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ORIGINAL ARTICLE

A new way of carbon accounting emphasises the crucial role of sustainable timber use for successful carbon mitigation strategies

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Abstract The roles of forest management and the use of timber for energy in the global carbon cycle are discussed. Recent studies assert that past forest management has been accelerating climate change, for example in Europe. In addition, the increasing tendency to burn timber is an international concern. Here, we show a new way of carbon accounting considering the use of timber as a carbon neutral transfer into a pool of products. This approach underlines the robust, positive carbon mitigation effects of sustainable timber harvesting. Applying this new perspective, sustainable timber use can be interpreted not as a removal but a prevention of carbon being converted within the cycle of growth and respiration. Identifying timber use as a prevention rather than a removal leads to the understanding of timber use as being no source of carbon emissions of forests but as a carbon neutral transfer to the product pool. Subsequently, used timber will then contribute to carbon emissions from the pool of forest products in the future. Therefore, timber use contributes to carbon mitigation by providing a substantial delay of emissions. In a second step, the carbon model is applied to results of a previous study in which different timber price scenarios were used to predict timber harvests in Bavarian forests (Germany). Thus, the influence of the economic dimension "timber price" on the ecological dimension carbon sequestration was derived. It also shows that these effects are stable, even if an increasing tendency of burning timber products for producing energy is simulated. Linking an economic optimization to a biophysical model for carbon mitigation shows how the impact of management decisions on the environment can be derived. Overall, a sustainably managed system of forests and forest products contributes to carbon mitigation in a positive, stable way, even if the prices for (energy) wood rise substantially.

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1 Introduction

Forest management and its effect on climate change are widely discussed in international literature. Naudts et al. (2016) draw the conclusion that 250 years of forest management in Europe has led to a considerable contribution to greenhouse gas emissions. Whereas the authors of that study obviously neglected the positive substitutional effects of using forest products instead of alternative fossil-based products, others question the carbon neutrality of using biomass as an energy source in general (Johnston and van Kooten 2015). Both criticisms show that the method of how to account for certain, often time-dependent effects severely influences the derived results, and the policy recommendations. Therefore, it is necessary to investigate the principles of different carbon modelling approaches and the underlying presumptions.

Undoubtedly, forest management decisions have an influence on the carbon balance of forests themselves as well as on that of the subsequent chain of wood products. A forest sequestrates carbon dioxide from the atmosphere through the process of photosynthesis, uses it to create biomass and finally releases parts of it back to the atmosphere through respiration. The difference between the amount of carbon uptake and release by plants is called the net primary production. By subtracting the heterotrophic respiration (the decomposition of dead organic matter) from this total, the net ecosystem production can be calculated. Further subtracting the carbon emissions that result from disturbances (calamities and wood removals), results in the net biome production (Penman 2003). Within the socio-political discussions the net biome production is commonly used as a definition of the carbon cycle of the forest sector which often leads to the problematic conclusion that harvest activities in forests generate in situ carbon emissions from forests (Lemprière et al. 2013). Despite this flaw, this is the default model used by the Intergovernmental Panel on Climate Change (Eggleston et al. 2006; Hiraishi et al. 2014).

Several other approaches have been developed that include the effects of how harvested timber is actually used. Three of the most important of these are collectively known as the "Dakar approaches" (Brown et al. 1998), consisting of the stock change approach, the production approach and the "atmospheric flow approach". Ford-Robertson (2003) addressed the issue of fictive sinks and sources within carbon models. In the course of his discussion, he suggested that the lifetime of wood products should be considered when calculating their source effects. This approach is called the "simple decay model", as it results in emissions being distributed across the years following the harvest instead of them being considered as immediate emissions. Each of these methods adds a product carbon pool to the forest carbon pool and subsequently calculates separate carbon fluxes for each pool. These approaches differ in the way each particular model is constructed, but for practical application the main difference lies in the way imports and exports of timber are credited to particular national-level carbon pools (Winjum et al. 1998). Within all of these approaches, however, timber extraction through harvest is still handled as an action that immediately induces carbon emissions in the forest. The sink effect of converting the extracted wood into products is then calculated separately and allocated to the product pool. The atmospheric flow approach ignores—by its methodology—the theoretical system border between the forest and product pools. This atmospheric flow approach looks at the carbon fluxes between these pools and the atmosphere, rather than looking at changes in the various pools that act only indirectly on atmospheric carbon exchange. However, this new perspective is not really properly applied, because in practice the model is still calculated using separate pools (Green et al. 2006). Thus, the focus is still on changes in and among the various carbon pools themselves rather than on atmospheric carbon fluxes. Thinking within this framework of separate carbon pools, which is in line with the IPCC guidelines (Penman 2003; Eggleston et al. 2006; Hiraishi et al. 2014), is typical for most of the recent publications in this field (Donlan et al. 2012; Dymond 2012; Lun et al. 2012; Klein et al. 2013; Chen et al. 2014; Lamers et al. 2014; Kayo et al. 2015; Köhl et al. 2015; Pilli et al. 2015; Raši et al. 2015; Braun et al. 2016), for an overview of older publications see also Hennigar et al. (2008). Contrary to the assumptions of the separate pools, timber harvests can actually influence the atmospheric carbon cycle by removing carbon dioxide from the forest carbon cycle: they extend the time during that the carbon is stored in the wood products. Therefore, it is not the harvest, but instead the product that eventually adds to the carbon in the atmosphere, i.e. when the carbon fixed in the product is released at the end of the product's lifetime. Consequently, using wood as an energy source cannot be considered as carbon neutral, because using it is identical with the end of its lifetime.[1] This use will therefore release carbon into the atmosphere that would otherwise still be stored (cf. Lemprière et al. 2013; Johnston and van Kooten 2015). While it is still true that mechanical harvests and wood processing consume fossil fuels, thus contributing additional carbon to the atmosphere, this is not a part of the forest carbon cycle discussed here, but part of the fossil carbon cycle. There is still the problem of how the carbon in wood products can best be considered within the present (forest) carbon models (Ellison et al. 2011). In this paper, we present an approach that excludes all artificial sink and source effects and provide a simple solution to that problem. We couple a modern, risk sensitive forest optimization model with the accounting of carbon in various pools. Several management strategies under different price scenarios for fuelwood are analysed regarding their consequences for the carbon balance.

Using a model that is able to consider ecological and social aspects besides the economic ones, we directly access the requirements of sustainable forest management as defined as "the process of managing permanent forest land to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction in its inherent values and future productivity and without undue undesirable effects on the physical and social environment" (ITTO 2006).

Published studies have shown the important influence of forests on the carbon cycle (Benítez et al. 2007), but research about the effects of the economic objectives of forest management on carbon balances is lacking: van Kooten et al. (1995) as well as Tahvonen (1995) investigated effects of policies (such as taxes and subsidies) on carbon balances, but not of management decisions. Cunha-e Sá et al. (2013) took the reverse approach by accounting for the benefits of carbon mitigation and how this will influence forest management. Sohngen and Mendelsohn (2003) investigated an optimal solution for carbon sequestration. However, in practice, financial returns and not carbon mitigation are optimised. Diaz-Balteiro and Romero (2003) and Hoen and Solberg (1994) combined a carbon model with economic objectives by using multi-objective approaches, whereas Baskent and Keles (2009) used

[1]This is an effect of our definition and contrary to the everyday meaning of the phrase "fuelwood is carbon neutral". In this statement the forest (the carbon inflow) and the product (the carbon outflow) is subsumed in the term "energy wood". Here, the product is strictly separated from the forest. As the product can only emit carbon (dead material is not able to sequester carbon) it not carbon neutral in our way of thinking. Of course, the whole system of forests and forests might act as carbon neutral.

a linear programming approach. While these studies did not include risk aspects in their investigations, Knoke and Weber (2006) suggested a conceptual approach to consider risks. However, they considered only the forest ecosystem. Studies like that of Köthke and Dieter (2010) showed the influence of carbon balancing assessment mechanisms on management decisions. But as long as the trading system for emission permits does not work properly in the industrial sector, it is still unclear if the forest sector will be integrated into this system in the near future. Given this uncertainty, the present situation can be better described using the opposite approach where forest management decisions are seen in terms of their influence on the carbon balance. Rather than simulating policy options in the model, the model should be used to derive results upon which policy decisions could be based.

Our hypothesis is: Adaptions of forest management decisions due to expected timber price changes will strongly impact the carbon balance of managed forests and forest products.

