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Estimating net climate impacts of timber production and utilization in fossil fuel intensive material and energy substitution

Ashraful Alam, Harri Strandman, Seppo Kellomäki, and Antti Kilpeläinen

Abstract: We utilized an ecosystem model and life cycle assessment tool for studying carbon flows between the ecosystem, technosystem, and atmosphere for scenarios utilizing forest biomass (biosystem) against fossil fuel intensive materials (fossil system). The net climate impacts were studied for a Norway spruce (*Picea abies* (L.) Karst.) stand over two consecutive rotation periods (2 × 80 years) in the boreal conditions in central Finland (62°N, 29°E). The effects of alternative forest management on the carbon dynamics in the biosystem were studied in comparison with the fossil system by using an unmanaged and baseline thinning regime. The results showed that the biosystem produced carbon benefits compared with the similar system with the use of fossil fuel intensive materials and energy. The unmanaged stand stored the highest amount of carbon and retained carbon the longest when solely the ecosystem was considered. Studying the ecosystem and the technosystem together, the biosystem was found effective in storing and increasing the residence of carbon with or without changing the life span of biomass-based products. We found that the increase of the life span of biomass-based products could reduce emissions up to 0.28 t $CO_2 \cdot ha^{-1} \cdot year^{-1}$ depending on the management regimes over the study period. The increased stocking regimes could increase negative net climate impact by 47% over the study period compared with the use of baseline thinning in the biosystem. The proper climate mitigation strategies should consider the benefits from forest management and forest biomass in storing carbon into both the ecosystem and technosystem.

Key words: forest management, life cycle assessment, materials, substitution, timber, net climate impact.

Résumé : Nous avons utilisé un modèle écosystémique et un outil d'analyse du cycle de vie pour étudier les flux de carbone entre l'écosystème, le techno-système et l'atmosphère pour des scénarios utilisant la biomasse forestière (biosystème) plutôt que des matériaux voraces en combustibles fossiles (système fossile). Les impacts nets du climat ont été étudiés pour un peuplement d'épicéa commun (*Picea abies* (L.) Karst.) pendant deux rotations consécutives (2 × 80 ans) dans le centre de la Finlande (62°N, 29°E). Les effets d'un aménagement forestier alternatif sur la dynamique du carbone dans le biosystème ont été étudiés comparativement au système fossile en utilisant un régime d'éclaircie correspondant à la pratique courante et un régime sans aménagement. Les résultats ont montré que le biosystème a été bénéfique en termes de carbone comparativement au système semblable utilisant de l'énergie et des matériaux voraces en combustibles fossiles. Le peuplement non aménagé a emmagasiné la plus grande quantité de carbone et retenu le carbone le plus longtemps lorsqu'on tenait compte seulement de l'écosystème. En étudiant simultanément l'écosystème et le techno-système, le biosystème s'est avéré efficace pour séquestrer et augmenter le temps de séjour du carbone en changeant ou non la durée de vie des produits à base de biomasse. Nous avons trouvé que l'augmentation de la durée de vie des produits à base de biomasse pouvait réduire les émissions jusqu'à 0,28 t $CO_2 \cdot ha^{-1} \cdot an^{-1}$ dépendamment du régime d'aménagement durant la période étudiée. Les régimes qui augmentaient la densité pouvaient accroître l'impact négatif net du climat de 47 % au cours de la période étudiée comparativement à l'utilisation d'une éclaircie conventionnelle dans le biosystème. Les stratégies appropriées d'atténuation du climat devraient tenir compte des bénéfices provenant de l'aménagement forestier et de la biomasse forestière associés au stockage du carbone dans l'écosystème et le techno-système. [Traduit par la Rédaction]

Mots-clés : aménagement forestier, analyse du cycle de vie, matériaux, substitution, bois, impact climatique net.

Introduction

Forests and forest biomass offer several ways to mitigate climate change, for example by (*i*) increasing the carbon density in existing forests (i.e., ecosystem) and (*ii*) increasing the use of biomass-based products to increase both carbon stored in products (i.e., technosystem) and substitution of fossil carbon. Thus, the substitution of fossil fuel intensive materials and energy with renewable forest biomass is a feasible option in limiting the emissions of CO_2. In the forest ecosystem, atmospheric carbon is sequestrated by the growing trees, and the carbon stored in biomass is released back to the atmosphere in the detritus cycle, where carbon in trees is transferred to soil in the form of litter for decay. Similarly, carbon in forest biomass used in the technosystem for materials and energy is emitted into the atmosphere through the combustion and degradation in time perspective (i.e., residence time) specific for different materials (Gustavsson et al. 2006; Kilpeläinen et al. 2014). The amount of CO_2 in the

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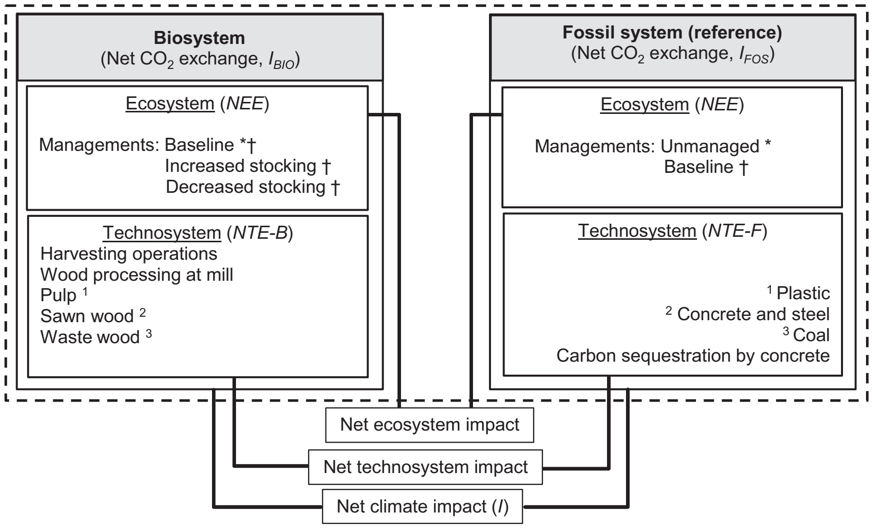
Fig. 1. Broken lines define the system boundary for the biosystem and the reference fossil system considering various management options in both systems. The difference between the systems are calculated for (*i*) net ecosystem CO_2 exchange (NEE) referred to as Net ecosystem impact, (*ii*) net technosystem CO_2 exchange (NTE) referred to as Net technosystem impact, and (*iii*) net CO_2 exchange (I_{BIO} – I_{FOS}) indicating Net climate impact (*I*). In the analysis, the unmanaged regime in the reference fossil system was compared with baseline management in the biosystem (see asterisk). Baseline management in the reference fossil system was compared with all management options utilized in the biosystem (see dagger). In the technosystem, substitution occurred as follows: pulp for plastic, sawn wood for concrete and steel, and waste wood for coal. Forest management regimes are defined in Table 3.



atmosphere is, therefore, affected through a balance between uptake and emission processes occurring in both the ecosystem and technosystem (e.g., Alam et al. 2013; Sathre et al. 2013; Kilpeläinen et al. 2014).

