Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

Review

Closing an Open Balance: the Impact of Increased Roundwood Harvest on Forest Carbon

Sampo Soimakallio (Finnish Environment Institute)[1,2], Hannes Böttcher (Oeko-Institut)[2], Jari Niemi (Finnish Environment Institute), Fredric Mosley (European Forest Institute), Sara Turunen (Tapio Ltd), Klaus Josef Hennenberg (Oeko-Institut), Judith Reise (Oeko-Institut) and Horst Fehrenbach (ifeu)

[1] corresponding author: sampo.soimakallio@syke.fi
[2] authors should be considered joint first author

Abstract: Fossil-based emissions can be avoided through using wood in place of non-renewable raw materials as energy and materials. However, increasing wood harvest influences forest carbon stocks. This effect may reduce the overall climate benefit of wood use significantly but is widely overlooked. We carried out a systematic review of simulation studies and compared differences in forest carbon and amount of wood harvested between more and less intensive wood harvest scenarios for three different time perspectives; short (1-30 years), mid (31-70 years) and long (71-100 years). Out of more than 450 reviewed studies 44 provided adequate data. Our results show that increased harvesting reduced carbon stocks over 100 years in temperate and boreal forests roughly 1.6 (stdev 0.9) t_C per t_C harvested. The value proved to be robust when outliers explicitly influenced by other factors than change in harvest rate, such as increase in fertilization or forest area, were removed. Interestingly, no significant difference in carbon impacts was found for average values of boreal and temperate forests or between short and long time-horizons. However, impacts tend to be greatest in the mid-term. This carbon balance indicator that we estimated can be interpreted as carbon debit of wood harvest in forests. It is significant compared with the typical GHG credits in technosphere generated by avoiding fossil emissions in substitution and increase in carbon storage in harvested wood products, and should not be ignored. Our estimates provide default values that can directly be included in GHG balances of products or assessment of mitigation policies and measures related to wood use. However, more systematic scenarios and transparent data in which different factors influencing forest carbon stocks are separately studied are clearly required to provide better constrained estimates for specific forest types.

Keywords: forest carbon; carbon stock; roundwood harvest; climate change mitigation; life cycle assessment; scenarios; modelling

1. Introduction

In climate change mitigation, forests take an ambivalent role as they hold significant carbon storage and sequestration potential and provide a source of renewable raw material. Both options, however, form opposing alternatives: wood harvest reduces forest carbon stocks (negative forest carbon balance) and thus reduces its ability to act as a carbon reservoir [1]. On the other hand, less harvest means more carbon in forests (positive forest carbon balance) but also less wood for society for energy and material services [2]. Climate change mitigation strategies often suggest that wood use is increased from a given reference level to substitute fossil-based raw materials [3,4]. However, as it is common practice in life cycle assessment that forest biomass derived from managed forests is considered carbon neutral [5–7], the trade-off between increasing wood harvests and storing carbon in forests has not hit the required focus in the discussion of the role of forest use in climate change mitigation [8]. This trade-off may last for decades, or being even permanent, if the increase in harvest is sustained and leads to overall lower forest carbon stocks (**Error! Bookmark not defined.**).

© 2022 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

Increased wood use can help to mitigate climate change if the GHG emissions avoided exceed the GHG emissions generated [9]. Basically, this means that the credits of fossil emissions avoided when substituting wood for non-renewable raw materials and the carbon sequestered in harvested wood products exceed the debits caused in forest carbon stock due to increased wood harvest [10]. The credits in the technosphere are highly subjective to the way wood is used and the related assumptions on carbon permanency in products [11] and alternative raw materials substituted [12,13]. Globally, approximately 40% of the roundwood harvest ends up as harvested wood products (**Error! Bookmark not defined.**). However, only 44% of the carbon in harvested wood products produced between 1992 and 2015 was left in 2015 (**Error! Bookmark not defined.**), thus less than 0.17 units of the carbon harvested from forest remained in the HWP carbon stock over a quarter of a century. Furthermore, a recent systematic review study shows that at market-level one unit of carbon harvested from forest substitutes on average 0.55 units of fossil carbon, ranging from 0.27 to 1.16 [14].

While impacts of increased harvest on forest carbon stocks have been assessed under specific scenario conditions (e.g. [15–17]), there is a lack of overview studies providing generic information on impacts that can be taken up by GHG effect assessments of wood use. In this paper we attempt to fill this gap through a systematic review. We synthesize existing knowledge from scenario studies on how forest carbon balances react in short- (1-30 years), mid- (31-70 years) and long-term (71-100 years) when roundwood harvest rates are increased compared to a reference. We hypothesize that 1) increased roundwood harvest from a given reference level reduces the forest carbon balances (i.e. less carbon is stored), that 2) this effect is declining over time, and that 3) there is a large variation in the effect between studies and scenarios explained by the underlying assumptions and used forest models.