2 Materials and methods

Due to the complexity of the model, we present the core components of the model in a separate section first. The following section Model justification then describes the equations more thoroughly.

2.1 Main components of the model

2.1.1 Carbon storage in forests

To cover all aspects of the carbon cycle of a managed forest, one must consider three elements: the forest, the products and the substitution effects (Lippke et al. 2011; Höllerl and Bork 2013; Köhl 2013). The forest can be divided into living biomass, dead biomass and organic soil matter. Although international guidelines are designed to consider each of these sub-classes (Penman 2003; Eggleston et al. 2006; Hiraishi et al. 2014), we have simplified the model by only considering a part of the living biomass—namely, the volume of aboveground wood that is over 7 cm in diameter, referred to from here onwards as compact wood. Compact wood was used in the model because it is the indicator normally measured and controlled by forest managers (in Central Europe).

To calculate the carbon balance of the forest and forest products, we use the following sum:

$$\underbrace{g(t) - d_m(t)}_{\text{forest}} - \underbrace{\tilde{u}(t)}_{\text{product}} \tag{1}$$

The forest has a climate-relevant sink[2] effect that is equal to its net carbon sequestration $g(t) - d_m(t)$ (growth minus deadwood decomposition mass, in carbon units [tC/a], within the period between t and $t - 1$), whereas the use of wood as a product causes a climate-relevant emission effect of $\tilde{u}(t)$ (also in [tC/a]). The derivation of Eq. 1 is shown in the section "Model justification".

This approach can be called the carbon effect model, as it does not consider the *changes* in carbon pools but rather only the climate-relevant *effects* of these pool changes: the carbon fluxes. This new perspective solves the problem of timber harvests being treated as emissions from forests by excluding these fictitious emissions from the model. Generally, a

[2]The term *sink* is used in the sense of a *positive net carbon flux into a system* throughout the text.

sustainably managed forest is a carbon sink as long as it continues to store additional carbon in its net growth $g(t) - d_m(t)$. If this sink effect offsets the climate-relevant emissions of the products $\tilde{u}(t)$, the sink effect persists permanently in a sustainably managed forest.

2.1.2 Product lifetime

The emissions from the wood products made from the extracted timber do not take place until the end of the lifetime of these products. Until then the carbon mass in the product should be considered to contribute to the sink effect of the products in use—due to delayed emissions. It is temporarily deposited within the timber structure as long as the biophysical decomposition process has been stopped (frozen fluxes). This sink effect can be accounted for by modifying the carbon mass in the wood harvested $u(t)$ with a reduction factor, leading to the climate-effective carbon mass $\tilde{u}(t)$.

This approach does not directly calculate the absolute level of a "product pool", but instead calculates the preventative effect on carbon emissions of removing and using timber from the forests rather than allowing it to immediately begin to decompose as deadwood.

The reduction factor is calculated by

$$r_p(t) := \frac{u(t-T)}{\sum_{k=0}^{T-1} u(t-k)} \tag{2}$$

with t being the considered point in time and T the lifetime of the forest product in years. k is a counting index with lower bound 0 and upper bound $T-1$: $k \in \{0, 1, 2, 3, ..., T-1\}$. The development of Eq. 2 is shown in the section "Model justification".

To account for the product life cycle, literature provides a variety of figures that we used to derive average lifetimes T for various timber products: 67 years for construction timber and furniture, 28 years for engineered wood, 3 years for paper, cardboard and sanitary articles and 2 years for fuelwood and chips (Burschel et al. 1993; Karjalainen et al. 1994; Harmon et al. 1996; Pingoud et al. 1996; Skog and Nicholson 1998; Liski et al. 2001; Wirth et al. 2004a; Smith et al. 2006; Profft et al. 2009; Marland et al. 2010; Klein et al. 2013). Based on these product life cycles, average figures for the main grades of timber have been derived by weighting the proportions of their uses in Bavaria. According to Klein and Schulz (2012), on average, 64 % of harvested sawlog volume is used for sawn wood and 36 % of this volume is sawmill leftovers. Of these sawmills residues, 51 % is used for energy purposes and 49 % is used by the pulp and paper industry (Friedrich et al. 2012), resulting in an average lifetime of 44 years for an individual sawlog.

Between 2007 and 2010 in Bavaria, around 700,000 t/a of timber was used by the pulp and paper industry, and around 833,000 t/a by the engineered wood products industry (Friedrich et al. 2012). The latter covers 47.3 % (394,000 t/a) of their timber demand by "pulp and paper wood" (Mantau 2012). In the same time period, these industries produced 201,000 t/a of wood waste that was then used for energy production, compost or bark mulch (Friedrich et al. 2012). That means, on average, 36 % of the total amount of 1,094,000 t/a of pulpwood is used for chipboard production, 46 % for pulp and paper and 18 % goes to energy uses. A weighting of the individual lifetimes of these products led to a calculated average lifetime of 12 years for timber originally harvested for pulp and paper in Bavaria.

2.1.3 Substitution

Substitution effects were calculated using published figures. This effect is based on the fact that using the material and energy capacities of timber eliminates the need to manufacture alternative products. Thus, construction wood replaces concrete and bricks; paper, cardboard and chipboard replace plastics and using wood for energy avoids oil and gas consumption. Furthermore, all timber used for material purposes can eventually be exploited for its energetic value at the end of that product's lifetime. Such cascading of uses provide a double substitution effect. Figures from Rüter (2011) and Rock and Bolte (2011), which were in turn based on the findings of Sathre and O'Connor (2010a, b) were used for our calculations: 1.35 tC_{fossil}/tC_{timber} for material substitution and 0.67 tC_{fossil}/tC_{timber} for energy substitution. The substitution factor for energy means that burning timber results in about 50 % higher carbon emissions than burning fossil oil or gas to achieve the same amount of energy (as $1/0.67 \approx 1.5$). This addresses the recently published concerns by Johnston and van Kooten (2015).

The possibility of cascading uses was assumed for all industrial roundwood with one exception. Not all of the pulp and paper wood that is used for packaging was considered relevant for substitution. According to figures from the German paper industry, packing material constitutes, on average, 26 % of German paper production (VDP 2012). Considering additionally the timber use distribution derived in the previous section, the following modified final figures have been used for each of the main timber grades: 1.66 tC_{fossil}/tC_{timber} for sawlogs, 1.30 tC_{fossil}/tC_{timber} for pulpwood and 0.67 tC_{fossil}/tC_{timber} for chips and fuelwood.

2.2 Model justification

For an unmanaged forest at equilibrium, the carbon balance is

$$\underbrace{g(t) - d_n(t)}_{\text{forest}} = 0 \tag{3}$$

In contrast, the carbon balance for a managed forest with its associated timber products is calculated as:

$$\underbrace{g(t) - d_m(t) - u(t)}_{\text{forest}} + \underbrace{u(t) - \tilde{u}(t)}_{\text{product}} = \underbrace{g(t) - d_m(t)}_{\text{forest}} - \underbrace{\tilde{u}(t)}_{\text{product}} > 0 \tag{4}$$

The carbon in both the deadwood and the harvested wood is subtracted from the carbon present in the net growth. The carbon in the harvested wood is then added back, as it is stored in the products. A certain amount $\tilde{u}(t)$ is subtracted to account for releases from the products. The balance of a sustainably managed forest is positive, because by definition, in the long run, the amount $u(t)$ removed cannot exceed the net growth $g(t) - d_m(t)$. As $\tilde{u}(t)$ is always smaller than $u(t)$, it is also smaller than $g(t) - d_m(t)$. If the terms in Eq. 4 are assigned to the two categories "forest" and "product", there is only one reasonable solution to do so.

As already described, the forest has a climate-relevant sink effect that is equal to its net carbon sequestration $g(t) - d_m(t)$, whereas the use of wood as a product causes a climate-relevant emission effect of $\tilde{u}(t)$. In other words, $\tilde{u}(t)$ is not the actual amount of carbon released from timber products to the atmosphere at time t but the calculative share of future emissions that is caused by the products produced at this time. This calculative proportional contribution to the emissions is influenced by the life time of the products and is calculated by using an approach similar to a linear depreciation as shown in the next section.