The potential of the forest ecosystem to sequester and store carbon depends on the tree species, the growing conditions, and management controlling the overall ecosystem dynamics (Dixon et al. 1994; Jandl et al. 2007; Alam et al. 2013; Routa et al. 2013). The carbon density in the ecosystem is affected by the stock building into growing trees and soil as related to the management. The amount of carbon stored in forest ecosystems further depends on the frequency and timing of thinning. The harvest (intensity) affects the yield and share of timber (i.e., pulpwood and sawlogs), thus affecting the potential role of forest biomass in substituting fossil intensive materials (Kilpeläinen et al. 2014; Smyth et al. 2014).

In general, the carbon storage in the forest ecosystem is largest in the unmanaged mature or old-growth forests (e.g., Klein et al. 2013), thus giving an ultimate reference to identify the management and harvest effect on the carbon sequestration in the forest ecosystem. Carbon balance in unmanaged forests reach a stable phase (at the mature stage) between the carbon uptake in net production and carbon emissions in heterotrophic production (heterotrophic respiration) from decaying litter and humus. In such forests, net production refers to the ingrowth of seedlings and their growth in canopy gaps created by the death of trees in the long-term dynamics between regeneration, growth, and mortality. Until now, the carbon dynamics in mature unmanaged forests was poorly known, but Luyssaert et al. (2008), for example, claimed that "old-growth forests with tree losses do not necessarily become carbon sources, as has been observed in even-aged plantations".

When evaluating climate impact for timber production and utilization, it is important to consider factors such as net sequestration, degradation/combustion, and substitution effects of forest products as integrated. In this respect, carbon residence time is a useful way to track and identify carbon bound in forest growth (Kellomäki et al. 2013), but how long will carbon remain in the ecosystem and related technosystem depends on the management of the forest ecosystem and the properties of materials in use. Substituted materials, timing of substitution, and life span of the biomass products also affect climate impact calculation. Most studies are concentrated separately on forest management (e.g., Klein et al. 2013) and biomass utilization (Buchanan and Levine 1999; Hammond and Jones 2008) and usually do not cover the carbon sequestration combined with substitution effects of biomass under proper management.

In this context, we investigated the net climate impacts of the production and use of timber in substituting fossil fuel intensive materials and fossil energy. This was done by comparing annual net CO_2 exchanges between the forest-based biosystem and fossil system. The model-based analysis is subjected to a Norway spruce (*Picea abies* (L.) Karst.) stand growing in a medium fertile site (*Myrtillus* site type) in the boreal conditions in central Finland (62°N, 29°E) over two consecutive rotation periods. The management regimes of the biosystem included the baseline thinning (i.e., biomass was harvested and utilized following the current recommendation (Äijälä et al. 2014)), thinning with increased stocking (basal area through rotation 20% higher than in baseline thinning), and decreased stocking (basal area 20% lower than in the baseline thinning). In the reference fossil system, baseline thinning and unmanaged regimes were used as management regimes.

Methods, calculations, and sensitivity analysis

Study approach

System boundaries and outlines of calculations

The biosystem included the forest production and the utilization chain for 1 ha of forest land (Fig. 1). Two consecutive rotations over 80 years were used. At the beginning of simulation, a stand with 2500 seedlings·ha^{-1} was established. During the rotation, two to three thinnings were done before the final felling and the second rotation followed the same management procedure as used in the first rotation. The technosystem included manufacturing, utilization of biomass products (pulp, sawn wood), and waste wood from milling processes for substituting fossil fuel intensive

Table 1. Embodied emission values of carbon utilized in this study.

Material	Emission value ($t\ CO_2 \cdot t^{-1}$)	Reference(s)
Coal	3.10	Gustavsson et al. 1995; Alam et al. 2013; IPCC 2006
Plastic (low-density polyethylene)	2.70	Boustead 2005; IPCC 2006
Steel	2.89	Hammond and Jones 2011
Concrete (cement with fine and coarse aggregate and water)	0.04	Kjellsen et al. 2005
Pulp	0.29	UPM 2010*a*
Sawn wood	0.15	UPM 2010*b*

Note: Values were converted into $t\ CO_2 \cdot t^{-1}$ from the original sources where necessary. Energy content of biomass, coal, and oil (for plastic products) was used as 3.2, 7.8, and 11.75 $MWh \cdot t^{-1}$.

materials and energy (plastic, concrete, or steel, coal), and end use of products.

In the analysis, the fossil and biosystems were compared with focus on (Fig. 1): (*i*) the substitution and climate impacts including dynamics of carbon flows in ecosystems, (*ii*) carbon balance in the ecosystem and technosystem, (*iii*) retention of carbon in the ecosystem and technosystem, and (*iv*) performance of carbon in the ecosystem and technosystem under varying management regimes.

Both systems provided the same energy or material services. Therefore, the substitution calculation for each category of forest products was used: (*i*) sawn wood materials substituted concrete or steel with their equal share (for a square metre of wall or apartment building with the same thermal transmittance), (*ii*) pulp materials substituted polyethylene (e.g., for disposable plastic items assuming that both are similar in weight), and (*iii*) waste wood items substituted coal (for energy generation in same units, megawatts per hour). Based on this classification, we first calculated the embodied emissions for each product (Table 1). Thereafter, this was scaled to our functional unit (i.e., tonnes of CO_2 emissions per hectare of forest land). The scaling factor was specific for different materials and fuel, and it ranged from 0.41 in coal to 3.82 in concrete (Sathre and O'Connor 2010; Cavalli 2015).

In the calculations, wood density of 400 $kg \cdot m^{-3}$ and carbon content of 50% were used for the dry wood (Lamlom and Savidge 2003; Saranpää 2003). In using biomass, 50% of the harvested pulpwood and sawlogs were converted into useable pulp and sawn wood products (the rest being waste wood). The embodied carbon emissions in materials (products) include all of the emissions in different phases, from producing and providing raw material and manufacturing raw material to materials in terms of CO_2. In estimating embodied emissions, the productivity and fuel consumption of necessary machines are based on the available literature (Table 1). With regard to reabsorption of CO_2 during the life span of concrete, 8% of that emitted in the production was refixed by carbonation (Gajda 2001; Gustavsson et al. 2006; Dodoo et al. 2009).

Net climate impacts (I)

The difference in net CO_2 exchange between fossil system (I_{FOS}) and biosystem (I_{BIO}) gives an annual value indicating the net climate impact *I* (eq. 1) (Kilpeläinen et al. 2011, 2014, 2016). The value of the net climate impact can be positive or negative. The negative net climate impact indicates that the biosystem is producing lower emissions compared with its corresponding fossil system, while a positive impact means that produced emissions are higher for the biosystem:

$$\text{(1)} \quad \text{Net climate impact } (I) = \text{Biosystem } (I_{BIO}) - \text{fossil system } (I_{FOS})$$

To calculate the net climate impacts *I*, we estimated the annual net CO_2 exchange for both the biosystem (I_{BIO}) and fossil system (I_{FOS}), including the flow of carbon in an ecosystem (NEE) and technosystem (NTE-B or NTE-F). The equations (2–7) are provided in Table 2 for the biosystem and fossil system.

Table 2. Equations used in the biosystem and fossil system for net climate impact calculations.

