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Opportunity Costs of In Situ Carbon Storage Derived by Multiple-Objective Stand-Level Optimization—Results from Case Studies in Portugal and Germany

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Abstract: Considering in situ carbon storage in forest management has gained momentum under increasing pressure to decarbonize our economies. Here, we present results from case studies in Portugal and Germany showing the opportunity costs of in situ carbon storage derived by multiple-objective optimization. We used a stand-level model to optimize land expectation value under uncertainty as a reference, then derived opportunity costs by including the enhancement of the average carbon storage in aboveground biomass as a second objective. Using the optimal (compromise) solution when considering both objectives simultaneously, we show opportunity costs of EUR 119 (Portugal) and EUR 68 (Germany) per Mg CO_{2eq}. These opportunity costs are higher than conservative, but lower than alternative cost estimates for future damages caused by current CO_2 emissions. An important result was that suggested reference solutions in both countries (though only for low discount rates in Portugal) were mixed forests without clearfelling. In Germany, this implicitly elevated carbon storage. Such "closer-to-nature-forest-management" systems were also mostly suggested by the optimization tool when carbon storage was an objective.

Keywords: climate change; in situ carbon storage; optimization; social costs

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1. Introduction

Increased atmospheric greenhouse gas emissions such as carbon dioxide remain a major global issue [1]. As carbon dioxide concentrations rise, so does the global temperature, causing more severe storms, increased drought, rising oceans, loss of species, and more health risks [2,3]. In response to this, multiple international initiatives aim to reduce the amount of carbon dioxide present in the atmosphere by reducing emissions and stimulating carbon storage in terrestrial ecosystems [4].

Carbon sequestration and storage in forest ecosystems is often promoted as a solution for reducing carbon dioxide concentrations in the atmosphere. Globally, forests play a major role as a significant carbon sink [5–7], storing nearly half of the carbon found in terrestrial ecosystems [8]. As a result, enhancing carbon sequestration and storage in forest ecosystems is increasingly becoming a fundamental goal for sustainable forest management [9–11].

Considering in situ carbon storage in forest management has gained momentum [12–15] under the increasing pressure to decarbonize our economies [16]. Carbon forestry often employs silvicultural prescriptions intended to improve growth and productivity and/or enhance aboveground carbon storage [17,18]. However, there is ongoing discussion regarding the effects of different silvicultural approaches on carbon storage [11,19]. In this regard, there is still a need for developing optimization tools and assessment frameworks to guide informed decision making.

Dynamic models to maximize the sum of discounted cash flows from timber production and the value of carbon storage in size-structured, mixed forest stands represent the forefront in current optimization approaches (e.g., [20]). Common approaches build on economic maxima, where one objective function aggregates all discounted cash or value flows, but commonly ignore the impact of uncertainty on decision making. Kolo et al. [21] provide an example of how to integrate uncertainty into multi-objective optimization, while discounted value flows from carbon sequestration and water supply enter one objective function in addition to discounted cash flows from timber harvesting.

Here, we adopt an alternative approach and consider the economic return from timber production and average carbon storage as separate objective functions, ruling out any compensation among both objectives. Using the optimal (compromise) solution when considering both objectives simultaneously, opportunity costs become available relative to optimizing only economic return from timber production. Such optimization of economic return provides a consistent "business-as-usual" reference, against which opportunity costs and increases in carbon storage can be assessed [22]. The opportunity costs provide important information to evaluate whether storing more carbon in existing forests might be efficient, and whether forest owners would accept a given carbon price. In addition, our modelling approach suggests the optimal silvicultural system (either clearfelling of forest stands consisting of just one tree species, or partial harvesting with early establishment of new age cohorts in mixed forests). These different silvicultural systems can influence carbon storage as well. The aim of our alternative optimization method is to show economic trade-offs of in situ carbon storage and the associated opportunity costs, and the variation of carbon storage with different silvicultural systems, derived by multiple-objective, stand-level optimization. We compare the resulting silvicultural systems with standard clearfelling systems using results from case studies in Portugal and Germany.