This difference in the modelling approaches is crucial for understanding and is therefore illustrated again in Fig. 1. For simplicity, deadwood amounts have been ignored in the figure because they are dealt with in both model approaches in essentially the same way. While the two approaches reach the same total result, they represent reality differently. Commonly used approaches model separate pools that interact directly with the environment in the

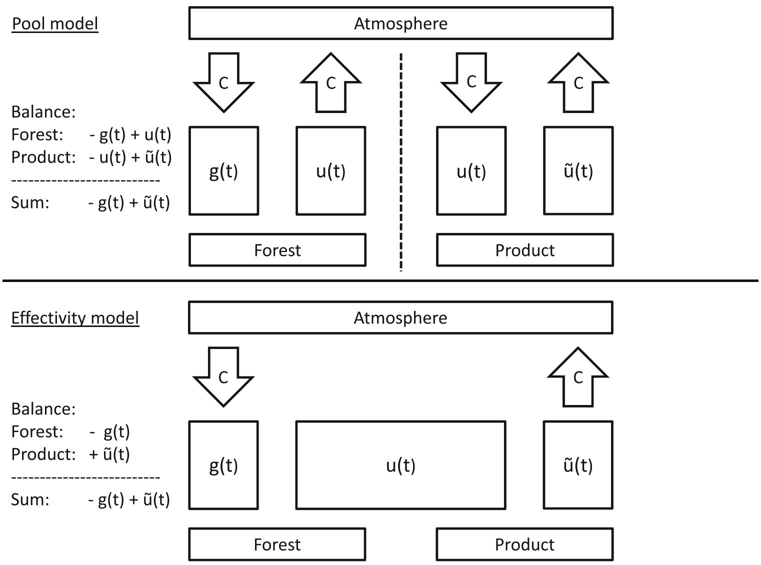

Fig. 1 Comparison of the carbon fluxes of the standard pool model and the effect model. $g(t)$ are carbon fluxes due to forest growth, while $u(t)$ are fluxes due to the timber usage. The comparison shows that the pool model generates additional (calculative) fluxes due to the pool borders

form of the movement of gaseous carbon dioxide into and out of the atmosphere. The effect model tries to improve this representation of reality by only modelling the climate-relevant carbon fluxes.

2.2.1 Carbon effects of forest products

Let us assume that there is a certain amount of harvested wood $u(t)$ from a forest (quantified in terms of its carbon content, e.g. in [tC/a], see also Fig. 2) at time t, and that this wood is used in various ways after harvest. To keep things simple, we will assume for the moment that only one use of timber is possible, for example, sawn wood. This means that the carbon amount present in the harvested timber $u(t)$ is still stored in the sawn wood, with some losses due to the wood waste generated during the cutting and production processes. Furthermore, if we assume that the amount of harvested wood $u(t) = u$ is constant over time (e.g. on an annual basis), the same amount of sawn wood will reach the end of its lifetime T at the same time t (static model). Then, at this time, the carbon u is released into the atmosphere. However, an amount of $u \cdot (T - 1)$ is stored at any time in the products in use, and is thus removed from the natural cycle of carbon between the forest and the atmosphere. This means, at any time t the carbon amount $u + u \cdot (T - 1) = u \cdot T$ is held back from atmosphere and the carbon amount of u is released again. Therefore, the amount of carbon released as a greenhouse gas is reduced through this storage effect by a factor of

$$r_p := \frac{u}{u \cdot T} = \frac{1}{T} \tag{5}$$

to

$$\tilde{u}(t) := r_p \cdot u(t) \tag{6}$$

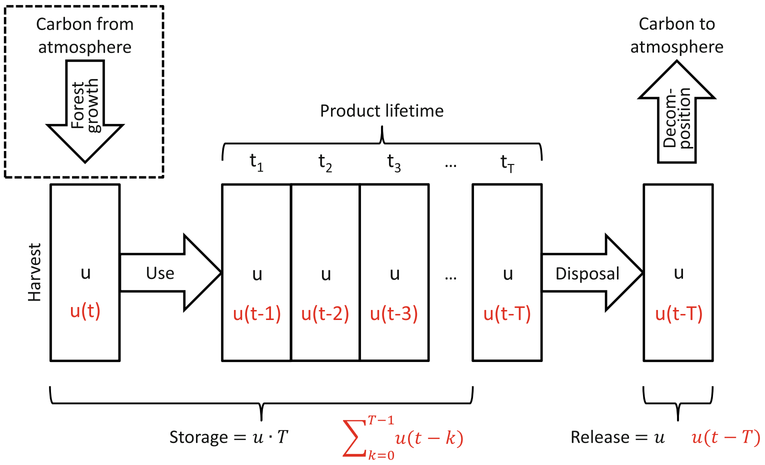

Fig. 2 Model of the carbon pool product life time. *Black coloured figures* are the factors of the static model, while *red figures* belong to the dynamic model, which considers changes of wood use over time. $u(t)$ are carbon fluxes due to timber usage that are temporarily deposited within the timber in use ("frozen fluxes")

The carbon amount of $u(t)$ in newly produced products contributes with a share of r_p to the emissions and with a share of $1 - r_p$ to the maintenance of the carbon pool in products. The static model can be easily extended to create a dynamic model by reintroducing the time dependence of $u = u(t)$. Here, the amount u that reaches the end of its life at time t is equal to the amount used T years before, $u(t - T)$. The total amount of carbon stored in the products is then the sum of the currently used amount $u(t)$ and the amounts used in the periods before (from time $t - 1$ to $t - (T - 1)$) that have not yet reached the end of their lifetimes. In this case, the reduction factor is calculated by

$$r_p(t) := \frac{u(t-T)}{\sum\limits_{k=0}^{T-1} u(t-k)} \tag{7}$$

with t being the considered point in time and T the lifetime of the forest product.

One can see that the mitigation effect of the products does not consist of a system of storage and emission, but only constitutes a delay in emissions. Every new product contributes to this systematic delay of the emissions with a share of $1 - r_p$ by maintaining the amount of forest products in use.

2.3 Scenario analysis

Carbon balances in our analysis were calculated using data generated by the planning-support tool YAFO (Härtl et al. 2013; Härtl 2014). To consider risk due to timber price fluctuations and calamities, we used a Value at Risk optimization. The Value at Risk is a threshold of the net present value that is exceeded with a given probability if you assume that the potential outcomes of an uncertain net present value are distributed normally (Stambaugh 1996; Jorion 1997; Knoke et al. 2012). We used a probability of 99 % for this threshold to reflect a risk-averse behaviour of the decision maker. The interest rate was set at 1.5 %, as a rate that can be achieved in Central European forests

(Möhring and Rüping 2008). We assume that for most forest owners feasible investment alternatives are typically within the forest sector.

The approach considers the optimization of forest management by maximizing discounted financial returns. It uses nonlinear programming techniques and accounts for age-dependent regeneration costs, calculates ingrowth volumes and can include additional area- and volume-based constraints at the enterprise level. To do so, hypothetical forest enterprises were constructed from national inventory data, representing the different types of forest owners in Bavaria. Within each growth region, one enterprise was created which combined all inventory plots in state and federal forests, one was made up of all plots in forests owned by municipalities, and two were created from plots in privately owned forests: small private forests (less than 20 ha) and large private forests. These four hypothetical enterprise types (state forest, municipality forest, small private forest and large private forest) in 14 growth regions resulted in 54 forest enterprises of different sizes, each comprised of three to 373 forest stands.

The national forest inventory of Germany (BWI) uses a regular 4 × 4 km or 2 × 2 km grid of sampling points. At each grid point, measured trees were selected by angle-count sampling. These measured trees then are treated as a representative sample of the whole forest area. Bavarian forests include a big range of different site conditions. Whereas the north west is dominated by European beech (*Fagus sylvatica* L.), oak (mainly *Quercus robur* L.) and Scots pine (*Pinus sylvestris* L.) stands on Germanic Trias rock strata, the south is mainly occupied by Norway spruce (*Picea abies* (L.) H.Karst.) and European beech stands in the Molasse basin and the alpine limestone region. Half of the forest area is managed by the state or by municipalities applying continuous cover forestry schemes whereas in private forests often mono-species stands that are structured in age classes still prevail.