2. Methods

2.1. Choosing the data sources

A systematic literature review (SLR) [18] was used as a method to identify, select and critically analyse research in order to respond the research question formulated in this paper. The fundamental aim of the SLR was to find peer-reviewed articles that consider at least two forest management scenarios and provide data on the development of forest carbon stocks and harvest volumes of roundwood over a certain relevant time horizon. SLR was chosen to find the most relevant research papers from large mass and to minimise possible bias. We followed good practice guidance to carry out SLR [19]. Peer-reviewed publications were systematically selected from an external data research. More precisely, information came from secondary data by using Google Scholar as a search engine. The main criterion was that each article would include at least two forest management scenarios. The search was limited to the most recent publications that appeared between years 2016 and 2020. After testing multiple different combinations, the following query was used: "FOREST MANAGEMENT SCENARIOS" AND "CARBON". The chosen query returned practical amount of 427 documents in the Google Scholar database (see SI1). In comparison, two tested queries without any time limitation: "FOREST" AND "CLIMATE CHANGE" query returned in total of 2 280 000 documents and "FOREST MANAGEMENT" AND "CARBON" 267 000 documents. With time limitation 2016-2020, the results were still 203 000 for "FOREST" AND "CLIMATE CHANGE" and 22 600 for "FOREST MANAGEMENT" AND "CARBON".

In the first selection, the abstracts of the identified 427 publications were assessed (SI1). In case it was evident based on the abstract that the publication did not consider forest management scenarios which are required to respond to our research question, the publication was excluded from the second round. A short list of altogether 79 publications was created for studying the entire publication (out of which 9 publications were not available). In order to be selected for further calculations, the publication had to contain explicit and transparent data for both forest carbon stock or sink and wood harvest rate for at least two different forest management scenarios for at least one time horizon. Altogether 15 articles were concluded to provide the required data. Additionally to these 15 publications, 32 studies containing relevant data were identified based on the authors knowledge and added to the dataset. In total, CBI values for 231 scenario pairs were calculated from 44 publications.

2.2. Definition of carbon balance indicator (CBI)

We characterize the impact of increased roundwood harvest on forest carbon using the carbon balance indicator (CBI), initially presented by Pingoud et al. (**Error! Bookmark not defined.**). The CBI is defined for time frame *T* as the dimensionless ratio (t_C/t_C) between the difference in forest C stock $\Delta C_{stock}(T)$ and the difference in C in harvested biomass $\Delta C_{harvest}(T)$ over a certain given time horizon *T* between two scenarios of different harvest intensity.

Carbon balance indicator (CBI) is calculated using following equation (1):

$$\Delta C_{stock}(T) / \Delta C_{harvest}(T) \quad (1)$$

in which

$\Delta C_{stock}(T)$ is the difference in forest C stock in tonnes of carbon (t_C) and

$\Delta C_{harvest}(T)$ is the difference in C harvested between two different forest management scenarios over a certain given time horizon T in tonnes of carbon (t_C).

Note that CBI(T) is defined only when T>0 and $\Delta C_{harvest}(T) > 0$ (**Error! Bookmark not defined.**). We consider T between 1 and 100 years. Where available, CBI(T) was calculated for T = 20, 50 and 100a. In case data for these three different time horizons were not available, the closest possible time horizon was chosen, and included in relevant categories, namely short term (1-30a), mid-term (31-70a) or long term (71-100a). A positive CBI(T) value means that the forest carbon balance is reduced (i.e. less carbon is stored in the forest) when the harvest rate is increased. A CBI(T) value of 1 implies that the forest carbon stock is reduced by exactly the amount of carbon that is harvested. However, branches, stumps, roots etc., are typically not (at least totally) removed from the forest. In this case harvest of roundwood results in decaying of them, thus carbon dioxide emissions and higher CBI(T) values than 1. The same holds true if increased harvest results in reduced tree growth, e.g. due to forest degradation or cutting forests in good growing conditions [10,20]. On the other hand, CBI(T) is reduced if the biomass removal improves forest growth so that the carbon stock is eventually increased more than in a less intensive harvest scenario, e.g. through improved forest structure.

2.3. Gathering data on forest carbon balances and harvest rates

To calculate the CBI (carbon balance indicator) value, data on forest carbon stocks and stock changes and harvest rates for the scenarios were extracted using one or a combination of the following methods:

1) CBI value explicitly provided in the study;

2) Forest carbon balance and harvest rates gathered from numerical data, e.g., extracted from tables or text;

3) Forest carbon balance and harvest rates gathered from visual data, such as figures and charts, by estimation.