System	Equation
Biosystem	
Net CO_2 exchange, I_{BIO} = NEE + NTE-B	2
Net ecosystem CO_2 exchange, NEE = $C_{seq} + C_{decomp}$	3
Net technosystem CO_2 exchange, NTE-B = $C_{man} + C_{bio}$	4
Fossil system (reference system)	
Net CO_2 exchange, I_{FOS} = NEE + NTE-F	5
Net ecosystem CO_2 exchange, NEE = $C_{seq} + C_{decomp}$	6
Net technosystem CO_2 exchange, NTE-F = $C_{fos} + C_{seq\text{-}con}$	7

Note: NEE, net ecosystem CO_2 exchange; NTE-B, net technosystem CO_2 exchange in the biosystem; NTE-F, net technosystem CO_2 exchange in the fossil system; C_{seq}, sequestrated carbon in the forest ecosystem; C_{decomp}, emissions of carbon from decomposing litter and humus; C_{man}, emissions of carbon from forest management, logistics, and manufacturing; C_{bio}, emissions of carbon from materials based on biomass; C_{fos}, emissions of carbon from fossil fuel intensive materials and energy; $C_{seq\text{-}con}$, sequestrated carbon in concrete.

In the calculations, the flow of carbon to the forest ecosystem (sequestration of carbon in biomass growth) and technosystem (sequestration of carbon in concrete) had negative values, indicating the removal of carbon from the atmosphere and storing it in the forest ecosystem and concrete. The values were positive for carbon flows back to the atmosphere.

Computations for annual net CO_2 exchange (I_{BIO} and I_{FOS})

Net ecosystem CO_2 exchange (NEE) for alternative and reference management

A gap-type forest ecosystem model (SIMA) (Kellomäki et al. 1992*a*, 1992*b*, 2008) was used to calculate the NEE (see eqs. 3 and 6). The growth of trees in plantation or as established naturally is controlled by the temperature conditions, the availability of light, soil water, and nitrogen, and the CO_2 concentration in the atmosphere. The risk of trees dying in a given year is related to the competition between trees reducing growth. Trees may further die randomly. Organic matter in litter and dead trees ends up in the soil and decays, releasing CO_2 and nitrogen. Management controls the ecosystem dynamics including regeneration (natural regeneration, planting of given species in a desired spacing), frequency and intensity of thinning, and final felling at the end of the selected rotation. For more details of the model and its performance, see Kellomäki et al. (1992*a*, 1992*b*, 2008), and Routa et al. (2011).

The simulations were done for Norway spruce grown on a site of medium fertility (*Myrtillus* site type) in the boreal conditions (central Finland, Joensuu region: 62°39′N, 29°37′E, temperature sum 1150–1200 degree-days). The initial condition of the simulation was a managed stand felled for planting before the start of the simulation. Similar initial conditions were used for alternative management regimes, with 67 t mass·ha^{-1} of litter and humus on soil (Kellomäki et al. 2008). Regardless of management options, the initial stand was an even-aged one, with a diameter at breast height of 2.5 cm. A stand density of 2500 seedlings·ha^{-1} was used in planting.

The simulations were extended over 160 years including two 80 year rotations, which represented the same management. The management included baseline thinning (i.e., biomass was harvested and utilized following the current recommendation (Äijälä et al. 2014)), thinning with increased stocking (basal area through rotation 20% higher than in baseline thinning), and decreased stocking (basal area 20% lower than in baseline thinning). At the end of both 80 year periods, all of the timber (pulpwood and sawlogs) was removed in the final felling.

The same total period (160 years) and initial conditions were used in the unmanaged stand excluding thinning and final felling, but natural regeneration was allowed throughout the study period. In the simulations, the sequestration of carbon (C_{seq}) indicates annual growth of stems, branches, foliage, and coarse and fine roots. The decomposition of soil organic matter (C_{decomp}) includes CO_2 emissions from litter and humus layer of the forest floor. The annual difference between sequestration and emissions indicates the NEE.

Net technosystem CO_2 exchange (NTE)

In the biosystem, NTE-B was calculated following eq. 4, including the carbon emitted in management, biomass harvest, logistics, and manufacturing (C_{man}) and the carbon emitted from the use of biomass-based products (C_{bio}). The biomass from each thinning and final felling was assorted into energy biomass and timber. In converting timber to pulp and sawn wood, the emissions represent heat and electricity needed in milling processes. First, the timber was assorted into pulpwood and sawlogs, i.e., a diameter of the stem part >17 cm indicates sawlogs and a diameter of 6.5–17 cm indicates the stem part pulpwood. The rest of the stem <6.5 cm in diameter (stem top) remains in the forest ecosystem as branches, needles, and stump-root system. Thereafter, the pulpwood and sawlogs were converted into usable form of pulp and sawn wood. The emissions from the use of C_{bio} were calculated by applying eq. 8 adopted from Karjalainen et al. (1994):

$$\text{(8)} \qquad \text{PU} = d - \frac{a}{1 + be^{-ct}}$$

where PU is the fraction of products in use, a (120), b (5), and d (120) are dimensionless fixed parameters regardless of the product's life span, and c (per year) is the life span of a product. The c value is dependent on the utilized life span, e.g., from 0.65 for a short-life up to 0.0275 for a long-life, and t (year) is time. The half-life values were used in such a way that the short-life corresponds to the use of pulp and the long-life was for sawn wood (Table 3). Carbon in waste wood originating from pulpwood and sawlogs is released completely in the first year of their use.

In the fossil system, the calculation of NTE-F followed eq. 7, where $C_{seq\text{-}con}$ represents carbon sequestered in concrete and C_{fos} is the carbon emitted from the manufacture and use of fossil fuel intensive materials and energy. The emissions of carbon from the use of fossil resources were based on their life span and calculated following eq. 8. For simplification, the life span of fossil fuel intensive materials was assumed to be similar as in biomass-based products.

Retention and stocks of carbon in the forest ecosystem and technosystem

During sequestration, carbon enters into the forest ecosystem and may be retained there for several decades depending, e.g., on frequency and intensity of thinning, rotation length, and the decomposition rate of litter and humus (Kellomäki et al. 2013). Similarly, the carbon in biomass used in the technosystem may be retained from a year to several decades depending on the timing of the harvest and the life span of the products. The duration of carbon retention in the ecosystem or technosystem is referred to as the residence time (τ) (eq. 9). The residence time is obtained by dividing the stock of carbon (e.g., tonnes of CO_2 per hectare) in the ecosystem or technosystem by the emission rate (q) (e.g., tonnes of CO_2 per hectare per year) from a system:

$$\text{(9)} \qquad \tau = \frac{\text{Capacity of a system to hold carbon}}{\text{Rate of carbon flow through a system}} = \frac{\text{Stock}}{q}$$

Carbon stocks refer to the carbon in stems, branches, leaves, and the stump-root system in growing trees, dead trees including decaying wood, and litter and humus in the forest floor. In the simulation, the initial value of the humus layer was estimated to be 123 t CO_2·ha^{-1} based on the amount of litter and humus related to the site type and temperature sum (Kellomäki et al. 2008). The technosystem carbon stock refers to the carbon bound in stem wood that was moved from the ecosystem to the technosystem for utilization.

Sensitivity analysis

Sensitivity analysis was done to assess the efficiency of carbon management in the forest ecosystem and in the use of forest-based carbon in materials in substituting fossil fuel intensive materials. In the sensitivity analysis, the thinning intensity with increasing/decreasing stocking in relation to the baseline thinning regime indicated how sensitive the net climate impact was to the management (Table 3), with changes in the subsequent potential to replace fossil fuel intensive materials in the technosystem. In the technosystem, the sensitivities of net climate impacts were analyzed by changing the share of waste wood and the life span of the products in use. In the reference situation, the share of waste wood in pulping and sawing was 50% of the total timber used in the milling process (Sipi 2002). In both cases, the value of waste wood was reduced to 30% or increased to 70% (Table 3).