For our analysis of the carbon balance, we used four timber price and harvest scenarios derived from 18 oil price scenarios. Based on an investigation of different oil price studies (Kesicki et al. 2009; OECD/IEA 2010; EIA 2011; IMF 2011), we constructed three scenarios by ordering the original scenarios into quartiles according to their crude oil price predictions for the year 2035. Group 1 contained all scenarios below the first quartile, group 3 all those above the third quartile and group 2 all remaining scenarios. Group 1 was considered to be a cluster of constant oil price scenarios. The group 2 scenarios predicted an average increase of 115 % in the oil price from 2010 to 2035, and group 3 a considerably higher increase of 280 %. Thus, group 1 was called the base, or A0 scenario, group 2 the A100 scenario and group 3 the A300 scenario. The additional A50 scenario was created by halving the price increase of the A100 scenario and was introduced to cover possible price-reducing effects due to unconventional oil sources (fracking) and fluctuating gas prices. All scenarios have been calculated based on the same silvicultural treatments (selective thinning with the rotation period modified by the optimization).

Our carbon study relates to the results derived in Härtl and Knoke (2014) and Härtl (2015). Tables 1 and 2 show the price developments for the scenarios A100 and A300. In the A0 scenario, the prices for 2010 are set constant over the whole time horizon. Table 3 shows the amounts of timber supply for all scenarios split up into different main timber grades. The data set used, which was based on national inventory data, and the optimization approach provided by YAFO are described in detail in Härtl et al. (2013). To convert the volume of timber into carbon units, we used the factors given in Table 4. The principles behind the timber price estimations and two of the scenarios (the base scenario (A0) as well as the A100 scenario) are described in Härtl and Knoke (2014).

Table 1 Timber prices in the scenario A100 for spruce and beech for different years

Species	Year	B	C	D	P	F
Spruce	2010	76	62	46	37	29
	2015	76	62	46	37	29
	2020	76	62	48	48	48
	2025	81	68	68	68	68
	2030	93	87	87	87	87
	2035	114	106	106	106	106
	2040	135	126	126	126	126
Beech	2010	104	60	51	46	50
	2015	104	60	51	46	50
	2020	104	78	78	74	78
	2025	105	105	105	101	105
	2030	133	133	133	129	133
	2035	161	161	161	156	161
	2040	188	188	188	184	188

B, C and D: prices for different sawlog qualities (B: high, C: normal, D: low; spruce prices for diameter class 25–29 cm, beech prices for diameter class 40–49 cm). P: pulpwood. F: fuelwood. All prices in (€/m^3)

2.4 Financial evaluation

In a further step, the financial consequences of the carbon balance results were investigated. Three different approaches were used:

- Carbon loss: The potential differences of the timber price scenarios regarding the carbon sequestration of the system of forests and forest products were valued using prices for emission permits. Thus, potential economic damages due to reduced sink effects can be derived.
- Carbon storage: In a second approach, the total carbon sink effect of the system was evaluated to derive the economic benefit of this service.

Table 2 Timber prices in the scenario A300 for spruce and beech for different years

Species	Year	B	C	D	P	F
Spruce	2010	76	62	46	37	29
	2015	76	62	46	37	29
	2020	86	76	76	76	76
	2025	131	123	123	123	123
	2030	182	170	170	170	170
	2035	233	217	217	217	217
	2040	283	264	264	264	264
Beech	2010	104	60	51	46	50
	2015	104	60	51	46	50
	2020	117	117	117	113	117
	2025	185	185	185	180	185
	2030	252	252	252	247	252
	2035	319	319	319	315	319
	2040	386	386	386	382	386

B, C and D: prices for different sawlog qualities (B: high, C: normal, D: low; spruce prices for diameter class 25-29 cm, beech prices for diameter class 40–49 cm). P: pulpwood. F: fuelwood. All prices in (€/m^3)

Table 3 Timber supply within the different price scenarios

	A0	A50	Diff	%	A100	Diff	%	A300	Diff	%
Fuelw.	5,921,918	5,522,894	−399,024	−7	5,558,240	−363,678	−6	4,609,619	−1,312,299	−22
Sawlog	12,290,054	10,657,125	−1,632,928	−13	10,601,970	−1,688,084	−14	10,280,138	−2,009,916	−16
Pulpw.	2,426,949	2,270,433	−156,516	−6	2,324,114	−102,835	−4	1,924,842	−502,107	−21
Chips	2,310,720	2,305,838	−4882	0	3,836,216	1,525,496	66	5,901,926	3,591,206	155
material	14,717,003	12,927,558	−1,789,444	−12	12,926,084	−1,790,919	−12	12,204,980	−2,512,022	−17
thermal	8,232,638	7,828,731	−403,907	−5	9,394,457	1,161,818	14	10,511,545	2,278,907	28

Average values between 2010 and 2040 for main timber grades. All figures in (m^3/a). The column "Diff" shows the difference to the base scenario

Table 4 Conversion factors to calculate carbon amounts (tC) from timber volume (m^3) (Burschel et al. 1993)

Tree species (genus)	Density by volume (t/m^3)	Carbon ratio (tC/t)
Spruce (*Picea* Mill.)	0.3771	0.5
Fir (*Abies* Mill.)	0.3700	0.5
Pine (*Pinus* L.)	0.4307	0.5
Larch (*Larix* Mill.)	0.4873	0.5
Douglas fir (*Pseudotsuga* Carrière)	0.4124	0.5
Beech (*Fagus* L.)	0.5543	0.5
Oak (*Quercus* L.)	0.5611	0.5
Other valuable hardwood	0.5642	0.5
Other hardwood	0.3768	0.5

– Compensation: A third approach was used to investigate the level of financial compensation a given forest enterprise would need to receive to avoid financial losses from managing their forest to maximise carbon sequestration. For eight model forest enterprises in two representative growth regions of Bavaria, we calculated the net present values (NPV) that can be achieved by managing the forest according to the most effective scenario (in terms of carbon sequestration) under the timber price assumptions of the other scenarios. The difference between this NPV and the financially optimized NPV for a particular scenario gives the financial losses for supplying an additional carbon sink effect that might have to be compensated for by the public through subsidies or other payments. If the amount of these compensation payments was to be related to the additional carbon storage amount, cost-benefit ratios could be derived that would allow a comparison with other methods of carbon emission reductions.

The annuities were then calculated for the 30-year investigation period with an interest rate of 1.5 % (Möhring and Rüping 2008). A price of 4.70 €/t CO_2 was chosen for the emission permits; this was the spot market price at the European Energy Exchange in Leipzig on 12th December 2013.

3 Results

3.1 Carbon effects

The climate-relevant sink effect of the compact wood amount in a forest is equal to its growth-related carbon sequestration amount (minus deadwood). Table 5 gives the annual results of our numerical example during the next decades, according to the simulated 5-year periods. This is the forest part $g(t)$ of expression (1) discussed in the methods section (deadwood is not covered by the model). We present results for the four different timber price scenarios. The sink effect of the forests across all scenarios is quite stable, ranging between 4.0 and 4.3 million tC/a (1.7–1.8 tC/(ha · a)). The A50 scenario shows a slightly higher sink effect, because the reduced harvests moderately increased the stock volume.

Table 6 shows the results for the carbon emissions from wood products (the term $\tilde{u}(t)$ in expression 1). The modelled average emission effects from these products are between

Table 5 Climate relevant carbon sink effects of the forest

Year	A0	A50	Diff	A100	Diff	A300	Diff
2015	−3,626,494	−3,686,806	−155,150	−3,789,007	−498,753	−4,202,526	−1,297,819
2020	−4,433,292	−4,714,984	−1,170,702	−4,860,731	−2,077,522	−5,091,719	−2,340,523
2025	−4,361,813	−4,618,431	−1,003,728	−4,813,183	−1,229,707	−4,211,258	1,129,445
2030	−4,071,752	−4,594,169	−1,289,535	−4,200,170	585,555	−3,737,512	1,217,446
2035	−4,125,618	−4,429,780	−340,782	−3,841,463	1,416,625	−3,670,443	770,292
2040	−3,440,341	−3,763,199	−516,059	−3,197,949	44,632	−3,026,530	−105,504
Total							
(tC)	−120,296,551	−129,036,837	−8,740,286	−123,512,517	−3,215,966	−119,699,940	596,611
(tC/a)	−4,009,885	−4,301,228	−291,343	−4,117,084	−107,199	−3,989,998	19,887
(tC/ha/a)	−1.66	−1.78	−0.12	−1.71	−0.04	−1.65	0.01
$\sigma_{\bar{x}}$ (tC/ha/a)	0.06	0.07		0.10		0.11	

All figures in metric tons of carbon. Periodic figures in tons per year. The column “Diff.” shows the difference to the base scenario. $\sigma_{\bar{x}}$: Standard error of the mean

Table 6 Climate relevant carbon emissions of the wood products manufactured after 2010