There is a margin of human error in the 3) method, although the figures were estimated as carefully as possible using plot digitizer software. The method of data collection used for collecting data from individual studies is shown in SI1.

Harvest rates expressed in cubic metres were converted to tonnes of carbon by using the constant ratio 0.2 t_C/m^3.

2.4. Statistical cut-off method

For some scenario pairs analysed, very small differences of harvest rates between the scenarios led to the denominator approaching zero (CBI = Δ forest carbon / Δ harvest). The initial range of CBI values therefore varied widely from -40 to 23.38. Extreme values are unlikely to be explained by mere harvest difference but some other factors, including human errors in data collection. Tukey's fences (1977) were used to detect the outliers from the calculated CBI values. CBI values were first divided into groups based on time horizon before determining the outliers. Values below Q_1 - 1.5(Q_3 - Q_1) or above Q_3 + 1.5(Q_3-Q_1) were considered as outliers, with lower quartile Q_1 (the value under which 25 % of the CBI values are found when arranged in increasing order) and upper quartile Q_3 (the value under which 75 % of the CBI values are found when arranged in increasing order) being 0.74 and 1.85, 0.83 and 2.53, 0.69 and 1.95, for short-, mid-, and long-term time-horizon groups, respectively. This resulted in detection of 7, 12, and 3 outliers in the short-, mid-, and long-term time horizons, respectively.

While Tukey's fences is an accepted method for detecting outliers, it is generally not recommended to remove datapoints when the data is widely scattered. In this case, most of the obtained CBI values appeared to be in relatively narrow range, as can be seen from the quartiles. In addition, the scenarios behind values that were detected as outliers often did not pass our own criteria-based cut-off rules (1-4) (see below). This suggests that the method works well enough to remove extremely low or high CBI values that are the result of errors or are primarily caused by other factors than the difference in roundwood harvest between scenario pairs.

2.5. Criteria-based cut-off method

We noted that there are significant differences in the underlying assumptions of the modelling studies considered (SI1). Some of these assumptions are not related to differences in harvest rates. However, they can significantly influence CBI values, thus also the average values and standard deviation. To exclude CBI values clearly influenced by factors other than difference in harvest rate, we applied a set of four cut-off rules (see SI1) to all studies from which CBI values were derived. Very small relative differences in harvest amounts between scenarios (denominator in Equation 1) may result in very high ratios and thus absolute values of the indicator and overemphasize changes in forest C stocks and factors other than the difference in harvest rate. We assessed the difference in harvest rates between scenarios compared and excluded CBI values of scenario pairs where the difference was lower than 5% from the highest harvest rate (cut-off rule 1). In addition, there are assumptions on forest growth that can influence the difference in forest carbon balances between scenarios (numerator in Equation 1). In particular, applying synthetic fertilization or planting faster growing tree species in more intensive harvest scenarios boost tree growth in the short-, mid- or long-term, and may compensate the loss in carbon balances compared to less intensive harvest scenario. In addition, assuming different climate conditions or differences in forest area in scenarios compared may influence CBI. In general, such scenario pairs are not suitable for assessing effects of different harvest intensities as they do not provide "ceteris paribus" conditions. To exclude such scenario pairs, we assessed if there were explicit differences between scenarios in fertilisation rate and/or tree species composition influencing tree growth (cut-off rule 2), in consideration of climate change effects (cut-off rule 3), and in forest area (cut-off rule 4), and excluded CBI values of scenario pairs for which one of the cut-off rule 1-4 held true.

3. Results

Calculation of CBI

A total of 44 studies out of more than 450 reviewed (SI1) presented sufficient data required for calculating CBI (Table 1). We calculated CBI for the selected time horizons by comparing two different, i.e., more and less intensive harvest scenarios to each other. These scenarios represent, for example, no harvest, continuation of some sort of business as usual and intensification or extensification of harvest rates from a given reference level.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

In all scenario comparisons the less intensive scenario was considered as reference, independent of the original scenario description.

Considering separately short-, mid-, and long-term time horizons, 231 CBI values were calculated (Table 1) for a wide range of different scenarios, geographical scopes, forest types and time horizons (SI1, 2). Considering all data, average values observed for CBI were 0.99 (std 1.94), 1.13 (std 5.51) and 1.54 (std 2.68) for short-, mid-, and long-term time-horizons (Table 1).