2. Materials and Methods

We used a stand-level optimization model developed by Knoke et al. [23] to include carbon storage as a second objective together with economic return as the first objective in an optimization process. We define opportunity costs, OC, as the decline of the economic return with the increase in the carbon stored in a forest stand.

$$OC = -\frac{\Delta Economic\ return}{\Delta Carbon} \quad (1)$$

As indicators, i, included in the optimization process, we use the average storage of carbon and the associated CO_2 equivalents in the forest stand's aboveground biomass and the soil expectation value, SEV, to represent the economic return [24]. The optimization builds on second-order cone programming to allocate stand area proportions, a_{st}, to various tree species, s, and to harvesting periods, t, simultaneously. For example, $a_{Beech,50} = 0.1$ would mean establishing beech at 10% of the stand's area to harvest and replant at age 50. This means that our method allows partial harvesting to establish young tree cohorts in each considered period [25,26]. The optimization uses distances, D_{iust}, between most desirable indicator levels, Y^*_{iu}, and indicator levels achieved by an actual decision, y_{iust}, as criteria for finding the optimal solution. u symbolizes a specific uncertainty scenario, as we consider an expected and a pessimistic achievable indicator level for all possible decisions.

$$D_{iust} = \frac{Y^*_{iu} - y_{iust}}{Y^*_{iu} - Y_{iu*}} \cdot 100 \quad (2)$$

The absolute distances $Y_{iu}^{*} - y_{iust}$ are normalized between zero (least desirable outcome Y_{iu*}) and 100% (most desirable outcome Y_{iu}^{*}). The achieved decision outcomes, y_{iust}, are the actual contributions of any decision to an indicator, i, when establishing a certain tree species, s, to harvest and replant at period t.

The optimization seeks to minimize the Euclidian distance between the most desirable and the achieved level across all considered indicators and uncertainty scenarios. Minimizing Euclidian distances is compatible with risk avoidance, as it considers uncertainty reductions by diversification. Risk-avoidant people use diversification to buffer uncertainty when making decisions [27]. Euclidian distances consider such diversification effects and imply that decision outcomes behave similarly to uncorrelated random variables. Euclidian distances for our decision simulations were computed as follows:

$$D_{iu} = \sqrt{\sum_{s}^{S} \sum_{t}^{T} (w_i \cdot a_{st} \cdot D_{iust})^2} \quad (3)$$

The constant w_i is a weighting factor used to vary the importance of each objective. For example, we use $w_{SEV} = 0,\ 0.1,\ \ldots,\ 0.9,\ 1.0$ and $w_{Carbon} = 1 - w_{SEV}$. These variations allow us to analyze different levels of carbon stored and associated levels of opportunity costs. Finally, to quantify opportunity costs, we use results corresponding to the weighting factors, w_i, that led to minimum opportunity costs.

Then, the final optimization problem was:

$$\min_{a_{st}} \beta \quad (4)$$

s.t.

$$\beta = max(D_{iu}) \quad (5)$$

$$\beta \geq D_{iu}\ \forall\, i, u \quad (6)$$

$$\sum_{s}^{S} \sum_{t}^{T} a_{st} = 1 \quad (7)$$

$$a_{st} \geq 0 \quad (8)$$

For both indicators, we consider eight different uncertainty scenarios, u, for different combinations of optimistic and pessimistic indicator levels among three tree species, possibly mixed at stand level, to represent the uncertainty forest managers are confronted with. The carbon storage and soil expectation values used for reporting opportunity costs and for the trade-off analyses refer to the expected indicator levels. A detailed description of the stand-level optimization model can be found in Knoke et al. [23].

2.1. Portuguese Case Study Data

The Portuguese case study data (Table 1) reflects the forest conditions in Northwest Portugal. The growth of the forest species was simulated using the StandsSIM-MD module [28] of the sIMfLOR platform [29]. It uses the GLOBULUS 3.0 model for Eucalyptus globulus L. [30] and the PINASTER model for *Pinus pinaster* A. [31,32]. The simulations for Castanea sativa were obtained from yield tables [33]. Silvicultural costs and prices were obtained from the CAOF table [34] and from relevant stakeholders in the sector. For a detailed characterization of stakeholders in forested landscape in Northwest Portugal, refer to Marques et al. [35].

