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REVIEW

Closing an open balance: The impact of increased tree harvest on forest carbon

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Abstract

Fossil-based emissions can be avoided by using wood in place of non-renewable raw materials as energy and materials. However, wood harvest influences forest carbon stocks. Increased harvest may reduce the overall climate benefit of wood use significantly, but is widely overlooked. We reviewed selected simulation studies and compared differences in forest carbon and amount of wood harvested between harvest scenarios of different intensities for three different time perspectives: short- (1–30 years), mid- (31–70 years), and long-term (71–100 years). Out of more than 450 reviewed studies 45 provided adequate data. Our results show that increased harvest reduces carbon stocks over 100 years in temperate and boreal forests by about 1.6 (stdev 0.9) t_C per t_C harvested (referred to as carbon balance indicator (CBI)). CBI proved to be robust when outliers explicitly influenced by factors other than changes in the harvest rate, such as fertilization or increase in forest area, were removed. The carbon impacts tend to be greatest in the mid-term, but no significant difference in was found for average values between short and long time-horizons. CBI can be interpreted as carbon opportunity costs of wood harvest in forests. Our results indicate that even after 100 years, CBI is significant compared to the typical GHG credits expected in the technosphere by avoiding fossil emissions in substitution and increasing carbon stocks in harvested wood products. Our estimates provide typical values that can directly be included in GHG balances of products or assessments of mitigation policies and measures related to wood use. However, more systematic scenarios with transparent information on influencing factors for forest carbon stocks are required to provide better constrained estimates for specific forest types.

KEYWORDS

climate change mitigation, forest carbon, forest management, life cycle assessment, modelling, scenarios, tree harvest

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1 | INTRODUCTION

In climate change mitigation, forests have 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 (Erb et al., 2018). 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 (Pingoud et al., 2018). Climate change mitigation strategies often promote increasing wood use from a given reference level to substitute fossil-based raw materials (Creutzig et al., 2015; Lauri et al., 2017). However, as it is common practice in life cycle assessment that forest biomass derived from managed forests is considered carbon neutral (Agostini et al., 2014; Cowie et al., 2021; Giuntoli et al., 2020), the trade-off between increasing wood harvest and storing carbon in forests has not attracted the required focus in the discussion of the role of forest use in climate change mitigation (Forests in focus, 2021). This trade-off may last for decades, or even become permanent, if the increase in harvest is sustained and leads to overall lower forest carbon stocks (Pingoud et al., 2018).

Increased wood use can help mitigate climate change if the GHG emissions avoided exceed the GHG emissions generated (Pingoud et al., 2010). 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 (Soimakallio et al., 2021). The credits in the technosphere are highly dependent on the way wood is used and the related assumptions on carbon permanency in products (Zhang et al., 2020) and alternative raw materials substituted (Leturcq, 2020; Myllyviita et al., 2021). Globally, approximately 40% of the roundwood harvest ends up as harvested wood products (Lauri et al., 2017). However, only 44% of the carbon in harvested wood products produced between 1992 and 2015 remained in 2015 (Zhang et al., 2020), 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 (Hurmekoski et al., 2021).

While impacts of increased tree harvest on forest carbon stocks have been assessed under specific scenario conditions (e.g. Holtsmark, 2013; Pingoud et al., 2012, 2016), 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 review. We synthesize existing knowledge from the found and relevant set of scenario studies on how forest carbon balances react in short- (1–30 years), mid- (31–70 years) and long-term (71–100 years) when cutting of living trees and tree harvest rates are increased compared to a reference. We hypothesize that (1) increased tree harvest rate from a given reference level reduces the forest carbon balances (i.e. less carbon is sequestered), 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

Papers containing relevant information for our aim consider at least two forest management scenarios and provide data on the development of forest carbon stocks and harvest volumes of trees over a certain relevant time horizon. Papers only focusing on the intensification of logging residue or other dead wood harvest were excluded. A selected set of papers were reviewed, and those found to be relevant were included in a database that would enable the comparison of studies across regions, countries and biomes. In total, CBI values for 233 scenario pairs were calculated from 45 publications. This set was carried out in the following steps:

1. Multiple literature searches were carried out using various types of relevant keywords such as "forest," "carbon," "scenarios," "harvest" and browsing some of the hits of whose title seemed promising, to know if they contained relevant data. If relevant data were found, paper was included in the review. Iterations showed that differences in goal setting, research questions, selected approach, and style of reporting resulted in that only a few studies could be considered relevant. In addition, papers that were known in advance by the authors to include relevant data were collected. In total, 33 papers were added (Blattert et al., 2020; Böttcher et al., 2008, 2018; Chen et al., 2018; Gustavsson et al., 2021; Gutsch et al., 2018; Härtl et al., 2017; Heinonen et al., 2017; Helin et al., 2016; Holtsmark, 2012; Hynynen et al., 2015; Jandl, Ledermann, et al., 2018; Jevšenak et al., 2020; Knauf et al., 2015; Krause et al., 2020; Leskinen et al., 2020; Mund et al., 2015; Oehmichen et al., 2018; Olguin et al., 2018; Pang et al., 2017; Pilli et al., 2017;

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Pingoud et al., 2016; Pukkala, 2017; Pukkala, 2018; Rüter et al., 2016; Seidl et al., 2007; Seppälä et al., 2019; Skytt et al., 2021; Smyth et al., 2014; Soimakallio et al., 2016, 2021; Valade et al., 2018; Zubizarreta-Gerendiain, Pukkala, & Peltola, 2016) in step 1.

2. A systematic literature review (SLR) (Tranfield et al., 2003) was carried out. SLR was chosen to complement the list of the relevant research papers from large mass and to minimise a possible bias in the results due to the authors' choice of papers. We followed good practice guidance to conduct SLR (Xiao & Watson, 2019). Publications were systematically selected from external data research. More precisely, information came from secondary data 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 carried out in July 2020 and was limited to the most recent publications that appeared between the years 2016 and 2020. After testing multiple different combinations (SI1), the following query was used: "FOREST MANAGEMENT SCENARIOS" AND "CARBON." The chosen query returned a practical number 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 a total of 2,280,000 documents and "FOREST MANAGEMENT" AND "CARBON" 267,000 documents. With time limitations of 2016–2020, the results were still 203,000 for "FOREST" AND "CLIMATE CHANGE" and 22,600 for "FOREST MANAGEMENT" AND "CARBON" (SI1).
3. In the first selection from SLR, 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. A short list of altogether 79 publications was created for studying the entire publication (out of which 9 publications were not available). To be selected for further calculations, the publication had to contain explicit and transparent data for both forest carbon stock or sink and tree harvest rate (except those considering only logging residue harvest) for at least two different forest management scenarios for at least one time horizon. It turned out that many promising papers that we found through the keyword search excluded the required information and the transparency needed to extract the information necessary for the analysis. Altogether 14 articles found from SLR were concluded to provide the required data and 12 of them (Baskent, 2019; Baul et al., 2017; Bösch et al., 2017; Creutzburg et al., 2017; Diaz et al., 2018; Dong et al., 2018; Griess et al., 2019; Gustavsson et al., 2017; Jandl, Jandl, & Schindlbacher, 2018; Li et al., 2019; Satir, 2018; Zubizarreta-Gerendiain, Garcia-Gonzalo, et al., 2016) were added in step 3 (2 were added already in step 1).

2.2 | Definition of carbon balance indicator (CBI)

We characterized the impact of increased tree harvest on forest carbon using the carbon balance indicator (CBI), initially presented by Pingoud et al. (2016). 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 tree biomass $\Delta C_{harvest}(T)$ over a certain given time horizon T between two scenarios of different harvest intensities. It can potentially include different fractions of forest biomass, i.e., above- and below-ground living biomass, dead wood, litter, as well as soil carbon.