In order to analyse how much exceptionally low (i.e. negative) or high (i.e. significantly higher than 1) values influence both the average values and standard deviation, we applied the statistical cut-off method (see Methods). This reduced the number of calculated CBI values by less than 10%. The corresponding average values of CBI were 1.33 (std 0.81), 1.78 (std 1.12) and 1.23 (std 0.90) for short-, mid- and long-term time-horizons. Consequently, the statistical cut-off decreased the number of negative CBI values and significantly reduced standard deviation in all classes, especially in mid-term where standard deviation was the highest before the cut-off. (Table 1)

Table 1. Number of studies and CBI values for short- (1-30a), mid- (31-70a) and long-term (71-100a) time horizons in terms of tc/tc.

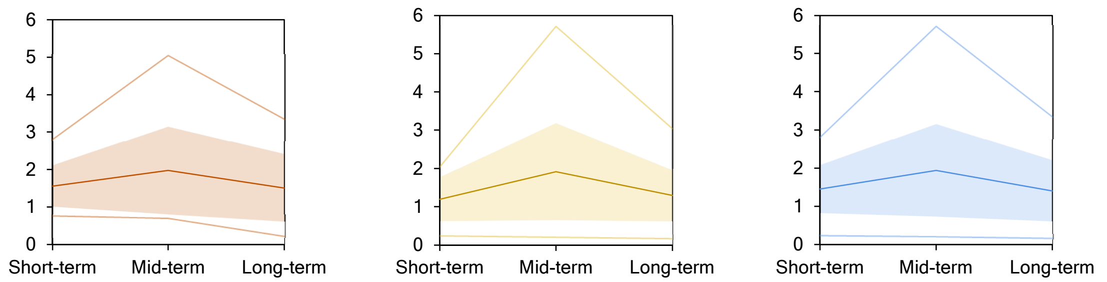
		Short-term	Mid-term	Long-term	Total / All
All data	Number of studies	29	27	25	44
	Number of CBI values	80	86	65	231
	CBI average value	0,99	1.13	1.54	1.20
	CBI median value	1.29	1.51	1.24	1.31
	CBI standard deviation	1.94	5.51	2.68	3.82
	Minimum CBI value	-7.85	-40	-5.04	-40
	Maximum CBI value	4.3	23.38	17.70	23.38
	No. negative values	9	11	5	25
Statistical cut-off	Number of CBI values	73	74	62	209
	CBI average value	1.33	1.78	1.23	1.46
	CBI median value	1.36	1.57	1.23	1.36
	CBI standard deviation	0.81	1.12	0.90	0.98
	Minimum CBI value	-0.83	-0.59	-1.04	-1.04
	Maximum CBI value	3.05	5.04	3.34	5.04
	No. negative values	4	2	4	10
Criteria-based cut-off	Number of CBI values	51	54	47	152
	CBI average value	1.41	1.95	1.41	1.60
	CBI median value	1.50	1.57	1.27	1.51
	CBI standard deviation	0.61	1.21	0.80	0.95
	Minimum CBI value	0.24	0.21	0.17	0.17
	Maximum CBI value	2.80	5.70	3.34	5.70
	No. negative values	0	0	0	0

In order to analyse how exclusion of CBI values, which explicitly are influenced by factors other than adequate difference in harvest rate, affects the average values and standard deviation, we applied predefined criteria-based cut-off rules (see Methods). This reduced the number of CBI values by roughly one third, to 152. The corresponding average values were 1.41 (std 0.61), 1.95 (std 1.21) and 1.41 (std 0.80) for short-, mid-, and long-term classes (Table 1).

Applying the criteria-based cut-off rules resulted in a similar set of datapoints as when applying statistical cut-off rule. This indicates that the extremely low (negative) and high values represent outliers in the data set and are most likely explained by factors other than differences in roundwood harvest rates (Table 1). The main difference between the statistical cut-off method and the exclusion criteria was that the exclusion criteria removed all the negative CBI values, while the statistical cut-off did not. Both cut-off methods revealed an increasing trend in average CBI values from short- to mid-term, and decreasing trend from mid- to long-term (Table 1) Similar temporal behaviour was also observed for single scenario comparisons (SI2 Fig. S4). (SI2,Fig. S4).

The development of average CBI values over time was found to be similar in the subsets of boreal geographies, temperate geographies and all studies (Fig. 1). Average values increased from short to mid-term and decreased from mid to long-term. In addition, long-term average CBI values were approximately at the same level compared to short-term values.

In most cases, studies presented multiple datapoints or a continuous time series which allowed the extraction and calculation of CBI in all time-classes resulting in trajectories as shown in Fig. 2 and SI Fig. S3 and S4. These studies provide a more consistent representation of the temporal development of CBI values as compared to Fig. 1. When comparing the short- to long-term development trajectories in Fig. 2, 44% of the scenario pairs decline over time, while 56% increase.