2.2. German Case Study Data

The German biophysical data were obtained from empirical growth functions published by Pretzsch et al. [36] (for spruce and beech). For silver fir, the spruce function was used, but adapted (see Knoke et al. [23]). Survival probabilities were taken from Brandl et al. [37] and stumpage prices from Paul et al. [38]. Further information concerning the growth response after partial harvesting and the growth suppression of young tree cohorts growing in gaps are provided in Knoke et al. [23].

Table 1. List of species and data sources used for our simulations.

Portuguese Case Study	
Species	**Data Sources**
Maritime pine	[28,29,31,32,34,35]
Chestnut	[28,29,31,32,34,35]
Eucalyptus	[28–30,34,35]
Germany Case Study	
Species	**Data Sources**
Spruce	[23,36–38]
Silver fir	[23,37,38]
Beech	[23,36–38]

2.3. Discount Rate

It is well known that the discount rate has an enormous impact on any carbon cost assessment [39]. Benítez et al. [40] published a regression function which suggests risk-adjusted discount rates for different countries, assessing the carbon sequestration potential worldwide. Their function proposes discount rates of 4.2% and 2.1% for Portugal and Germany, respectively. We corrected these rates downwards (3% for Portugal and 1.5% for Germany) while retaining a similar relation according to lower discount rates. For example, see the rates were suggested by [41] to describe the decision behavior of German forest owners. Finally, we used Portugal's discount rate to optimize German forests and Germany's discount rate to optimize Portuguese forests to obtain information concerning the sensitivity of our results to changes in the discount rate.

2.4. Social Costs of Carbon as a Benchmark

The social cost of carbon (SCC) provides a concept to support decision makers in finding appropriate climate change mitigation policies. SCC represents the change in the appropriately discounted value of economic welfare caused by damages associated with the additional units of CO_2 emitted presently [39]. In theory, the SCC corresponds to the maximum amount society should be willing to pay in order to avoid the damages associated carbon emissions [42]. We used conservative published values for the SCC [39,43] to obtain a benchmark with which we can compare the opportunity costs of forest owners who enhance the average carbon storage in their stands.

3. Results

3.1. Opportunity Costs

For both case studies, we refer to optimal solutions for risk-avoidant forest owners seeking to optimize their economic return under uncertainty as a normative reference solution. This means that our program suggests how risk-avoidant decision makers could achieve the best compromise between economic return and mitigating the consequences of uncertainty. We assume that such forest owners prefer economically robust forest outcomes, not only for the expected indicator outcomes, but also for pessimistic ones.

The opportunity costs of storing additional carbon were lower in Germany than in Portugal. Discount rate sensitivity was also highest in Germany, where opportunity costs dropped from EUR 68 to EUR 19 per additional Mg CO_{2eq} stored in the forest when changing the discount rate from 1.5% to 3% (Table 2).

Our optimization of the reference scenario for the Portuguese case study suggested an average storage of 46.72 Mg CO_{2eq} per hectare and a land expectation value of EUR 5739 per hectare (discount rate 3%). The reference stand consists only of eucalyptus (100%) and is managed as a clearfelling coppice system. When considering the average carbon storage as an additional objective, we obtained mixed forests without clearfelling, which we classify as "closer-to-nature-forest-management" (CrNFM) [44], for $w_{Carbon} < 1$, but the minimum opportunity costs were obtained for $w_{Carbon} = 1$. This solution increased the average carbon storage by +52.97 Mg CO2eq per hectare. Increasing the carbon storage reduced the soil expectation value from EUR 5739 to −553 per hectare, representing opportunity costs of EUR 119 per additional Mg CO2eq stored in the forest.