The carbon balance indicator (CBI) is calculated using the following equation (1):

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

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 $\Delta C_{harvest}(T) > 0$ (16). 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 one implies that the forest carbon stock is reduced by exactly the amount of carbon that is harvested. It can be expected that CBI(T) value exceeds one in the short run. This is because any harvest of living and growing trees at least temporarily decreases tree growth. In addition, branches, stumps, roots etc., are typically not (at least totally) removed from the forest. In this case, harvest of trees results in decaying of them, thus carbon dioxide emissions (Pingoud et al., 2016; Soimakallio et al., 2016). On the other hand, CBI(T) should decline in time 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 (at least for above- and below-ground living biomass) and harvest amounts (total tree removals including thinning and final fellings) for the scenarios were extracted. The selected studies included different forest carbon pools, ranging from above- and below-ground living biomass only to living above- and below-ground biomass and dead wood and studies including above- and below-ground living biomass, dead wood, litter, and soil carbon.

For data extraction, we used one or a combination of the following methods:

1. CBI value explicitly provided in a 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.

In case data was not available on an annual basis, linear development was assumed between data points, which might cause some error in case the modelled development of forest carbon stocks or tree harvest rates varies significantly in cumulative terms from that of linear development. However, there is no reason to assume this error would be significant. In addition, there is a margin of human error in the third 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 using the constant ratio $0.2\,t_C/m^3$.

2.4 | Statistical cut-off method

For some scenario pairs analysed, very small differences in harvest rates between the scenarios led to the denominator approaching zero (CBI = Δforest carbon/Δharvest). 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 the 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 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 the 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 are 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 seldom passed our 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 factors other than the difference in tree 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. In studies where the harvest data had to be extracted from graphs, 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), to prevent extraction error becoming the definitive factor in the CBI value. 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, potentially at the cost of increased nutrient leaching and toxic effects on micro-organisms, or planting faster growing tree species, potentially at the cost of reduced wood density 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 the effects of different harvest intensities as they do not provide “ceteris paribus” conditions. To exclude such scenario pairs, we assessed if the studies included clearly and transparently differences between scenarios in fertilisation rate and/or growth rate of planted tree species (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 at least one of the cut-off rules 1–4 held true.

2.6 | Statistical testing

An unpaired two-sample *t*-test was used to analyse differences in CBI values between the sample groups. The significance threshold was set at 0.05.

3 | RESULTS

3.1 | Calculation of CBI

A total of 45 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, the continuation of some sort of business as usual and intensification or extensification of harvest rates from a given reference level. In all scenario comparisons the less intensive scenario was considered reference, independent of the original scenario description.

Considering separately short-, mid-, and long-term time horizons, 233 CBI values were calculated (Table 1) for various different scenarios, geographical scopes, forest types and time horizons (SI1 and 2). Considering all data, average values observed for CBI were 1.02 (std 1.92), 1.13 (std 5.51) and 1.54 (std 2.68) for short-, mid-, and long-term time-horizons (Table 1).

3.2 | Applying different cut-off methods

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 1.34 (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).

To analyse how the 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 Section 2). This reduced the number of CBI values by roughly one-third, to 154. The corresponding average values were 1.43 (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 the statistical cut-off rule. This indicates that the extremely low (negative) and high values represent outliers in the dataset and are most likely explained by factors other than differences in tree 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 the short- to mid-term, and a decreasing trend from the mid- to long-term (Table 1). Similar temporal behaviour was also observed for single scenario comparisons (SI2, Figure S4).