Year	A0	A50	Diff	A100	Diff	A300	Diff
2010	818,240	800,276	−17,964	795,349	−22,891	780,785	−37,455
2015	831,924	721,706	−110,218	698,844	−133,080	683,998	−147,926
2020	691,870	638,930	−52,941	691,644	−226	1,177,951	486,081
2025	693,981	646,977	−47,004	1,001,944	307,964	1,176,399	482,418
2030	696,815	751,327	54,511	1,115,519	418,703	1,019,401	322,585
2035	803,040	821,221	18,181	950,300	147,260	1,000,242	197,202
Total							
(tC)	22,679,354	21,902,179	−777,175	26,268,002	3,588,648	29,193,880	6,514,527
(tC/a)	755,978	730,073	−25,906	875,600	119,622	973,129	217,151
(tC/ha/a)	0.31	0.30	−0.01	0.36	0.05	0.40	0.09
$\sigma_{\bar{x}}$ (tC/ha/a)	0.01	0.01		0.03		0.03	

All figures in metric tons of carbon. Periodic figures in tons per year. The column "Diff" shows the difference to the base scenario. $\sigma_{\bar{x}}$: Standard error of the mean

0.7 and 1.0 million tC/a (0.3-0.4 tC/(ha · a)) and show—with the exception of the A50 scenario—a small increase when moving from the base scenario towards the A300 scenario. The periodic results reflect higher volatility of the harvested timber volume with rising timber prices. In the base scenario, the emissions range from 0.7 to 0.8 million tC/a, while in the A300 case they fluctuate between 0.7 and 1.2 million tC/a.

The effect of substitution is shown in Table 7. The substitution effect ranges between 5.3 and 6.0 million tC/a (2.2-2.5 tC/(ha · a)), and is the biggest component of the carbon balance. It is also the factor that is most clearly influenced by the timber price scenarios. Whereas the maximum variation in both the sink effect of the forest and the emissions from products is 0.1 tC/(ha · a), the substitution effect varies by about 0.3 tC/(ha · a). The base scenario shows the biggest substitution effect with 2.5 tC/(ha · a).

Finally, Table 8 shows the sum of all three carbon effects. The total carbon balance is between 8.4 and 9.2 million tC/a (3.5-3.8 tC/(ha · a)) and demonstrates a clear trend, with the base scenario having the highest value and declining steadily until the A300 scenario which shows the lowest effect. Nevertheless, in all scenarios, the total system of forest and wood products represents a considerable carbon sink, with or without considering the substitution effects.

To put our approach in context, we compare it with the atmospheric flow approach and the simple decay approach as published in Eggleston et al. (2006): In chapter 12, equation 12A.3 describes the emissions from AFOLU (agriculture, forestry and land use) as follows:

$$-44/12 \cdot (NEE - E - E_W) = \tag{8}$$

$$-44/12 \cdot (NEE - C_{HWPDC}) = \tag{9}$$

$$\begin{aligned} -44/12 \cdot {} & [\Delta(\text{AFOLU without HWP}) + \Delta C_{HWPIU_{DC}} \\ & + \Delta C_{HWPSWDS_{DC}} + P_{EX} - P_{IM}] = \end{aligned} \tag{10}$$

$$-44/12 \cdot [\Delta(\text{AFOLU without HWP}) + H - C_{HWPDC}] \tag{11}$$

where NEE is the net ecosystem exchange of carbon, E the carbon release to the atmosphere from timber products, E_W the carbon release to the atmosphere from timber products in solid waste disposal sites, P_{EX} the carbon transfer in the form of exported wood-based biomass, P_{IM} the carbon transfer in the form of imported wood-based biomass, $C_{HWPDC} = E + E_W$, $\Delta C_{HWPIU_{DC}}$ the annual change of timber products in use from domestic consumption, $\Delta C_{HWPSWDS_{DC}}$ the annual change of timber products in disposal sites that came from domestic consumption and H the carbon in annual harvest of roundwood for products, including fuelwood.

If we now relate that approach to our model we can state that the quantity "AFOLU without HWP" must be equal to $g(t) - u(t)$ and H is equal to $u(t)$. If we do not consider disposal sites, C_{HWPDC} equals E. Additionally, we do not consider imports or exports and calculate in carbon units making the factor $-44/12$ obsolete. We can now write:

$$\begin{aligned} -44/12 \cdot [\Delta(\text{AFOLU without HWP}) + H - C_{HWPDC}] \equiv \\ g(t) - u(t) + u(t) - E \end{aligned} \tag{12}$$

That is the atmospheric flow approach using our notation. The simple decay approach then goes a step further and assumes that the harvests $H = u(t)$ remain part of the AFOLU

Table 7 Substitution effects of the wood products

Year	A0	A50	Diff	A100	Diff	A300	Diff
2010	−5,205,198	−5,085,157	120,041	−4,686,549	518,648	−4,065,204	1,139,994
2015	−6,318,426	−5,083,608	1,234,818	−3,866,916	2,451,510	−3,823,806	2,494,621
2020	−5,260,754	−4,142,863	1,117,891	−3,999,203	1,261,551	−5,940,279	−679,525
2025	−5,715,732	−4,553,785	1,161,947	−6,324,590	−608,858	−6,262,234	−546,502
2030	−6,065,154	−5,905,935	159,219	−7,124,926	−1,059,772	−5,991,509	73,644
2035	−7,254,847	−6,919,436	335,411	−6,673,788	581,059	−6,075,189	1,179,657
Total							
(tC)	−179,100,549	−158,453,917	20,646,632	−163,379,859	15,720,691	−160,791,104	18,309,445
(tC/a)	−5,970,018	−5,281,797	688,221	−5,445,995	524,023	−5,359,703	610,315
(tC/ha/a)	−2.47	−2.19	0.29	−2.26	0.22	−2.22	0.25
$\sigma_{\bar{x}}$ (tC/ha/a)	0.12	0.15		0.22		0.17	

All figures in metric tons of carbon. Periodic figures in tons per year. The column "Diff" shows the difference to the base scenario. $\sigma_{\bar{x}}$: Standard error of the mean

Table 8 Carbon balance of the total system forest and products

Year	A0	A50	Diff	A100	Diff	A300	Diff
2010	−4,386,958	−4,284,881	102,077	−3,891,200	495,757	−3,284,418	1,102,539
2015	−9,112,996	−8,048,708	1,064,287	−6,957,079	2,155,916	−7,342,333	1,770,662
2020	−9,002,176	−8,218,917	783,258	−8,168,289	833,886	−9,854,047	−851,872
2025	−9,383,565	−8,525,239	858,326	−10,135,829	−752,264	−9,297,093	86,472
2030	−9,440,090	−9,748,777	−308,687	−10,209,577	−769,488	−8,709,620	730,470
2035	−10,577,425	−10,527,994	49,430	−9,564,951	1,012,474	−8,745,391	1,832,033
2040	−3,440,341	−3,763,199	−322,857	−3,197,949	242,393	−3,026,530	413,811
Total							
(tC)	−276,717,746	−265,588,576	11,129,171	−260,624,374	16,093,372	−251,297,164	25,420,583
(tC/a)	−9,223,925	−8,852,953	370,972	−8,687,479	536,446	−8,376,572	847,353
(tC/ha/a)	−3.82	−3.67	0.15	−3.60	0.22	−3.47	0.35
$\sigma_{\bar{x}}$ (tC/ha/a)	0.40	0.38		0.42		0.41	

All figures in metric tons of carbon. Periodic figures in tons per year. The column "Diff" shows the difference to the base scenario. $\sigma_{\bar{x}}$: Standard error of the mean

Table 9 Financial evaluation of the carbon balances (see figures in Table 8) according to the three different calculation methods

Method		A0	A50	A100	A300
Carbon losses	(€/ha/a)		3.33	4.82	7.61
Carbon storage	(€/ha/a)	83	80	79	76
Compensation	(€/ha/a)		22	45	114
	(€/t C)		143	200	323
	(€/t CO_2)		39	54	88

Average annuities for each scenario

pool, meaning the carbon is not withdrawn from the forest and is not counted as a part of emissions (Eggleston et al. 2006, Vol. 4, chapter 12, page 12.30). We then get:

$$g(t) - u(t) + u(t) - E = \\ g(t) - E \tag{13}$$

as the representation of the simple decay approach of Ford-Robertson (2003) in our notation. While standard methods use stock-change approaches to calculate the emissions from the product pool (method A under tier 3 of the guidelines), we propose a direct estimation of E by the variable $\tilde{u}(t)$ applying a flux data method with direct output estimates, suggested as method C under tier 3 of the 2006 guidelines. These alternative methods have the advantage of not needing long historical input data to calculate the product pool (Eggleston et al. 2006, Vol. 4, chapter 12, page 12.16). The concept of $\tilde{u}(t)$ enables us to estimate the carbon release from timber products by using the amount harvested as both variables are correlated via the lifetime dependent reduction factor. Therefore, we can also describe our approach as a simple decay approach with direct output estimates.