Table 2. Opportunity costs off additional carbon in forest stands in Portugal and Germany. Default discount rates 3.0% and 1.5% for Portugal and Germany, respectively (corresponding results in bold and italics).

		Discount Rate			
		1.5		3.0	
		Carbon Is No Objective	**Carbon Is an Objective**	**Carbon Is No Objective**	**Carbon Is an Objective**
Portugal	**Tree species [%]**	$w_{Carbon} = 0$	$w_{Carbon} = 1$	$w_{Carbon} = 0$	$w_{Carbon} = 1$
	Maritime pine	17.5	0	***0***	***0***
	Chestnut	5.8	100	***0***	***100***
	Eucalyptus	76.7	0	***100***	***0***
	Soil expectation value [EUR per hectare]	7545	2249	***5739***	***−533***
	Average carbon storage [Mg CO_2 equivalent per hectare]	46.61	99.69	***44.64***	***99.69***
	Opportunity costs [EUR per Mg CO_2 equivalent]	99.97		***118.79***	
Germany	**Tree species [%]**	$w_{Carbon} = 0$	$w_{Carbon} = 0.4$	$w_{Carbon} = 0$	$w_{Carbon} = 0.2$
	Spruce	***38.9***	***37.3***	47.3	43.2
	Silver fir	***49.6***	***46.3***	50.3	48.9
	Beech	***11.5***	***16.4***	2.4	7.9
	Soil expectation value [EUR per hectare]	***8560***	***8077***	1012	541
	Average carbon storage [Mg CO_2 equivalent per hectare]	***279.02***	***297.23***	242.19	266.94
	Opportunity costs [EUR per Mg CO_2 equivalent]	***68.12***		18.95	

The reference scenario without considering carbon as an objective for the German case study was a classical CrNFM system, dominated by silver fir (49.6%), while spruce covered 38.9% and beech covered 11.5%. Considering carbon as a second objective and using $w_{Carbon} = 0.4$ to obtain minimum opportunity costs, the average carbon storage was elevated by +7.13 Mg CO_{2eq} per hectare, while the soil expectation value (discount rate 1.5%) decreased by EUR 468 per hectare. This corresponds to an opportunity cost of EUR 119 per additional Mg CO_{2eq} stored (Table 2).

In both case studies, elevated carbon storage went hand-in-hand with enhanced proportions of less-profitable broadleaves (with chestnut increasing from 19.2% to 100% in Portugal, and beech from 11.5% to 16.4% in Germany). In addition, more standing volume accumulated over time as a result of postponed harvests.

3.2. Trade-Offs between Economic Return and Carbon Storage

Economic return and carbon storage were strongly negatively correlated ($\rho = -0.85$ *to* -0.97, Figure 1). In Portugal, carbon storage–economic return trajectories were long and had small slopes, indicating high economic losses to be accepted for enhancing carbon stored in the forest. The silvicultural systems were mainly CrNFM systems when considering carbon as an objective. This produced mixed forests managed without clearfelling, except when maximizing carbon storage, which allocated 100% of the stand to chestnut. However, the carbon stored in the Portuguese CrNFM systems was not necessarily higher than in the clearfelling system, particularly when the carbon objective had low weight, e.g., $w_{Carbon} = 0.1$.