Max value	2.80	5.04	3.34	2.04	5.70	3.04	2.80	5.70	3.34
Average	1.56	1.98	1.51	1.20	1.92	1.29	1.41	1.95	1.41
Minimum value	0.76	0.69	0.22	0.24	0.21	0.17	0.24	0.21	0.17
Standard deviation	0.54	1.17	0.90	0.57	1.27	0.67	0.61	1.21	0.80
Data points (n)	28	26	25	21	28	22	51	54	47

Figure 1. Average, standard deviation (orange, yellow and blue zones) and min-max values for aggregated carbon balance indicator (CBI) values in terms of tc/tc from studies covering boreal geographies (left), temperate geographies (middle) and all studies (right). Only showing datapoints remaining when applying exclusion criteria.

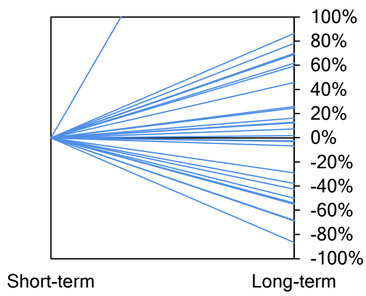


Figure 2. Percentage change in carbon balance indicator (CBI) value of scenario pairs (n=27) over short- to long-term time classes. Over time the CBI value declines for 12 pairs and increases for 15 pairs. The comparison is limited to scenario pairs for which CBI values in both short- and long-term time-classes were available after applying exclusion criteria.

4. Discussion

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

4.1. Factors influencing CBI

A large variation in CBI values derived from the studies reviewed were recognised. Our results show that time horizon and geographical region may influence the results although no clear conclusion on the sign can be drawn. Applying either statistical cut-off rule or our criteria-based cut-off rules narrowed down the variability in the results significantly when clear outliers were removed from the dataset. Such outliers are probably explained by factors other than difference in harvest rate which either strengthen or compensate the reduction in forest carbon stock due to increased harvest rate. Besides factors considered in our criteria-based cut-off, there are also other underlying factors that may influence the CBI values. These include methodological choices such as carbon pools considered (e.g., above-ground living biomass, above- and below-ground dead and living biomass, inclusion of litter and soil carbon pools), scenario-specific factors such as assumed forest management type (e.g., even-aged or continuous cover forestry) and harvesting type and intensity (e.g., final felling or thinning), and factors related to forest type and growth (e.g., tree species, soil type, fertility etc.). These factors were not analysed in this paper due to limitations in data availability that did not allow for a consistent analysis.

4.2. Temporal dynamics of CBI

We hypothesized that there would be a drop in CBI over time. However, based on the observed average CBI values both after statistical and criteria-based cut-off, as well as further divided into scenario pairs from single studies, the CBI value often increased from short- to mid-term, and decreased from mid- to long-term (Table 1, Fig. 1, 2, SI2 Tables S2 and S3). In some cases, the mid-term peak and the following drop could be explained by a reduction in carbon sink due to reduced growing stocks and partial compensation when new stands are established [21]. Nevertheless, as shown in Table 1 and Figure 2, there is no clear trend that would indicate a decrease in CBI values between the short- and long-term. In fact, there are several scenario pairs in which the indicator continuously increases over time [22–27]. Consequently, our hypothesis that CBI values would decline over time could not be confirmed given the time horizon (up to 100 years) considered. Because the temporal dynamics of CBI are dependent on the development of the forest carbon stocks in both scenarios compared, there could be multiple factors that contribute to the outcome. These include the development of harvest intensity, forest age structure, tree growth conditions, natural mortality and soil carbon balances.

4.3. Putting CBI in context

Substitution of non-renewable raw materials for wood results in the reduction of net GHG emissions only when reduction in forest carbon balances is lower than the combined effect of increase in carbon storage in harvested wood products and avoided fossil emissions due to increased wood use (**Error! Bookmark not defined.**). This requires a comparison of CBI values to unit-based increase in carbon remaining in harvested wood products and avoided fossil emissions (so called displacement factors, DFs). On average these two factors together provide carbon credits of roughly 0.7 units per each unit of carbon harvested from forest in the short-term (see Introduction) and less than that in mid- and long-term due to decarbonization of alternative products to be substituted (**Error! Bookmark not defined.**) and continuous release of carbon from harvested wood products [28]. The average CBI values (0.99-1.95) calculated in this paper as carbon debits were higher than the above-mentioned average carbon credits for all the time horizons considered. This implies an increase in atmospheric CO_2 concentrations due to increased wood use. Only options which generate more GHG credits than debits result in a net reduction of atmospheric GHG concentrations. Examples of such may be wood efficiently used for

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

construction and bioenergy employed with carbon capture and storage (**Error! Bookmark not defined.**).