3.2 Financial evaluation

The results of the financial evaluation are shown in Table 9. As the investigation of the carbon balances found the base scenario to provide the biggest sink effect (see Table 8), this scenario was chosen as the reference case for evaluating reduced carbon sink effects and compensation payments. This means that the reduced effects relate to the differences between the individual sink effect of the increasing timber price scenarios and the base scenario. To calculate the required compensation payments, the harvest schedules from the base scenario were considered desirable; hence, they were also used in the increasing price scenarios to calculate the net present value (NPV) that could be achieved with this particular management plan. The difference between this NPV and that of the optimal solution—in terms of carbon sequestration—then gives the expected financial loss that must be compensated.

The carbon losses (in terms of prices for emission permits) due to reduced sink effects range between 3 and nearly 8 €/(ha · a), and occur with the rising price scenarios from A50 to A300. The differences between the absolute carbon storage values resulted in 76 to 83 €/(ha · a). The value of carbon storage reduces with rising timber price scenarios, resulting in a decrease in the amount of carbon stored when moving from the base to the A300 scenario. The amount of compensation necessary to achieve the better carbon balance provided by the base scenario with increasing timber prices ranges from 22 to 114 €/(ha · a), or from 143 to 323 €/t C.

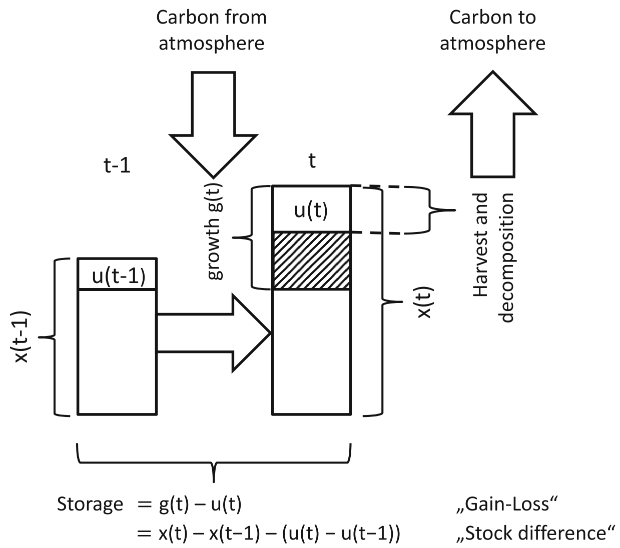

Fig. 3 Model of the forest carbon pool as a closed system with inputs and outputs (standard carbon models). The hatched area shows the additional carbon storage after one period. $x(t)$ represents the total carbon stock of the forest. $g(t)$ is the additional carbon flux into the forest due to growth. $u(t)$ are fluxes due to timber usage

4 Discussion

4.1 Effects of forest management

Most approaches of carbon balances separate the pool of carbon in forests from that of carbon in forest products. Unfortunately, this separated view can lead to doubtful interpretations of the influence of forest management on the carbon balance of forests because timber harvests are automatically seen as some kind of transfers between the separated pools.

If a forest is considered as a part of the carbon cycle that interacts with its environment by absorbing and emitting certain amounts of carbon dioxide, the periodic change in forest carbon can be calculated either based on stock changes or by balancing the input and output fluxes. As Fig. 3 shows, this change in stocks, at any point in time t with respect to the preceding point $t-1$, can be expressed as the difference between the amount of growth $g(t)$ that occurs in this period and the volume $u(t)$ that is removed from the forest by harvests ("gain-loss method"). All of these volumes are considered in terms of the total mass of carbon (e.g. in [tC/a]). Alternatively, this difference can be found by calculating the change in the remaining stock ("stock difference method"): $x(t) - u(t)$ minus $x(t-1) - u(t-1)$, if $x(t)$ equals the total stock.

Both methods conform with intergovernmental agreements according to IPCC (Eggleston et al. 2006; Hiraishi et al. 2014), but imply that any biomass leaving the forest stock—including harvested timber, as it crosses the defined system border—generates immediate carbon emissions from the forest. For an unmanaged natural forest, this model might be reasonable, because the volume or mass $u(t)$ (in [tC/a]) "leaving" the forest is identical to the carbon volume or mass $d(t)$ that is emitted from the forest to the atmosphere by wood decomposition processes (e.g. modelled with the factors used by Rock et al. 2008).

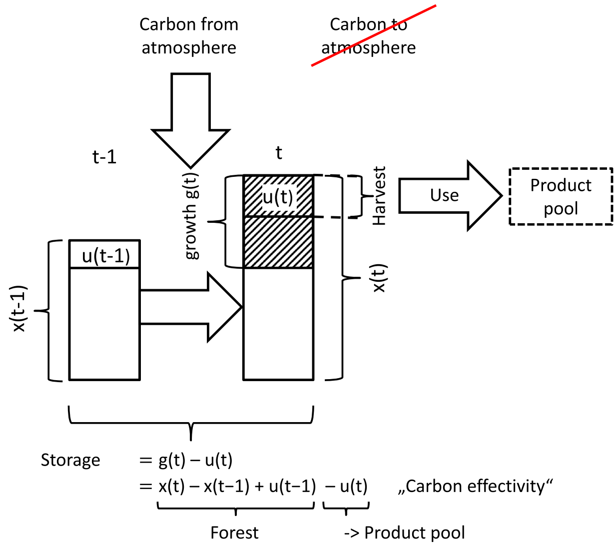

Fig. 4 Model of the forest carbon pool as a permanent carbon sink (effect model). The hatched area shows the additional carbon storage after one period. In the carbon effect model this amount of carbon storage is identical with the growth (in carbon units). $x(t)$ represents the total carbon stock of the forest. $g(t)$ is the additional carbon flux into the forest due to growth. $u(t)$ are fluxes due to timber usage

But, as already mentioned, once wood is removed for material or energy uses, the defined boundaries of this model are too narrow to describe the reality sufficiently. Even if an additional product pool is included that accounts for the timber volume that is removed from the forest as a carbon uptake, this formal separation of the two pools systematically underestimates the carbon mitigation effects of managed forests compared to unmanaged ones. This is because in a managed forest timber use is accounted for as an emission, although, in reality, there is no immediate emission from that timber in the forest. The only emissions in situ are caused by respiration. In a sustainably managed forest with regular timber extraction, respiration can never be as high as growth, or even higher than it (on average), otherwise the forest would collapse over time. If both are equal, no timber extraction is conducted, for example in a natural unmanaged forest. The wood removed from the forest continues to store the carbon in its cell structure and does not immediately interact with the environment, i.e. the atmosphere. It therefore would be a logical error in modelling to count this as an emission (compare Fig. 3 with Fig. 4: the carbon of the harvested timber $u(t)$ is not released to the atmosphere as the standard model of Fig. 3 assumes but actually stays stored within the timber in use as shown in Fig. 4). The underlying weakness of the standard method is the balancing of carbon fluxes that are directly related to source and sink effects (that are, by definition, interactions with the atmosphere) with the calculative fluxes between carbon pools, because these two types of fluxes are fundamentally different phenomena.

Moura Costa and Wilson (2000) presented another approach to account for the benefits of the emission delay caused by the use of wood. They suggested an "equivalence factor" E_f defined by $E_f = 1/T_e$ with T_e being an average "equivalent time" of 55 years. This time is derived from the restrictive assumption that after a storage time of 55 years the global warming potential of 1 tCO_2 emitted to the atmosphere is completely compensated if the warming potential is summed up over 100 years. Then the carbon avoidance effect is 0.0182 tCO_2 per year for each tCO_2 stored. That means if the timber would be in use for 55 years the avoidance effect would be equal to 1 leading to no emissions at all. Our approach does not consider decay patterns of emissions to the atmosphere. The equivalent E_f would be 0.01. In other words, every year 1 % of the carbon emissions would be avoided through delay. Although derived from a different way of thinking, our factor r_p could be interpreted as a generalisation of E_f as we do not assume a fixed storage time (life time) of 55 or 100 years but link the emission effect to the actual life time directly by assuming an individual "equivalent time" of $T_e = T$. In that case, $Ef \cdot T = 1$. There would be no emission at all from the timber products (100 % avoidance by delay). On contrary, in our approach, the emissions are equal to $1/T$ at last (99 % avoidance by delay after 100 years). Therefore, our approach is more conservative as it do not limit the considered time horizon of the emission potential to 100 years but to the individual life times.