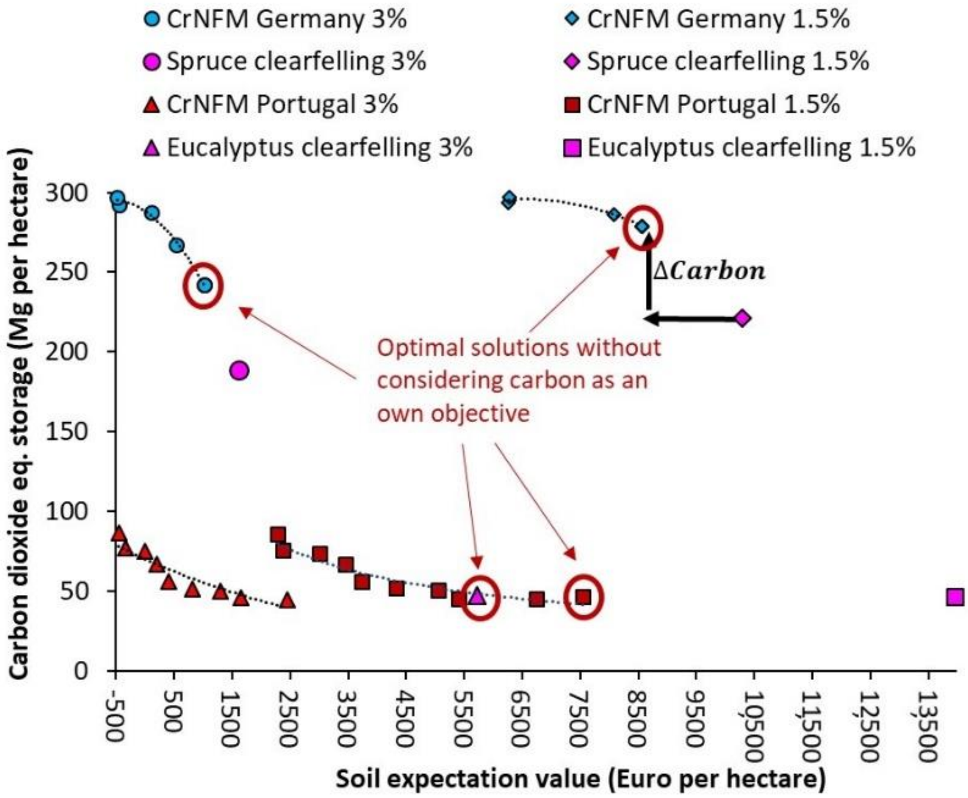

Figure 1. Trade-offs between the storage of carbon dioxide and the soil expectation value. The different carbon–SEV pairs were obtained using different weightings of the carbon and economic return objectives.

In Germany, the suggested silvicultural systems stored more carbon than in the case of Portuguese forests. Shifting from clearfelled silviculture to CrNFM alone significantly enhances carbon storage (+53 to +58 Mg CO_{2eq} per hectare), associated with EUR −607 (3% discount rate) and EUR−1723 (1.5% discount rate). These costs can, at least theoretically, be considered insurance premia which forest owners accept to pay to obtain robust solutions and protection against uncertainty. They are not associated with considering carbon storage as an objective. Rather, the enhanced carbon storage that results from applying CrNFM systems is a positive externality provided by forest owners to global societies. For the sake of comparison, the additional carbon stored by CrNFM systems could be represented as entailing low opportunity costs of EUR −11 (3% discount rate) and EUR −30 (1.5% discount rate) per Mg CO_{2eq}. Again, however, this ignores the benefit of increased robustness.

For the 1.5% discount rate, the carbon storage–economic return trajectory had a small slope, showing that enhancing carbon within CrNFM systems is relatively expensive. Given a 3.0% discount rate, enhancing carbon in CrNFM systems was more cost-effective, as indicated by the greater slope of the trajectory.

3.3. Social Costs of Carbon as a Benchmark

The carbon opportunity costs for the Portuguese and German case studies exceed the SCC published by United States Government [45] (discount rate 3%) and Nordhaus [39] (average discount rate 4.25%) (Figure 2). However, the SCC published by Nordhaus [39] for a discount rate of 3% already more than covers carbon opportunity costs. Given a discount rate of 3%, the SCC grows according to United States Government [45] until 2050; only then would it reach the carbon opportunity costs for the Portuguese and German case studies today.

