIONS

PB and AF designed the study and wrote the paper. Together with MN and ML who also contributed to writing, they structured and coordinated the study. PB designed the basis version of the ecosystem service evaluation system. PB, AF, MN, and ML adjusted it for the study at hand. KB and PB designed the carbon evaluation tool. All authors provided indispensable simulation data and interpretation. All authors contributed to the article and approved the submitted version.

FUNDING

This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 676754 (ALTERFOR). This research also received the support of the Forest Research Centre, a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UIDB/00239/2020) and of the Centre for Applied Ecology Prof. Baeta Neves (CEABN-InBIO), a research unit funded by FEDER through the Operational Programme for Competitiveness Factors—COMPETE and by FCT under the [UID/BIA/50027/2013] and POCI-01-0145-FEDER-006821.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2020.547696/full#supplementary-material

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Conflict of Interest: KB was employed by the company FERS Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.