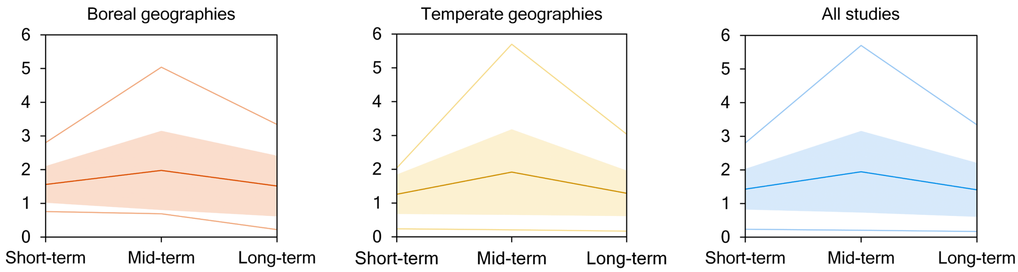
The development of average CBI values over time was found to be similar in the subsets of boreal geography, temperate geographies and all studies (Figure 1). Average values increased from short to mid-term and decreased from mid to long-term. In addition, there was no significant difference in CBI values between long- and short-term groups ($p = 0.89$) considering all studies. The differences in CBI values between short- and mid-term and mid- and long-term were significant, ($p = 0.006$) and ($p = 0.009$), respectively. Although no significant differences in CBI values between boreal and temperate geographies were found in short- ($p = 0.06$), mid- ($p = 0.86$), or long-term ($p = 0.33$) groups, the average CBI value in temperate geographies was lower in short-term, and the difference would have been significant if the threshold of 10% had been chosen.

3.3 | Development of CBI over time

In most cases, studies presented multiple datapoints or a continuous time series that allowed the extraction and calculation of CBI in all time-classes resulting in trajectories as shown in Figure 2 and SI Figures S3 and S4. These studies provide a more consistent representation of the temporal development of CBI values as compared with Figure 1. When comparing the short- to long-term development

TABLE 1 A number of studies and CBI values for short- (1–30a), mid- (31–70a) and long-term (71–100a) time horizons in terms of t_C/t_C.

	Short-term	Mid-term	Long-term	Total/All
All data				
Number of studies	30	27	25	45
Number of CBI values	82	86	65	233
CBI average value	1.02	1.13	1.54	1.21
CBI median value	1.33	1.51	1.24	1.32
CBI standard deviation	1.92	5.51	2.68	3.80
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	75	74	62	211
CBI average value	1.34	1.78	1.23	1.46
CBI median value	1.41	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	53	54	47	154
CBI average value	1.43	1.95	1.41	1.60
CBI median value	1.51	1.57	1.27	1.51
CBI standard deviation	0.61	1.21	0.80	0.94
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



	Boreal Short-term	Boreal Mid-term	Boreal Long-term	Temperate Short-term	Temperate Mid-term	Temperate Long-term	All Short-term	All Mid-term	All Long-term
Maximum 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	1.26	1.92	1.29	1.43	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	0.58	1.27	0.67	0.61	1.21	0.80
Data points	28	26	25	23	28	22	53	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 t_C/t_C from studies covering boreal geographies (left), temperate geographies (middle) and all studies (right). Only showing the datapoints remaining when applying the exclusion criteria.

trajectories in Figure 2, 44% of the scenario pairs decline over time, while 56% increase. When comparing average CBI values derived from the studies found from the SLR (step 3) to those added in step 1 (two studies added in step 1 but also found in SLR were considered here under SLR), there was no significant difference (SI2).

4 | DISCUSSION

4.1 | Factors influencing the CBI

A large variation in CBI values derived from the studies reviewed were recognised. Our results show that the time

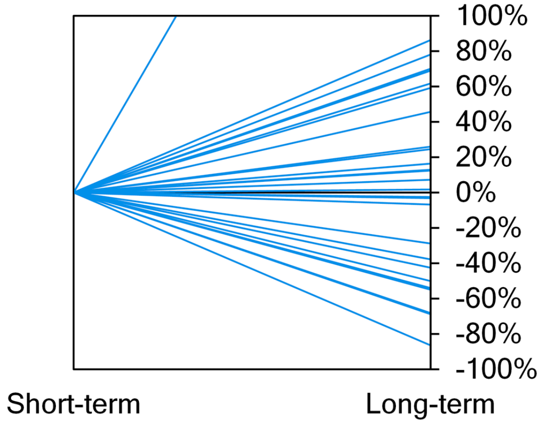


FIGURE 2 Percentage change in carbon balance indicator (CBI) value of scenario pairs ($n = 27$) over short- to long-term time classes. Over time, the CBI value declines for 12 pairs and increases for 15 pairs. The comparison is limited to scenario pairs for which CBI values in both short- and long-term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