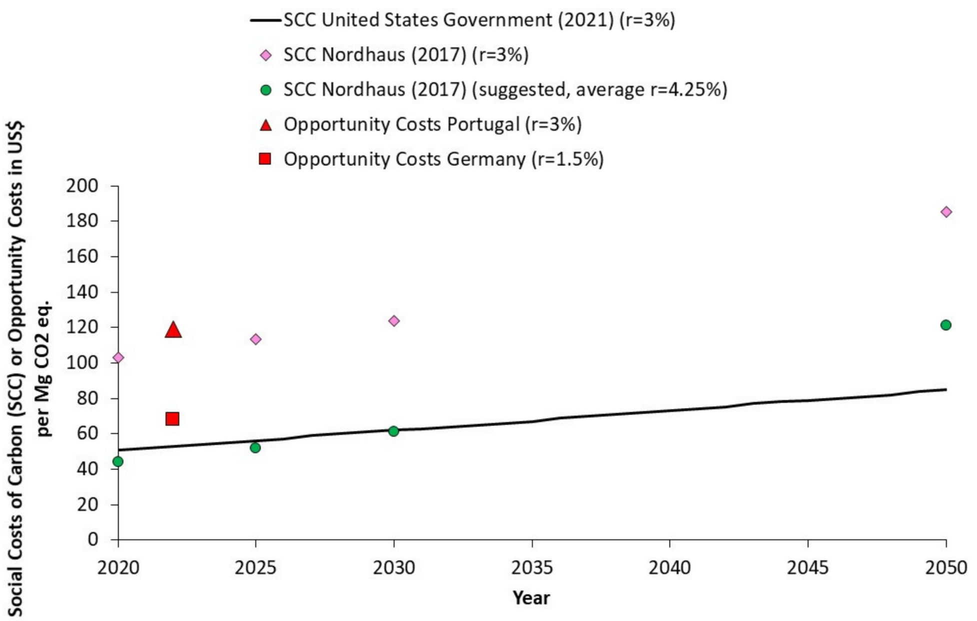

Figure 2. Comparison of forest owner's opportunity costs with published social costs of carbon (SCC). We used SCC published by United States Government [45] and Nordhaus [39]. SCC adopted from Nordhaus [39] were converted from 2010 to 2020 USD by the factor of 1.181789822 [43] and opportunity costs in EUR into USD by the factor of 1.04. r is the discount rate.

4. Discussion and Conclusions

Our study presents a new method to assess the increase in carbon stored in situ against an optimized reference scenario. The use of optimization tools to derive counterfactual reference scenarios was originally proposed by Knoke and Weber [46] as a possible solution to the additionality problem, which is a major obstacle to rigorously assessing the performance of nature-based solutions for carbon storage [22]. However, multiple-objective, stand-level models have rarely been used for this purpose, especially when considering the influence of uncertainty and disturbance risk.

Our baseline solutions for the German case suggest adopting CrNFM systems, which can offer advantages over clearfelling systems in terms of carbon storage and economic resilience [47]. For instance, Assmuth et al. [20] show that pricing carbon stored in a forest generates an unlimited rotation period consistent with continuous cover forestry; a classical CrNFM system. Our results suggest that by applying CrNFM systems to buffer uncertainties, risk-avoidant forest owners in Germany will provide carbon storage as a positive externality in much the same way that some farmers seek to promote agrobiodiversity to obtain natural insurance [48,49]. Despite these advantages, CrNFM systems have not yet been widely adopted. Developing tailored policies to support forest owners transitioning to these systems thus might support forest carbon stocks that are larger and more robust.

Empirically, our results show that opportunities to enhance in situ forest carbon at minimum opportunity cost are more prevalent in Germany than in Portugal. In Portugal, the economic superiority of eucalyptus coppice over alternative forest types entails a high marginal cost for allocating more area to oak or chestnut, which store more carbon. We had to exclude the economic objective completely ($w_{Carbon} = 1$) to enhance the carbon storage under minimum average opportunity costs for the Portuguese case. In the German case, by contrast, this was achievable with modest values of $w_{Carbon} = 0.4$ and $w_{Carbon} = 0.2$.