Fehrenbach et al. [29] demonstrated in a case study for Germany that including CBI in GHG balances is relevant for climate policy. They found the effectiveness of GHG mitigation options involving wood use to be considerably reduced when accounting for impacts of roundwood removals on carbon stocks in forests assuming a CBI value of 0.25 to 1.15 t CO2/m^3 wood under German conditions.

4.4. Interpretation of CBI

Most studies reviewed focus on managed forests that typically have lower forest carbon stocks on average compared to natural forests [1,30]. While old-growth forests form important reservoirs of carbon and bear a high potential of not accelerating climate change if they are protected from logging, managed forests, especially with lower average age, provide significant potential for increasing carbon storage. The general effect of CBI can be illustrated by assuming a conceptual forest landscape with an even distribution of age-classes. In such a landscape, also referred to as "normal forest", every year the harvested area and volume is equal to the share of trees that reach maturity. In such a system carbon flows are in balance as carbon stocks are in equilibrium (**Error! Bookmark not defined.**). An increase in harvest rate in such a landscape would imply that the rotation time is shortened and a larger area is harvested each year. As trees live shorter after the management change, the overall landscape carbon stock is being reduced and will never catch up with the less intensive system because the new equilibrium after full rotation will form at a lower level (**Error! Bookmark not defined.**).

CBI shows how much forest carbon stock is reduced as a response of increased harvest rate over a studied time horizon. However, CBI should not be taken directly as a guide for how forests should be managed, which depends on various environmental, economic and social values preferred. For example, besides wood extraction and early revenues, forest thinning has the aim to improve wood quality of the remaining trees to achieve higher revenues per cubic metre from wood sales. If thinning is reduced to increase carbon stocks in forests [31], there can be negative impacts on wood quality. In addition, expected climate change impacts on forests and also management effects through not well adapted species distributions can form good reasons for reducing carbon stocks in forests temporarily to allow a transition to better adapted species compositions and thus to increase forest resilience and permanence of forest carbon stocks in the long-run. On the other hand, protection targets for maintaining biodiversity and cut down GHG emissions in the short run may counteract.

CBI shows the reduction in forest carbon stocks as a response to an increased harvest rate. However, it does not necessarily reflect other impacts of increased wood demand as market resposes that can be manyfold. Increased wood demand might thus lead to measures to increase wood supply outside the forest area considered, including increasing the area under forest management at the cost of unmanaged forests, afforestation or reforestation of unforested areas, boosting of tree growth by, e.g., applying fertilization or introducing more rapidly growing species (**Error! Bookmark not defined.**). Also, efficiency increases in wood use can be a response to increased wood demand. Such market-mediated effects may compensate partly the carbon debit effect related to an increased harvest rate. On the other hand, they may also result in the opposite direction. For example, afforestation of agricultural land may increase food prices that causes deforestation of primary forests for increasing agricultural land elsewhere [32]. This indicates that assessing overall impacts of increased wood demand beyond the forest area and effectiveness of wood use for climate change mitigation requires considering also market impacts and conditions (**Error! Bookmark not defined.**), given that they may be highly uncertain and sensitive to the assumptions made [33].

4.5. Further research needs

Clearly more useful scenario data is required. Overall, our systematic review enabled the calculation of CBI values from only a limited amount of studies representing limited geographical scope, forest types and harvest intensities. In an optimal case, a set of consistent scenarios would consider different external impacts (climate change, disturbances) in ceteris paribus, for assessing effects of each assumption. Such consistency is needed to identify and isolate the impact of roundwood harvest from other influencing factors.

Scenarios for significantly different harvest intensities, including total set-aside (no harvest) would be needed for reference. A challenge is that forest simulation models are usually not representative for unmanaged forests or very low harvest intensities. This is an important shortcoming of current forest management models and also due to a lack of data from unmanaged and recently abandoned forests of different type and stage for parametrisation. Climate and environmental change scenarios can help to disentangle effects of climate change and increasing disturbances that are expected to decrease the CBI value (assuming higher carbon stocks are more susceptible to disturbances), while climate and environmental effects such as CO_2-fertilisation, extension of growing season etc. could lead to higher CBI as forest biomass carbon saturation levels increase.

Climate effects of forests are not limited to changes in carbon balances but may be reinforced, counteracted or even offset by changes in surface albedo, land-surface roughness, biogenic volatile organic compound emissions, transpiration and sensible heat flux [34], the cloud albedo effects through atmospheric aerosol emissions from forests [35,36]. Moving from GHG accounting to full climate effect accounting requires still significant further research work.