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 significantly narrowed down the variability in the results when clear outliers were removed from the dataset. Such outliers are probably explained by factors other than differences in harvest rate, which either strengthen or compensate for the reduction in forest carbon stock due to increased harvest rate. Besides the factors considered in our criteria-based cut-off rules, there are 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.). To assess the influence of carbon pools included, we compared studies that included living above- and below-ground biomass (LBM), living and dead biomass (BM), and biomass and soil carbon (BMS) and calculated CBI separately for each group (see Table S6). We found no significant differences (with significance threshold at 0.05) in CBI value characteristics between differing forest carbon pools accounted for in the studies (see Table S7). However, if the threshold had been set to 0.10, there would have been significant difference in long-term value between BM and BMS ($p = 0.07$), with the average CBI value being 44% higher in BMS. This shows that at least in short- and mid-term CBI is largely affected by changes in carbon stocks in living biomass, while changes in harvest intensity seem to affect dead wood and soil carbon pools to a smaller degree. However, in the long-term the significance of inclusion of the soil carbon pool was sensitive to the threshold chosen. Other influencing factors were not analysed as the original studies either did not provide sufficient information on the factors that would be required for assessing their influence on the results or the factors could not be grouped consistently across the different studies, e.g., forest management types because of varying definitions.

In some studies (Gustavsson et al., 2021; Holtsmark, 2012; Hynynen et al., 2015; Pang et al., 2017; Pingoud et al., 2016; Soimakallio et al., 2016, 2021) and scenario pairs (after cut-off criteria 19%, 4% and 11% of the CBI values calculated for short, mid and long-term), there was to some extent difference in the harvest rate of logging residues along with the harvest rate of living trees (SI1). This likely influences the value of CBI derived from such studies, as logging residues decay and cause CO_2 emissions over time in the reference scenario. Thus, CBI value related to increased harvest of logging residues only tends to be less than 1 (Pingoud et al., 2016), and the overall CBI value for increased tree harvest (living trees and logging residues) becomes smaller than that for increased living tree harvest only. The average CBI value for scenario pairs derived from these studies was 1.7, 1.5 and 1.0 for short, mid and long time-horizon. This is higher for short and lower for mid and long time-horizon compared to the averages after applying cut-off criteria (Table 1). However, as there are other factors influencing the CBI results simultaneously, it is difficult to conclude how much inclusion of increased logging residue harvest in the scenario pairs exactly affected.

No significant deviation was found between the CBI values derived from the studies included based on the SLR and those added outside the SLR (SI2). This implies that addition of more data into our dataset is not expected to change the results significantly.

4.2 | Temporal dynamics of the 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 group of studies from boreal and temperate regions, and into landscape and national level studies, the CBI value often increased from short- to mid-term, and decreased from mid- to long-term (Table 1, Figures 1 and 2, SI2, SI4, Tables S2, S4, and S5). In some cases, the mid-term peak and the following drop could be explained by a reduction in the carbon sink due to reduced growing stocks and partial compensation when new stands are established (Griess et al., 2019). 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 (Blattert et al., 2020; Heinonen et al., 2017; Jandl, Jandl, & Schindlbacher, 2018; Pukkala, 2018; Seppälä et al., 2019; Skytt et al., 2021). 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 depend 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 into context

Substitution of non-renewable raw materials for wood results in the reduction of net GHG emissions only when the 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 (Soimakallio et al., 2021). 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 the mid- and long-term due to decarbonization of alternative products to be substituted (Leturcq, 2020) and continuous release of carbon from harvested wood products (Rüter et al., 2019). The average CBI value (1.60 ± 0.95, for all time-horizons after criteria-based cut-off) calculated in this paper as a carbon debit is most likely higher than the above-mentioned average carbon credits. This implies that an increase in wood use leads on average to an increase in atmospheric CO_2 concentrations. Only options, which generate more GHG credits than debits result in a net reduction in atmospheric GHG concentrations. Examples of such may be wood efficiently used for construction and bioenergy employed with carbon capture and storage (Soimakallio et al., 2021).