Balancing carbon fluxes out of the forest pool against fluxes into the product pool leads to an accurate result for the two pools in total. Nevertheless, this pool model still generates and balances artificial carbon fluxes that do not occur in reality. Such a model supports the interpretation that setting aside forest areas through nature protection programs avoids carbon emissions that would otherwise result from timber harvests.

In a situation where a previously managed forest is no longer managed, the carbon mass $g(t)$ is stored in a certain time period between t and $t-1$ in the forest. The carbon mass $d_n(t)$ is emitted through biological decomposition. In a managed forest, during the same time period, the harvested carbon mass $u(t)$ and the deadwood mass $d_m(t)$ are removed from the forest and "emitted" according to the pool model. When the carbon stock change is calculated using the standard methods of subtracting losses from gains using $g(t)-d_n(t)$ in the unmanaged case, and $g(t) - d_m(t) - u(t)$ in the managed case, the results imply that the managed forest has a lower storage effect. If timber harvesting ceases in a managed forest (which is often proposed by nature conservation groups (e.g. Panek 2011)), in the years immediately following this halt in harvesting $d_n(t)$ will be lower than $d_m(t) + u(t)$, because there is normally relatively little deadwood in a managed forest. Because of this, the emissions $d_n(t)$ are similar to $d_m(t)$, at least initially.

This calculation method still neglects two key factors: First, the carbon mass $u(t)$ in the harvested wood is not immediately released, but rather, is stored in a timber product until the end of its lifetime. Thus, this calculative (fictitious) emission $u(t)$ is instantly transformed into a calculative sink effect of the same magnitude. In other words, it does not occur. The emission does not come into effect until the end of the lifetime of the wood product created from the extracted timber. Until this point, this carbon mass should be considered as part of the product, which provides a sink effect due to delayed emissions. This sink effect can be accounted for by modifying the carbon mass in the harvested wood $u(t)$ with a reduction factor, leading to the climate-effective carbon mass $\tilde{u}(t)$.

Second, the total carbon emissions $d_n(t)$ from an unmanaged forest will equal the total growth $g(t)$, because forest is the main potential natural vegetation (climax vegetation) in Central Europe and is therefore a system at equilibrium (Ellenberg 1996).

Our model covers only a certain time horizon with respect to the input parameters (in the presented case 30 years). This is sufficiently long to derive a tendency of the level of the carbon fluxes in and out of the forest but too short to cover the life time of many wood products. This aspect is considered in our model by calculating the preventative effect of the temporary storage over the whole life time period and summing it up into a reduction of the future carbon emissions to a calculative immediate carbon release that is already accounted at the initial time of the usage period. That allows to consider the overall effect of life time periods longer than 30 years within the investigated time horizon and avoids any kind of bias due to limited time horizons.

4.2 Carbon effects

In all the scenarios, there was only a slight increase or decrease in the stock volume of the forests (see Table 5). In those scenarios where some changes did occur—including a slight intermediate stock volume increase (A50) and a slight decrease (A100)—somewhat smaller carbon storage effects resulted than for the other two scenarios, where the growing stock increased more clearly.

There are further reasons for calculating the forest carbon by considering the volume of above-ground wood. The volume of above-ground wood below 7 cm (non-compact wood, or brushwood) can be estimated by either using expansion factors (Burschel et al. 1993; Schöne and Schulte 1999) or biomass functions (Wirth et al. 2004b; Wutzler et al. 2008; Zell 2008), but can generally be considered constant in its relationship to the compact wood volume, at least at the enterprise and regional level. The same can be assumed for the root volume, which is normally estimated based on the volume of above-ground biomass (UBA 2013), and the deadwood volume (UBA 2013), see also Penman (2003). Within the timber price scenarios investigated here, all of which have been calculated based on the same silvicultural treatments, the effect of treatment on deadwood production and forest residues found by Höllerl and Neuner (2011) and by Höllerl and Bork (2013) has been ignored. At the enterprise level, the long-term carbon stock in the organic soil matter can also be considered to be constant under Central European circumstances (Scheffer et al. 2010; Block and Gauer 2012; UBA 2013).

As a matter of principle, the forest is always a carbon sink within the presented model (or a zero emitter in the case of the natural steady state). This sink effect in Bavaria is about 1.7 tC/(ha · a) if the growing stock is maintained at the present size through active management. This result is comparable to the annual sequestration rate of 1.5 tC/(ha · a) reported by Klein and Schulz (2012) for the period 1987–2002, although the values are derived in different ways. While we added the harvested volumes to the sink effect of the forests, the value from Klein and Schulz (2012) reflects only the increase in growing stock between 1987 and 2002 in Bavaria. For the whole of Germany, Dieter and Elsasser (2002) reported a higher change in carbon stocks of 2.2 tC/(ha · a) in coarse wood. Klein et al. (2013) calculated sequestration rates at the stand level ranging from 0.3 to 0.7 tC/(ha · a) depending on tree species. If the reported product pool changes are added to these figures, a range of 0.6 to 1.1 tC/(ha · a) can be derived. For a non-managed forest, these authors showed sequestration rates of 1.9 to 2.2 tC/(ha · a). It should be noted, however, that Klein et al. (2013) investigated stands within an age range limited to 0 to 180 years, which represents the phase of the largest growing stock increase. Thus, their investigation did not cover the stage of long-term equilibrium. The same can be stated for the results of Luyssaert et al. (2008) who reported a similar rate of 2.2 tC/(ha · a) for boreal and temperate forests, because their data only adequately covers stands up to 300 years old. One possible conclusion from these results is that applying commercial harvests that do not exceed the average growth increment rates, results in a continuous sequestration rate similar to that of a natural (i.e. unmanaged) forest in its growing phase. The underlying reason for this is the similarity in total volume production.

In our way of thinking, timber harvests do not "release carbon otherwise stored in the biomass, litter, dead wood and soil carbon pools" as propagated for example again in Naudts et al. (2016), because it is only transferred from the pools mentioned into a new, additional, man-made pool of forest products that is not provided by nature. Therefore, wood extractions do not account for immediate carbon release from the forests. Using the numbers calculated by Naudts et al. (2016) and subtracting the 2.7 petagrams of carbon (PgC) accounted for wood extraction from the overall result we conclude that European forests contributed to carbon sequestration with 0.4 PgC since 1750 (without the emissions from the product pool).

The conclusion that maintaining a constant stock volume will result in a stable carbon flux into the forest that supports a constant carbon stock is compatible with the results reported by Nabuurs et al. (2013), who refer to this steady state condition as a "saturation" of the forests. While they judge this "saturation" effect negatively, we instead would like to emphasize the fact that a stable—or "saturated"—carbon stock in forests can be a positive indication of reaching an optimal stocking volume with a widely applied continuous cover forest management regime.

With regard to the carbon source effects of the products, there are only slight differences between the scenarios (a maximum difference of 0.09 tC/(ha · a)), although the proportion of various grades used for energy purposes rises by 10 percentage points between the base and the A300 scenarios (from 36 to 46 %). This effect is only marginal because the two mechanisms are counteracting one another: both the effect of relative volume shifts (between different timber grades) and the effect of absolute timber volume change. In the scenarios with increasing timber prices, where—relatively seen—more energy wood is used, there is—absolutely seen—less wood used in total. Therefore, the effect of more carbon emissions due to the shorter lifetime of energy wood is more or less compensated by the reduced amount of emissions from the smaller product pool that results from the reduced harvest amounts.

The most distinct difference between the scenarios can be seen within the substitution effects (see Table 7). In the increasing price scenarios, this effect is about 2.2 tC/(ha · a), whereas the base scenario provides 2.5 tC/(ha · a). This results from the larger amounts of timber harvests in the latter scenario, combined with a higher ratio of wood used for material purposes.