5. Conclusions

We showed that across a broad range of forest management scenarios increased harvest intensity negatively affects carbon storage in forest over short-, mid- and long-time horizon. This holds true in all the cases when exceptional values explicitly influenced by factors other than the difference in harvest rate were removed. The carbon debit through reduction in forest carbon storage is significant compared with the GHG credits generated by wood use in technosphere. Our estimates provide default values for effects of increased roundwood removals on forest carbon stocks valid for temperate and boreal forests that can directly be included in GHG balances of products or assessment of mitigation policies and measures related to wood use, if more representative information is not available.

Author Contributions: The work of SS, JN and ST was funded by Kone Foundation.

Authors of Oeko-Institut that contributed to this paper received funding through the LANDMARC project under the European Union's Horizon 2020 Research and Innovation Programme, grant agreement No 869367 and through the BioSINK project funded by the German Environment Agency, FKZ 3720 43 502 0.

Authors contributions: S.S. and H.B. developed conception and design of the paper. S.S, H.B., J.N., F.M., S.T. K.J.H., J.R. and H.F. collected and analysed the reviewed studies. S.S., J.N., and F.M. analysed the data, all authors were involved in the interpretation of results and discussion of findings. S.S., H.B., J.N., F.M. and S.T. drafted the manuscript.

Supplementary information: Articles included in the systematic review, selected for 2nd round of review, selected for calculation of carbon balance indicators, and data for carbon balance indicators (SI1).

Additional information on carbon balance indicator values calculated (SI2)The authors declare no conflict of interest.

References

1. Erb, K.H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M. and Pongratz, J., 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature, 553(7686), pp.73-76.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

2. Pingoud, K., Ekholm, T., Sievänen, R., Huuskonen, S. and Hynynen, J., 2018. Trade-offs between forest carbon stocks and harvests in a steady state–A multi-criteria analysis. Journal of environmental management, 210, pp.96-103.

3. Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A. and Fargione, J., 2015. Bioenergy and climate change mitigation: an assessment. Gcb Bioenergy, 7(5), pp.916-944.

4. Lauri, P., Forsell, N., Korosuo, A., Havlík, P., Obersteiner, M. and Nordin, A., 2017. Impact of the 2 C target on global woody biomass use. Forest Policy and Economics, 83, pp.121-130.

5. Cowie, A.L., Berndes, G., Bentsen, N.S., Brandão, M., Cherubini, F., Egnell, G., et al. Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. GCB Bioenergy, 00, 1–22 (2021).

6. Giuntoli, J., Searle, S., Jonsson, R., Agostini, A., Robert, N., Amaducci, S., Marelli, L. and Camia, A., 2020. Carbon accounting of bioenergy and forest management nexus. A reality-check of modeling assumptions and expectations. Renewable and Sustainable Energy Reviews, 134, p.110368.

7. Agostini, A., Giuntoli, J., Boulamanti, A., Marelli, L. (2014). Carbon accounting of forest bioenergy. Conclusions and recommendations from a critical literature review. Report EUR 25354 EN. Publications Office of the European Union, Luxembourg. doi:10.2788/29442, https://publications.jrc.ec.europa.eu/repository/handle/JRC70663

8. Forests in focus. Nat. Clim. Chang. 11, 363 (2021). https://doi.org/10.1038/s41558-021-01050-5

9. Pingoud, K., Pohjola, J. and Valsta, L., 2010. Assessing the integrated climatic impacts of forestry and wood products. Silva Fennica, 44(1), pp.155-175.

10. Soimakallio, S., Kalliokoski, T., Lehtonen, A. and Salminen, O., 2021. On the trade-offs and synergies between forest carbon sequestration and substitution. Mitigation and Adaptation Strategies for Global Change, 26(1), pp.1-17.

11. Zhang, X., Chen, J., Dias, A.C. and Yang, H., 2020. Improving Carbon Stock Estimates for In-Use Harvested Wood Products by Linking Production and Consumption—A Global Case Study. *Environmental Science & Technology*, *54*(5), pp.2565-2574.

12. Leturcq, P., 2020. GHG displacement factors of harvested wood products: the myth of substitution. *Scientific reports*, *10*(1), pp.1-9.

13. Myllyviita, T., Soimakallio, S., Judl, J. and Seppälä, J., 2021. Wood substitution potential in greenhouse gas emission reduction–review on current state and application of displacement factors. *Forest Ecosystems*, *8*(1), pp.1-18.

14. Hurmekoski, E., Smyth, C., Stern, T., Verkerk, P.J. and Asada, R., 2021. Substitution impacts of wood use at the market level: A systematic review. Environmental Research Letters.