Furthermore, the life span of products based on pulp and sawn wood was changed, applying the half-life approach, i.e., the year when half of the original mass was lost in use under the changed degradation rate compared with the reference situation. The reference life span for sawn wood was used based on the IPCC greenhouse gas reporting for Finland (Statistics Finland 2015). The reference life span value used for pulp was three times longer than that reported, assuming that pulp fibers are reused five to seven times, with a 70% collection rate of original fibers (Finnish Forest Industries 2015).

Results

Net ecosystem CO_2 exchange (NEE)

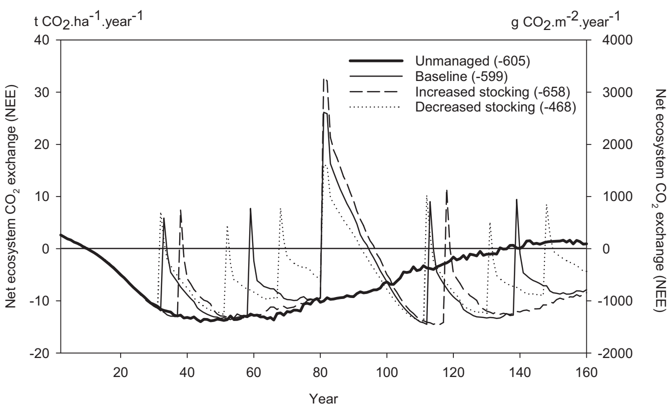
In general, CO_2 emissions from ecosystem exceeded the sequestration in the very early phase of the stand development (seedlings stage, <10 years), resulting in the net CO_2 increase in the atmosphere regardless of management (Fig. 2). In the next phase (10–60 years), the CO_2 sequestration substantially exceeded the CO_2 emission. This also held for the mature phase (60–80 years) regardless of the management. Over the whole simulation period (160-year), forests sequestered more carbon than released. The mean NEE ranged from –468 to –658 g CO_2·m^{-2}·year^{-1} during the simulation period. The sequestration was the largest under the thinning with increased stocking. The sequestration exceeded substantially that under the baseline thinning and further under the thinning with decreased stocking. Similarly, the increased stocking through rotations indicated an increasing time of carbon residence in the ecosystem.

Table 3. Summary of the reference situation and factors that were changed for the purpose of the sensitivity analysis in order to manage carbon in the ecosystem and technosystem.

Ecosystem	
Forest management	Thinning pattern
Reference thinning	Baseline thinning following the current recommendations
Thinning with increased stocking	Thinning thresholds increased by 20% (increased stocking) compared with baseline thinning
Thinning with decreased stocking	Thinning thresholds decreased by 20% (decreased stocking) compared with baseline thinning
⇓	
Technosystem	
Life time of products (years)	Share of biomass in products (%)
Reference life	Reference share
Pulp or plastic, 6	Pulp/sawn, 50
Sawn, 35	Waste, 50
Long-life	Higher share
Pulp or plastic, 12	Pulp/sawn, 70
Sawn, 70	Waste, 30
Short-life	Lower share
Pulp or plastic, 3	Pulp/sawn, 30
Sawn, 17	Waste, 70

Note: Results are presented in all combinations of the ecosystem and technosystem.

Fig. 2. Net ecosystem CO_2 exchange (i.e., difference between sequestration and decomposition) under different management regimes. Values in parentheses in the legend indicate mean net ecosystem CO_2 exchange over the simulation period.



Carbon stocks in ecosystem and technosystem

Ecosystem carbon stocks

Over the 160 year simulation period, the average CO_2 stocks in trees and soil were the highest (445 and 197 t CO_2·ha^{-1}) in the stand without management, while under the baseline thinning, the average CO_2 stock in trees was 191 and 111 t CO_2·ha^{-1} in soil (Fig. 3A). Compared with baseline thinning, the increased stocking enhanced the average ecosystem carbon stocks (both in trees and soil) by 17%, while the decreased stocking reduced by 21% the average CO_2 stock in the ecosystem.

Technosystem carbon stocks and emissions

The gross increase of carbon stocks in cumulative values is shown in Fig. 3B (panel *a*). Over two rotation periods (160 years), the highest total carbon in timber yield (734 t CO_2·ha^{-1}) was gained in baseline thinning. The corresponding value in cubic metres was 1003 m^3·ha^{-1}. Compared with baseline thinning, the timber yield was reduced by 11% under the thinning with decreased stocking and 4% under the increased stocking in thinning (Fig. 3B). This was mainly due to the lower yield of sawlogs, while the pulpwood yield increased by 3% and 10% compared with baseline thinning for the corresponding management regimes. Under the thinning with decreased stocking, the flows of CO_2 to the technosystem started 1 year (year 31) earlier than under the baseline thinning. Similarly, the carbon stock in the technosystem started to accumulate 5 years later than under the baseline thinning, when the thinning with increased stocking was used. Under no management, all of the biomass was left in the ecosystem.

Over the simulation period, the average carbon stocks in the technosystem were 39, 38, and 33 t CO_2·ha^{-1} under the baseline thinning and under thinning with decreased stocking and increased stocking, if the emissions from waste wood (Fig. 3B, panel *b*) and wood products (Fig. 3B, panel *c*) were taken into account in the calculation. During the first rotation, the highest average CO_2 stocks in the technosystem were for the management with decreased stocking (15 t CO_2·ha^{-1}) representing more frequent thinnings than the other management regimes. However, this was not the case for the second rotation, where carbon stocks decreased by 12% and 11% for increased stocking and decreased stocking, respectively, compared with that under the baseline thinning. At the end of the simulation period, carbon stocks were 152, 115, and 160 t CO_2·ha^{-1} for baseline thinning and the thinning with decreased and increased stocking, respectively.

Residence time of carbon in ecosystem and technosystem

The value of mean carbon residence time (years) varied among the management regimes depending on the timing and intensity of thinning and the utilization of biomass in the technosystem (Table 4). In both the first and second rotations, the mean residence time of ecosystem carbon was the highest under no management, but it was the lowest when carbon in the technosystem was added in the calculation. In the ecosystem and technosystem together, the highest value was for management with the baseline thinning (Table 4).

In the ecosystem, the mean carbon residence time over the whole simulation period increased by about 11% for management with increased stocking and decreased by about 18% for decreased stocking compared with baseline thinning. In the technosystem, the carbon residence time was the highest for the decreased stocking in the ecosystem due to higher intensity of biomass flow from the ecosystem to the technosystem. Compared with baseline thinning, the mean residence time of carbon in the technosystem decreased by about 24% under the increased stocking in the

Fig. 3. (A) Development of ecosystem carbon stocks in trees (panel *a*) and in soil (panel *b*) under different management regimes. Each reduction in tree carbon stocks corresponds to the harvesting of timber from the ecosystem and mobilized to the technosystem. Values in parentheses in the legend indicate mean carbon stock over the simulation period. Scales are different for panels *a* and *b*. (B) Panel *a*: Increase of carbon stocks in the technosystem due to accumulation of harvested pulpwood and sawlogs excluding the decrease in stock due to the emissions. Panel *b*: CO_2 emission from the waste wood (i.e., 50% of total harvested timber) for energy. Panel *c*: CO_2 emission from degradation of pulp and sawn wood products.