Fehrenbach et al. (2021) 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 the impacts of tree harvest on carbon stocks in forests assuming a CBI value of 0.25–1.15 $t\,CO_2/m^3$ (~0.34–1.57 t_C/t_C with conversion factor of 0.2 t_C/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 (Erb et al., 2018; Harmon et al., 1990). 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 a 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 (Pingoud et al., 2018). 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 a full rotation will form at a lower level (Pingoud et al., 2018).

CBI shows how much forest carbon stock is reduced as a response to increased harvest rate over a study 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 and growth of the remaining trees to achieve higher revenues per cubic metre from wood sales. In addition, expected climate change impacts on forests and management effects through not well-adapted species distributions can be 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 cutting down GHG emissions in the short run may counteract.

CBI shows the reduction in forest carbon stocks as a response to increased harvest rate. However, it does not necessarily reflect other impacts of increased wood demand as market responses 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 (Cowie et al., 2021). Also, the efficiency increases in wood use can be a response to increased wood demand. Such market-mediated effects may partly compensate for 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 (Searchinger et al., 2015). This indicates that assessing the overall impacts of increased wood demand beyond the forest area and the effectiveness of wood use for climate change mitigation requires considering also market impacts and conditions (Cowie et al., 2021), given that they may be highly uncertain and sensitive to the assumptions made (Plevin et al., 2010).

4.5 | Further research needs

Overall, our review enabled the calculation of CBI values from only a limited number of studies representing limited geographical scope, climatic conditions, forest types and harvest intensities. Thus, clearly more scenario data would be required to improve such coverage. 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 tree 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 the forest management simulation models used in the studies we reviewed are usually not representative for unmanaged forests or very low harvest intensities. This applies for models built on yield table and models using inventory data of managed forest for parametrisation or calibration (e.g. Hynynen et al., 2015; Seppälä et al., 2019; Soimakallio et al., 2021). This is an important shortcoming of current forest management models and due to lack of data from unmanaged and recently abandoned forests of different types and stages for parametrisation. Climate and environmental change scenarios can help disentangle the 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 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 (Luyssaert et al., 2018), and the cloud albedo effects through atmospheric aerosol emissions from forests (Cerasoli et al., 2021; Spracklen et al., 2008). However, moving from GHG accounting to full climate effect accounting still requires significant further research work.

5 | CONCLUSIONS

We show that across a broad range of forest management scenarios, increased harvest intensity negatively affects carbon storage in forests over short-, mid- and long-time horizon. This holds true after excluding studies that included influencing factors other than only the difference in harvest rate. The carbon debit through increased logging is significant compared to the GHG credits generated through wood use in the technosphere (i.e. substitution of fossil emissions and increase in carbon storage of harvested wood products). Our estimates provide average values for the effects of increased tree harvest on forest carbon stocks valid for temperate and boreal forests that can directly be included in GHG balances of products or assessments of mitigation policies and measures involving wood use, if more representative information is not available.

AUTHOR CONTRIBUTIONS

Sampo Soimakallio and Hannes Böttcher developed conception and design of the paper. Sampo Soimakallio, Hannes Böttcher, Jari Niemi, Fredric Mosley, Sara Turunen, Klaus Josef Hennenberg, Judith Reise and Horst Fehrenbach collected and analysed the reviewed studies. Sampo Soimakallio, Jari Niemi, and Fredric Mosley analysed the data. All authors were involved in the interpretation of results and discussion of findings. Sampo Soimakallio, Hannes Böttcher, Jari Niemi, Fredric Mosley and Sara Turunen drafted the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Zenodo 10.5281/zenodo.6607287.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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