Our carbon storage opportunity costs were higher than conservative, but lower than alternative cost estimates for future damages caused by current CO_2 emissions. If the social cost of carbon (SCC) represents society's maximum willingness to pay to avoid climate-related damages [42], enhancing forest carbon stocks is economical as long as the opportunity cost of doing so does not exceed the SCC. In both Portugal and Germany, the opportunity cost of compromise solutions often exceeded the SCC values suggested by Nordhaus [39] and the US government [45]. We used these values as a reference point because they are well-known and widely cited, but acknowledge that they remain controversial in both scholarly [50,51] and popular [52,53] discourse. Political and ethical issues aside, SCC estimates are significantly—even extraordinarily [54]—sensitive to scenario definitions and model specifications because they integrate modules for climate, socioeconomic trends, discounting, and damages [55,56]. For instance, a prominent controversy involves the damage functions used by integrated environmental-economic models [57,58], which produce estimates that Keen et al. [59] consider "impossible to reconcile" with the scientific literature on tipping points (see also [60–62]).

Consequently, some sources recommend much higher SCC valuations than the US does. German guidance suggests an SCC that starts at USD 218 in 2016 and climbs to USD 291 by 2050 (i.e., within our planning horizon), while France recommends ramping up from USD 103 to USD 916 over the same period [56,63,64]. Both figures consider global damages and are compatible with the range of global median estimates by Ricke et al. [65]. Our calculated opportunity costs for both Germany and Portugal satisfy these SCC estimates by a much larger margin than they exceed the Nordhaus/US reference values. This means that high-opportunity-cost carbon enhancement (e.g., in Portugal) could be uneconomical relative to the Nordhaus/US figures, but highly affordable if measured against German or French SCC guidance.

Our results should be interpreted normatively as a reference solution for understanding environmental–economic trade-offs in two very different forest systems [38,66,67]. We evaluated easy-to-generalize silvicultural systems typical of each case country without tailoring examples to a particular landscape, which requires treating disturbance as endogenous to stand type and neglecting spatial dimensions. In applied contexts, however, forest managers face a range of spatial disturbances such as fire, wind, and pest outbreaks [68–70]. Exploring how spatial allocation influences the performance of our portfolios would be an interesting but challenging problem for future research, although simultaneously optimizing for species selection and harvest scheduling while also accounting for spatially contingent uncertainty scenarios would likely only be computationally tractable through heuristic algorithms [71–73]. By contrast, our method offers an exact solution highlighting the "multicriteria premium": the economic opportunity cost incurred through the addition of competing non-economic objectives [23]. While it would be possible to apply the same method to evaluate trade-offs in (for instance) landscape mosaics that include agricultural land use types, for the purposes of this study, we concentrate specifically on management changes in forested areas.

The magnitude of the trade-off between SEV and carbon also depends on indicator selection and accounting methods. We used a climate indicator based on the average carbon storage in aboveground biomass across the planning period. Although we follow standard practice by discounting financial flows but not carbon storage, doing so implicitly weights the undiscounted objective, especially when uncertainty is high [74]. Our carbon indicator ignores product pools and substitution effects, but we expect that life-cycle analysis (LCA) would magnify the opportunity cost discrepancy between our case examples. In Germany, forestry largely feeds into long-lived timber products and bioenergy that substitutes for fossil fuels [21,75], whereas Portuguese eucalyptus coppices are mainly used for pulpwood production [76,77]. Thus, LCA would presumably mitigate the carbon–SEV trade-off to a greater extent in Germany than Portugal. While we support incorporating LCA more consistently into forest carbon accounting [78–80], our focus here is on the perspective of forest owners. Introducing additional assumptions about product assortments and lifetimes conflicts with this decision perspective, so we concentrate narrowly on carbon storage in standing timber.

Beyond these case studies, our approach offers an intuitive method for assessing forest-based carbon storage solutions, which have been criticized for low additionality, lack of permanence, and vulnerability to climate-linked disturbance risk [81,82]. We address these concerns by deriving reference scenarios that are robust to future uncertainty, observing how the optimal distributions of species and age classes shift to generate compromise solutions balancing economic performance against enhanced carbon storage, and then comparing the resulting opportunity costs to the marginal cost of emissions (SCC). This workflow can offer insight not only about how a climate-smart forest portfolio might look, but also about where and how policies can be targeted to support management changes at least cost.

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