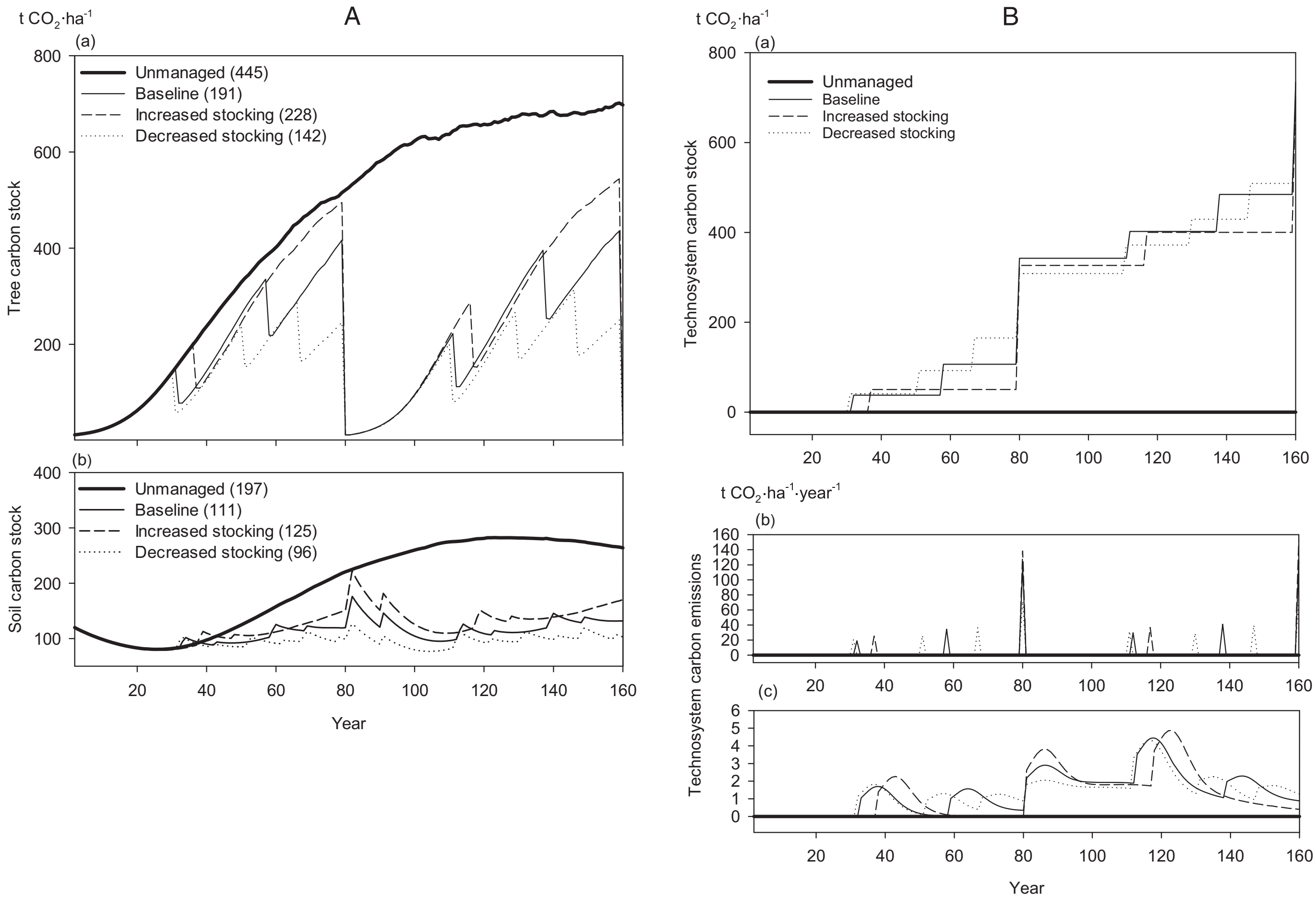
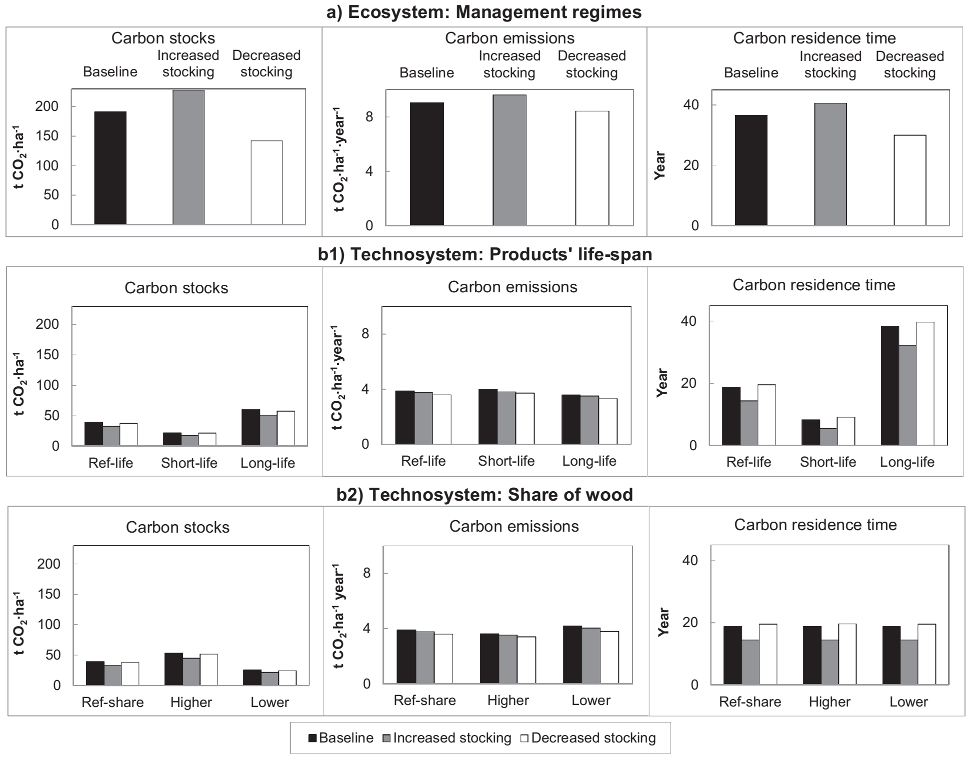


Table 4. Mean residence time (years) of carbon over rotations in the ecosystem and technosystem as a function of varying management regimes.