15. Pingoud, K., Ekholm, T. and Savolainen, I., 2012. Global warming potential factors and warming payback time as climate indicators of forest biomass use. Mitigation and Adaptation Strategies for Global Change, 17(4), pp.369-386.

16. Holtsmark, B., 2013. The outcome is in the assumptions: analyzing the effects on atmospheric CO 2 levels of increased use of bioenergy from forest biomass. Gcb Bioenergy, 5(4), pp.467-473.

17. Pingoud, K., Ekholm, T., Soimakallio, S. and Helin, T., 2016. Carbon balance indicator for forest bioenergy scenarios. Gcb Bioenergy, 8(1), pp.171-182.

18. Tranfield, D., Denyer, D. and Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British journal of management, 14(3), pp.207-222.

19. Xiao, Y. and Watson, M., 2019. Guidance on conducting a systematic literature review. Journal of Planning Education and Research, 39(1), pp.93-112.

20. Soimakallio, S., Saikku, L., Valsta, L. and Pingoud, K., 2016. Climate Change Mitigation Challenge for Wood Utilization - The Case of Finland. *Environmental science & technology*, *50*(10), pp.5127-5134.

21. Griess, V.C., Man, C.D., Leclerc, M.E., Tansey, J. and Bull, G.Q., 2019. Carbon stocks and timber harvest. Alternative policy approaches for the Great Bear rainforest and their consequences. Forest Policy and Economics, 103, pp.147-156.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 March 2022 doi:10.20944/preprints202203.0198.v1

22. Heinonen, T., Pukkala, T., Mehtätalo, L., Asikainen, A., Kangas, J. and Peltola, H., 2017. Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry. Forest Policy and Economics, 80, pp.80-98.
23. Pukkala, T., 2018. Carbon forestry is surprising. Forest Ecosystems, 5(1), pp.1-11.
24. Seppälä, J., Heinonen, T., Pukkala, T., Kilpeläinen, A., Mattila, T., Myllyviita, T., Asikainen, A. and Peltola, H., 2019. Effect of increased wood harvesting and utilization on required greenhouse gas displacement factors of wood-based products and fuels. Journal of environmental management, 247, pp.580-587.
25. Jandl, N., Jandl, R. and Schindlbacher, A., 2018. Future management options for cembran pine forests close to the alpine timberline. Annals of forest science, 75(3), pp.1-12.
26. Blattert, C., Lemm, R., Thürig, E., Stadelmann, G., Brändli, U.B. and Temperli, C., 2020. Long-term impacts of increased timber harvests on ecosystem services and biodiversity: A scenario study based on national forest inventory data. Ecosystem Services, 45, p.101150.
27. Skytt, T., Englund, G. and Jonsson, B.G., 2021. Climate mitigation forestry—temporal trade-offs. Environmental Research Letters, 16(11), p.114037.
28. Rüter, S., Matthews, R.W., Lundblad, M., Sato, A., Hassan, R.A. 2019. 12 Harvested wood products (HWP). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use.
29. Fehrenbach, H.; Bischoff, M.; Böttcher, H.; Reise, J.; Hennenberg, K.J. The Missing Limb: Including Impacts of Biomass Extraction on Forest Carbon Stocks in GHG Balances of Wood Use. *Preprints* 2021, 2021120499.
30. Harmon, M. E.; Ferrell, W. K.; Franklin, J. F. (1990): Effects on carbon storage of conversion of old-growth forests to young forests. Science 247 (4943), S. 699–702.
31. Pretzsch, H., 2009. Forest dynamics, growth, and yield. In Forest dynamics, growth and yield, pp. 1-39. Springer, Berlin, Heidelberg.
32. Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R. and Plevin, R., 2015. Do biofuel policies seek to cut emissions by cutting food?. Science, 347(6229), pp.1420-1422.
33. Plevin, R.J., Jones, A.D., Torn, M.S. and Gibbs, H.K., 2010. Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated.
34. Luyssaert, S., Marie, G., Valade, A., Chen, Y.Y., Djomo, S.N., Ryder, J., Otto, J., Naudts, K., Lansø, A.S., Ghattas, J. and McGrath, M.J., 2018. Trade-offs in using European forests to meet climate objectives. Nature, 562(7726), pp.259-262.
35. Spracklen, D.V., Bonn, B. and Carslaw, K.S., 2008. Boreal forests, aerosols and the impacts on clouds and climate. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366(1885), pp.4613-4626.
36. Cerasoli, S., Yin, J. and Porporato, A., 2021. Cloud cooling effects of afforestation and reforestation at midlatitudes. Proceedings of the National Academy of Sciences, 118(33).