The total result (see Table 8) shows a slight trend between the scenarios—the greater the timber price increase, the smaller the carbon sink effect. This effect decreases from 3.8 tC/(ha · a) to 3.5 tC/(ha · a) (10 % decrease). This results in a total sink effect of between 8.38 and 9.22 million tC/a for all forests in Bavaria, which is comparable to the 8.75 million tC/a, calculated by Klein and Schulz (2012) for a scenario with timber harvests equal to the volume increment.

Comparing the relative importance of the three individual effects shows that the substitution effect has the biggest influence. This result corresponds to the findings of other studies: Burschel and Weber (2001), Perez-Garcia et al. (2005), and Lippke et al. (2011) emphasized the major influence of the substitution effect, which ultimately means that timber use is more effective in terms of carbon sequestration than leaving the forest alone. This means that reductions of carbon emissions in other sectors of the industry are accounted for within the forestry sector. Therefore, any possible double counting of these benefits in a practical application has to be avoided carefully. Perez-Garcia et al. (2005) concluded that a growing stock decrease and shorter rotation periods led to a more favourable carbon balance than a high growing stock volume, because such a management strategy allows more wood products to be produced even faster. Contradictorily, from a similar pattern of results Pingoud et al. (2010) deduced that a high growing stock volume is more advantageous, because a long rotation period increases the ratio of large diameter classes in the forest. This increases the amount of sawlogs, thereby achieving a higher substitution potential. Thus, a high stock volume plus a high substitution effect may lead to an optimal total carbon balance.

These conflicting points of view highlight that focussing on current timber stock is not the best way to interpret carbon effects in forests. Instead, the carbon pool in the forest is not considerably influenced by the investigated management plans that vary rotation periods and timber grading, as long as these plans are sustainable in terms of the growth increment. Neither the present volume nor its change influence the carbon sink effect of the forest, but they instead impact the total volume production (or the current total increment). The total volume production can be manipulated through management so that it increases to a level above that of a non-managed forest, or at least, so that it does not significantly decrease from this level, e.g. by applying an appropriate basal area control scheme (Assmann 1953; Pretzsch 2004). Because removing some trees can potentially provide remaining trees with more room to grow, timber harvests can increase the potential for higher volume increments while still maintaining the carbon sink effect of the forest. Sustainable timber harvests with high ratios of material use log grades provide a high level of carbon sequestration over the whole system.

Our hypothesis can be accepted in the sense that we have shown a slight tendency towards a decline in the carbon sink effect of the forest-wood product system if increases in timber price are expected:

- If oil and timber prices are expected to rise in the future, this tends towards reduced harvests that will improve the sink effect of the forest carbon pool.
- At the same time, the product pool emits more carbon, and the substitution effects decrease. An explanation is that the relative amount of the harvests used for energy wood increases (cf. Härtl and Knoke 2014).
- This second effect overcompensates for the first, leading to a decreased total carbon sink effect.

These results are globally valid as we derived them from applying management decisions based on economic objectives. The underlying forest data from Bavarian was treated in all different price scenarios according to the same silvicultural scheme within the forest growth simulation. Therefore, being a *ceteris paribus* condition, it does not influence the relative shifts between the scenarios.

However, this effect of a decreasing carbon sink effect is small compared to the price effects found in the oil price scenarios investigated. Even if the oil price was to quadruple in the next 30 years (A300 scenario) the carbon sink effect would be reduced by about 10 % only. This means that the carbon balance of the system is quite stable with regard to management-induced changes.

4.3 Financial evaluation

From one point of view, it is possible to define a natural level of forest stocks that must be maintained by forest management. This requires one scenario to act as a reference case. The base scenario seems to be a reasonable choice, because it assumes constant timber prices in the future, and is therefore the most conservative prediction. From this reference, it is possible to evaluate shifts of the capability of carbon sequestration, as done for example by the REDD+ mechanism (UNFCCC 2007). All the increasing timber price scenarios investigated here resulted in lower sink effects than the reference. The costs of these losses can be interpreted either as economic damages or as externalities of the changes in forest management. One possibility for internalizing these costs would be to derive a fee which the forestry sector would be required to pay in order to harvest.

The second approach disclaims the natural reference and instead accounts for the total effects. As the entire system of forests and forest products acts as a carbon sink in all the scenarios, this point of view leads to an economic benefit provided by the forestry sector. In principle, it would be possible to derive a policy which establishes a right for forestry enterprises to be compensated for the provision of this service. Including the forestry sector in the emission permit trading system would create the potential for forest enterprises to sell annual emission permits to other branches of industry.

If the same calculations were executed with assumed environmental costs of the damages caused by climate change of about 75 €/t CO_2 (average values are between 70 and 80 €/t CO_2 (Krewitt and Schlomann 2006; UBA 2012)), the economic benefit provided by forestry would be between 1211 and 1332 €/(ha · a). For the total forest area in Bavaria (2.4 million ha), the benefit for society would be between 2.9 and 3.2 billion €/a.

Finally, the third approach of calculating necessary compensation amounts (to compensate foresters for managing their forests to optimise carbon sequestration) gives a completely different result. This illustrates the problems inherent to the emission permits trading system: for example that a market mechanism does not necessarily lead to "correct" prices that reflect the original intention for which the system was established. If the calculated compensation amounts relate to the additional carbon storage that can be achieved with forest management according to the base scenario, cost to benefit ratios result that describe the economic costs of requiring foresters to manage forests according to a certain plan—in this case, the base scenario. In other words, forest enterprises may not voluntarily follow the more carbon-effective base scenario unless they are allowed to sell emission permits at these derived prices. Therefore, including the forestry sector in the emission permit trading system will probably not have any positive effects if carbon prices remain at their current low level. Another problem would be that including forests will probably reduce the price of the permits even more, because the number of permits supplied would increase.

In addition to the intrinsic problems of the market-compliant approach of tradeable rights to pollute the environment, the comparison above shows that the required compensation amounts are indeed, in most cases, below the environmental costs of carbon emissions. This creates an economic benefit from avoiding the emissions. As shown in Table 9, the average cost is 54 €/tCO_2 (A100 scenario), so an investment in a timber harvest for material use would achieve an economic gain of 21 €/tCO_2 (the environmental costs of carbon emissions which would be avoided, 75 €/tCO_2, minus 54 €/tCO_2 of compensation payments). With an average additional carbon sink effect of 0.82 tCO_2/ha/a, an economic gain of about 17 €/(ha · a) or 41 million €/a (for the whole forest in Bavaria) can be derived. Nevertheless, the calculated high compensation costs between 39 and 88 €/tCO_2 suggest to focus on other, direct instruments to raise sequestration rates in forests, for example by supporting nature conservation projects on low-productive site conditions. Additionally, further aspects like transaction costs of making carbon benefits tradeable would rise the overall costs of carbon sequestration projects even more (Sovacool 2011; Bakam et al. 2012; Cacho et al. 2013).

5 Conclusions

For the transfer of our research into practice, we can conclude three globally valid things. First, combining the simple decay approach with direct output estimates using the carbon effect model is an easily applicable approach; it uses data readily available from the forest and forest product sector (stocks, harvests and amount of products produced) and does not require the actual size of the carbon pools, especially the forest products pool.

Second, maintaining a sustainable forest management with overall stable growing stock volumes (for example by establishing mixed species stands and applying selective thinnings within an overall framework of continuous cover forestry) and using forest products for a mix of material and energy uses provides a relatively stable system of carbon mitigation, even if economical framework parameters such as timber prices are changing dramatically. As shown in the results section, the mitigation effects only decrease slightly if a comprehensive, risk-sensitive forest management system is applied.

Third, it highly depends on the chosen model how management options or even effects of biophysical growth are judged with respect to their carbon sequestration capability. Models can influence our way of thinking about processes quite strong as they are the results of how we capture the environment within our intellectual world. Therefore, there is the danger of a self-fulfilling prophecy as the models then often reflect our pre-defined way of thinking. So we always have to think about if they are valid only within the chosen paradigm or not. If so, they do not have the power to prove the underlying construct of ideas as they are just a part or a result of that construct. For that reason, we think it is necessary to enrich the scientific and political discussion with alternative suggestions to illuminate the critical points where established paths of thinking may narrow our search for solutions for upcoming threats like climate change. Our proposed alternative carbon accounting model derived from a new way of thinking by strictly separating carbon fluxes between pools and pools from fluxes between pools and the atmosphere enables a clear sight on the benefits of using sustainable produced forest products as an unambiguous contribution to carbon mitigation policies.

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