	Mean carbon retention (years) (% changes)		
Management regime	Rotation 1 (1–80 years)	Rotation 2 (81–160 years)	Both rotations (1–160 years)
Ecosystem			
Baseline	37.4 (–)	35.4 (–)	36.4 (–)
Increased stocking	42.2 (+12.7)	38.9 (+9.8)	40.6 (+11.3)
Decreased stocking	30.6 (–18.4)	29.3 (–17.4)	29.9 (–17.9)
Unmanaged	44.6 (+19.2)	53.2 (+50.1)	48.9 (+34.3)
Technosystem			
Baseline	8.5 (–)	29.2 (–)	18.8 (–)
Increased stocking	2.2 (–73.6)	26.4 (–9.3)	14.3 (–23.8)
Decreased stocking	10.4 (+22.5)	28.7 (–1.5)	19.5 (+3.9)
Unmanaged	0.0 (–)	0.0 (–)	0.0 (–)
Eco and technosystem			
Baseline	45.9 (–)	64.6 (–)	55.2 (–)
Increased stocking	44.4 (–3.2)	65.4 (+1.2)	54.9 (–0.6)
Decreased stocking	40.9 (–10.8)	58.0 (–10.2)	49.4 (–10.5)
Unmanaged	44.6 (–2.7)	53.2 (–17.6)	48.9 (–11.4)

Note: Percent changes are shown in parentheses when various management options are compared with the baseline thinning. Simulation for unmanaged regime (reference forest management in fossil system) is done for a 160 year period and based on that two separate periods are calculated to make it comparable with other management regimes.

Fig. 4. Sensitivity of carbon stocks, carbon emissions, and carbon residence time in the (*a*) ecosystem and (*b*1 and *b*2) technosystem under varying management regimes, product's life span, and share of wood. Management regimes, product life span, and share of wood are defined in Table 3.



ecosystem and increased by about 4% under the decreased stocking in the ecosystem.

Effects of forest management on carbon stocks and residence time: sensitivity analysis

Compared with the baseline management, the increased stocking increased carbon stocks, carbon emissions, and carbon residence time, while these values were reduced under the decreased tree stocking. In the technosystem, the changes in the life span of materials substantially affected the mean carbon stock and the mean residence regardless of management regimes (Fig. 4). The longer life span of pulp and sawn products increased both carbon stocks (53%–56%) and carbon residence time (103%–124%) and decreased emissions (7%–8%) compared with the reference life span in the technosystem. The trend is the opposite in the case of using a shorter life span than in the reference, meaning that carbon stocks and residence time were reduced up to 47% and 62% respectively, but slightly increased the technosystem emissions (up to 4%) compared with the reference life span.

Similarly, the changes in the share of wood for different products and processing waste (waste wood) clearly altered the carbon flow through the technosystem. The increased share of wood for wood products from 50% to 70% in total harvested biomass substantially increased the carbon stocks in the technosystem but did not affect carbon emissions or carbon residence time in the technosystem (Fig. 4). However, the decreased share of wood to 30% in the total harvested biomass decreased carbon stocks but did not affect emissions or residence time in the technosystem.

Net CO_2 exchange of the biosystem (I_{BIO}) and fossil system (I_{FOS})

Figure 5 shows the annual cumulative net CO_2 exchanges of the biosystem (I_{BIO}) and fossil system (I_{FOS}) and the values shown at the end of the line corresponded to the sum of I_{BIO} and I_{FOS} values over the 160 year period.

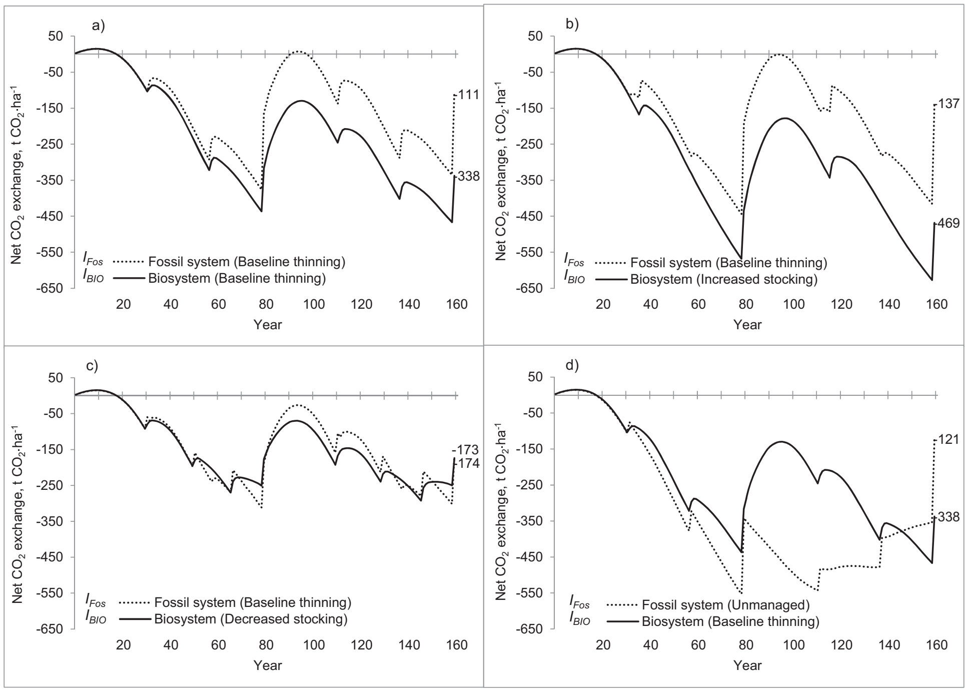
Until year 20, both the biosystem and fossil system were a source of carbon due to a higher decay rate of soil organic matter. The biosystem gained the substitution benefits from the initiation of the first thinning regardless of the management regimes. In the regimes using baseline and increased stocking, I_{BIO} was always lower with respect to that of I_{FOS} (Figs. 5*a* and 5*b*). Under the decreased stocking regime, the I_{BIO} did not completely overtake the corresponding fossil system (Fig. 5*c*). When the unmanaged stand was used as a reference (Fig. 5*d*), the fossil system benefitted mainly from the higher rate of carbon sequestration until the unmanaged stand became mature. Thereafter, the benefit decreased substantially as indicated by the sum of I_{BIO} and I_{FOS} calculated for different components in the biosystem and fossil system (Fig. 6).

Net climate impact of the biosystem

The difference in net CO_2 exchange between the biosystem and fossil system (net climate impact, *I*) and separately for the ecosystem (net ecosystem impact) and technosystem (net technosystem impact) parts are shown in Fig. 7. Net ecosystem impact was the highest for the increased stocking benefiting the biosystem. The technosystem impact was always negative and the biosystem gained benefits due to substitution. The net climate impacts ranged from –2 to –332 t CO_2·ha^{-1}. The negative net climate impact was the highest for management providing increased stocking and the net climate impact was near zero for the decreased stocking (Fig. 7).

In Fig. 8, the net climate impact is for the varying life span of products under alternative management regimes. Clearly, the longer the life span, the higher the negative net climate impact, with the greatest benefits obtained by management with increased stocking. The effect of the life span was small during the

Fig. 5. Annual cumulative net CO_2 exchange for the bio-system (I_{BIO}) and fossil system (I_{FOS}) under various forest management regimes for the 160 year period. Calculations were made according to the various management options, including emissions from sawn wood, pulp, and combustion of waste wood and net ecosystem CO_2 exchange (NEE). (*a*–*c*) For the I_{FOS}, NEE of baseline management was used and the same energy and services were produced as in baseline management, increased stocking, and decreased stocking, respectively. (*d*), I_{FOS} used NEE of the unmanaged regime and materials and energy were produced as in baseline management.



first rotation (1–80 years), but it became larger when the temporal dimension was extended to 160 years. On average, the net climate impacts ranged from 32 to −244 t CO_2·ha^{-1} during the first rotation and from 18 to −371 t CO_2·ha^{-1} for the whole study period (160 years), depending on the management regime.

Discussion and conclusions

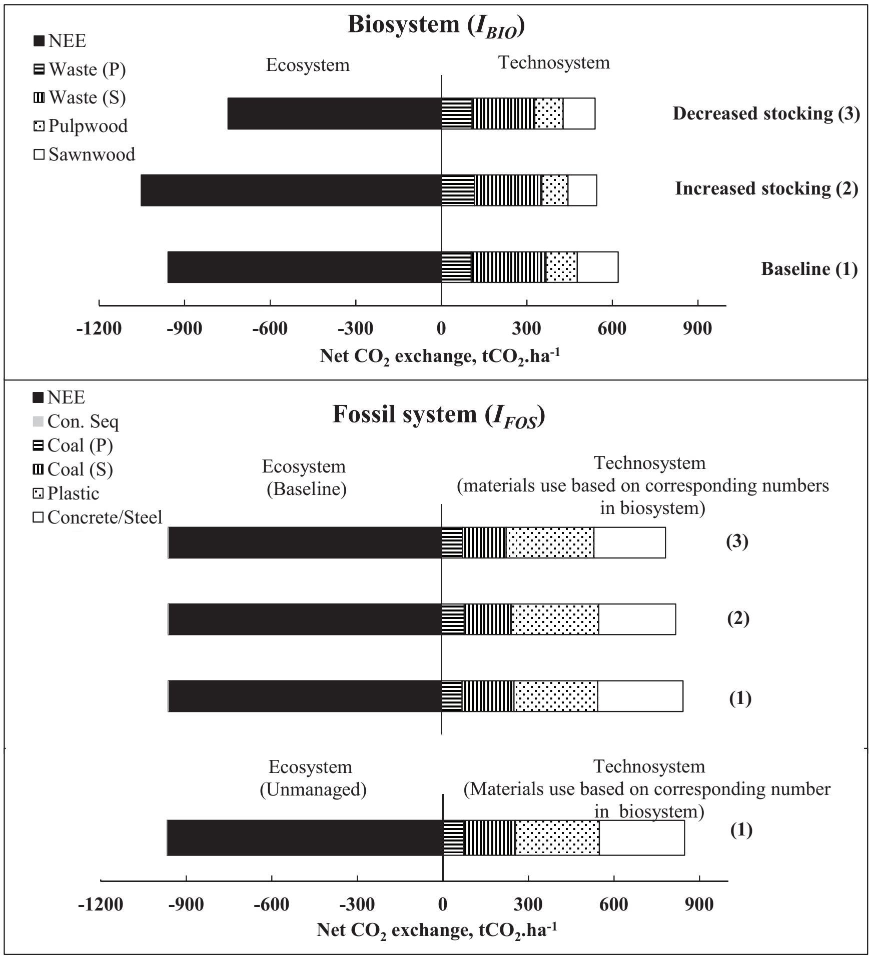
This study investigated the net climate impacts when forest biomass (biosystem) was used to substitute fossil fuel intensive materials and energy (fossil system). The net climate impact was calculated by comparing the net CO_2 exchange between the fossil system and biosystem, where both systems produced similar output in terms of materials and energy. The net CO_2 exchange included the emissions from production, combustion, and utilization of the materials and fuels in combination with ecosystem carbon dynamics (sequestration and emissions). Inclusion of ecosystem carbon dynamics in the fossil system enabled accounting for the net climate impacts for biomass against alternative references (i.e., unmanaged and baseline) (Alam et al. 2013; Hoover et al. 2014; Kilpeläinen et al. 2014; Skog et al. 2014; Røyne et al. 2016). Again, alternative forest management used in the biosystem enabled assessing of the effects of forest management on the biomass production and their subsequent potential for fossil fuel intensive materials substitution (Lippke et al. 2011). Thus, our approach made it possible to track down the entire carbon flows over the period studied, as they are related to both the production and the use of forest products against the use of fossil fuel intensive materials with respect to substitution and climate change mitigation.

Carbon sequestration into the ecosystem, carbon emissions from the soil, and the amount of harvested biomass were simulated using a forest ecosystem model over two consecutive rotations (2 × 80 years). This was done for a boreal Norway spruce stand growing on medium fertile site (*Myrtillus* type) in eastern Finland (62°39′N, 29°37′E) under varying forest management regimes. The effects of any natural disturbances were excluded from the simulations because natural disturbances, e.g., fire and snow, have not been a major concern in managed forests and also because weather and topography lack most features that could contribute to extreme fire risk, for example, in the Finnish boreal conditions (e.g., Zeng et al. 2006; Tanskanen 2007).

Our simulation showed that ecosystem carbon stock was the highest in unmanaged stands compared with that of managed forests. From the climate change mitigation point of view, this may not be a feasible option, since it is not possible for a forest ecosystem to store an unlimited mass of carbon (Karjalainen 1996). This is because after the mature phase of stand development, forests reach an equilibrium between regeneration, growth, and mortality (e.g., Eriksson et al. 2007; Lundmark et al. 2014) in the time perspective of 120–140 years in boreal conditions. In our case, the equilibrium was reached even earlier between systems when the unmanaged regime was used in the reference fossil system due to the combined effects of two reasons: diminishing rate of carbon sequestration and the emissions from the use of fossil materials. Temporal aspects, both the starting point and the duration of study periods, were also crucial in net climate impact calculations. The reference fossil system (with unmanaged regime) overtook the corresponding net CO_2 exchange in the biosystem (with baseline thinning), which in turn increased the negative net climate impacts in the biosystem. According to the results, the unmanaged forests provided only limited possibilities for climate change mitigation compared with the possibilities to store carbon in wood-based materials and to substitute materials and fuels in energy production. Our results support earlier studies (Krug et al. 2012; Klein et al. 2013) and indicated that drawing a system boundary excluding carbon storage and substitution effects of harvested biomass may produce variable results, as seen, for example, in Naudts et al. (2016).

When the reference fossil system (with unmanaged regime) was compared with the biosystem (with baseline thinning), the average avoided emissions over the study period were estimated to be 0.38 t CO_2·m^{-3} (avoided emissions per utilized cubic metre of tim-

Fig. 6. Total net CO_2 exchange of the biosystem (I_{BIO}) and fossil system (I_{FOS}) divided into different components over a 160 year period. Calculations were made according to the various management options, including emissions from the pulp and sawn wood and combustion of waste wood from pulpwood (Waste P) and sawlogs (Waste S) and net ecosystem CO_2 exchange (NEE). For the I_{FOS}, NEE of baseline and unmanaged regimes was used, and the same energy and materials services were produced as in baseline management (see '1'), increased stocking (see '2'), and decreased stocking (see '3').



ber). Our value is lower compared with a range of 0.47–0.72 t $CO_2 \cdot m^{-3}$ in earlier studies (Werner et al. 2010; Lundmark et al. 2014; Braun et al. 2016). The variability in the results occurred due to variations in system boundaries and assumptions made between these studies. Another reason, maybe even more important, is that the use of the consequential life cycle approach in our analysis (i.e., the difference in sequestration/emissions between alternative systems) resulted a value lower than these. When baseline thinning was used in the reference fossil system, the highest net climate benefits were gained for the biosystem that used the increased stocking regime, while a decreased stocking regime appeared to give lower net climate benefit than in the baseline case. This is caused by a higher number of thinning in decreased stocking regime compared with the others, thus reduced the production potential of forests and on-site carbon storage, especially during the last part of the rotation (Liski et al. 2001; Kaipainen et al. 2004; Alam et al. 2012).

Our results showed that the decrease in carbon residence time in the ecosystem caused by extracting timber from forests could be compensated for by increasing carbon stocks in the technosystem carbon pools. The highest mean carbon residence time in the ecosystem was found under the unmanaged regime, while in the technosystem, it was the highest under the decreased stocking regime because carbon flow increased from the ecosystem to the technosystem in this regime due to increased intensity and number of thinnings. Nevertheless, the decreased stocking regime could not increase the net climate impact mainly due to the fact that development of carbon stock based on long-life products (i.e., sawn wood) was reduced in this regime unlike in other studied managed regimes. However, assessing the technosystem and the ecosystem together, carbon residence time increased substantially in managed stands (Skog et al. 2014), mostly under the baseline thinning regime. If the temporal aspects are taken into account, the climate benefits due to substitution started to gain after the first thinning (time taken 31–37 years since stand establishment), which continued to increase over time due to accumulated utilization of harvested biomass, in line with studies published earlier (e.g., Sathre et al. 2013; Haus et al. 2014). However, the major share of benefits was obtained mainly during the second rotation if the substitution benefits gained during the first rotation were accumulated for the whole study period (160 years), but the benefits may be realized more quickly if the analysis were extended to a regional or national level with constant biomass supply and carbon sequestration (Kilpeläinen et al. 2016).

Our analysis at the stand level fits well the objective of the study, since it could follow the difference in carbon dynamics between the fossil system and the biosystem as well as identify emissions that were sourced from the production phase of materials to the phase until their end use. Materials from forest biomass other than the ones used in our study can be used, but drawbacks to this are to define the equivalent in functionality for alternative materials re-

Fig. 7. Net CO_2 exchange calculated as a difference between the biosystem and fossil system over the 160 year period. Net ecosystem impact = biosystem (NEE) – fossil system (NEE), net technosystem impact = biosystem (NTE-B) – fossil system (NTE-F), and net climate impact (I) = biosystem (I_{BIO}) – fossil system (I_{FOS}). In the I_{FOS}, reference management was either thebaseline or unmanaged regime as indicated in Figs. 1 and 6. Negative values indicate that I_{BIO} produces less emissions compared with the I_{FOS} and vice versa.

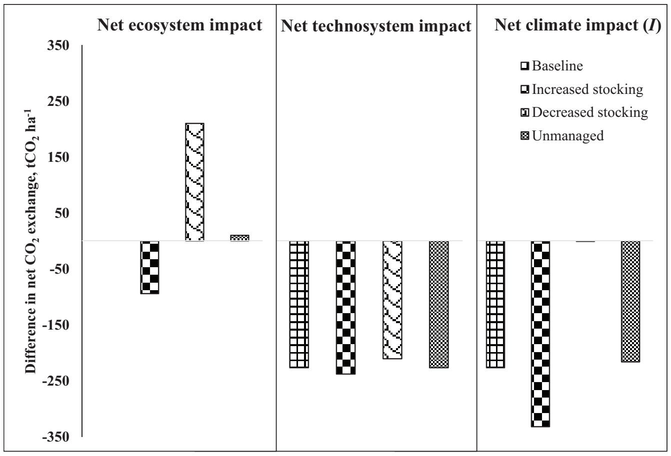
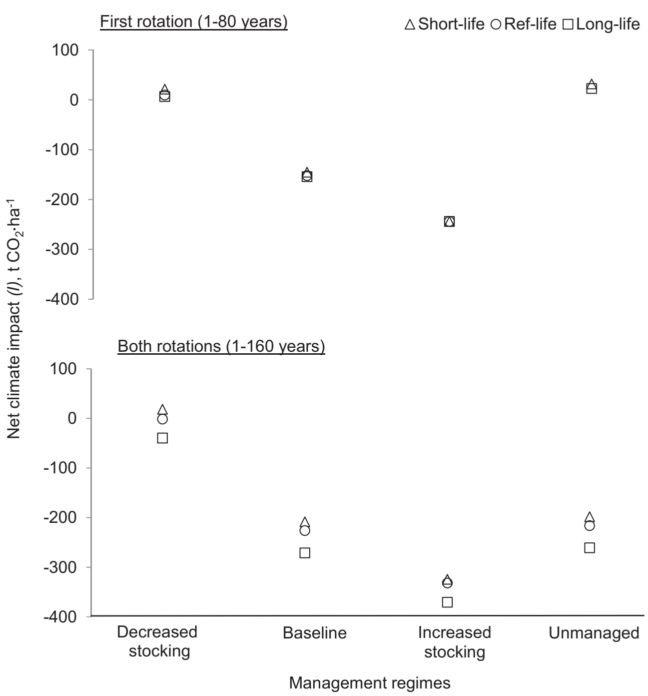


Fig. 8. Net climate impacts of the timber harvesting and utilization under alternative forest management regimes and varying life span of products during the first rotation (upper panel) and both rotations (lower panel). Management regimes and product life span are defined in Table 3.



placed and lack of comparative studies that include complete material information (Smyth et al. 2014). Our use of alternative materials for sawn wood (in concrete and steel) and pulp (e.g., in disposable plastic cups or packaging) seems reasonable (Hocking 1994; Sathre and O'Connor 2010; Werner et al. 2010; Dahlgren et al. 2015), but an alternative use for pulp products can be at the end of their life span replacing, for example, fossil fuel intensive energy (e.g., coal). When replacing coal, additional substitution benefits are gained in the biosystem, since emissions for pulp products are already accounted for earlier and at this point of their use, they can be assumed carbon neutral. Our sensitivity analysis also revealed that efficient use of wood products could gain substantial benefits given that they retain carbon longer over time in the biosphere, from 14 to 20 years, in the reference life span up to 32–40 years in the long-life span, resulting an increased net climate benefits, but all of these affects are strongly linked with forest management activities and their further effect on carbon sequestration capacity of the forest ecosystem. To realize their positive impacts on climate, there is a need for development in both forest management and timber utilization activities (Soimakallio et al. 2016).

To summarize, we found that the decrease in carbon stocks in the ecosystem caused by extracting timber from forests could be compensated for by increasing carbon stocks in the technosystem carbon pools. This increased net climate benefit of timber production and utilization compared well with the similar system with the use of fossil fuel intensive materials and energy. Tracking carbon over its life cycle helped to assess the net climate impacts of the entire production and utilization chain of forest biomass. This approach sets the basis for the development of carbon accounting procedures (IPCC 2006, 2014; Skog 2008) whenever forest biomass moves from the ecosystem and builds up the carbon stocks in various parts of the technosystem (e.g., energy system or wood product system) and substitute for fossil fuel intensive materials. At both the ecosystem and technosystem levels, the management and utilization of forests can be an effective strategy for storing and increasing residence time of carbon with or without changing the life span of the products. By doubling the life span of the biomass products, the emissions of 0.24–0.28 t $CO_2 \cdot ha^{-1} \cdot year^{-1}$ could be avoided, depending on the management regimes and the study period. Even without changing the life span, increased stocking in thinning regimes could increase negative net climate impact by 47% over the study period compared with the baseline thinning. The study suggests that future climate mitigation strategies should benefit from forest management and forest biomass to encourage changes in forest management to mitigate carbon emissions.

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