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

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1 **Title**

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

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26 **Abstract**

27 We utilized an ecosystem model and life cycle assessment tool for studying carbon
28 flows between the ecosystem, technosystem and atmosphere for scenarios utilizing
29 forest biomass (bio-system) against fossil-fuel intensive materials (fossil-system). The
30 net climate impacts were studied for a Norway spruce (*Picea abies* (L.) Karst.) stand
31 over two consecutive rotation periods (2x80 years) in the boreal conditions in central
32 Finland (62°N, 29°E). The effects of alternative forest management on the carbon
33 dynamics in the bio-system were studied in comparison with the fossil-system, by
34 using an unmanaged and baseline thinning regime. The results showed that the bio-
35 system produced carbon benefits compared to the similar system with the use of fossil-
36 fuel intensive materials and energy. The unmanaged stand stored the highest amount of
37 carbon and retained carbon the longest when solely the ecosystem was considered.
38 Studying the ecosystem and the technosystem together, the bio-system was found
39 effective in storing and increasing the residence of carbon with or without changing the
40 life span of biomass-based products. We found that the increase of the life span of
41 biomass-based products could reduce emissions up to 0.28 t CO₂.ha⁻¹.year⁻¹ depending
42 on the management regimes over the study period. The increased stocking regimes
43 could increase negative net climate impact by 47% over the study period, compared to
44 the use of baseline thinning in bio-system. The proper climate mitigation strategies
45 should consider the benefits from forest management and forest biomass in storing
46 carbon into both the ecosystem and technosystem.

47

48 Key words: Forest management, life cycle assessment, materials, substitution, timber,
49 net climate impact.

50

51 **1. Introduction**

52 Forests and forest biomass offer several ways to mitigate climate change, for example
53 by (i) increasing the carbon density in existing forests (i.e., ecosystem) and (ii)
54 increasing the use of biomass-based products in order to increase both carbon stored in
55 products (i.e., technosystem) and substitution of fossil carbon. Thus, the substitution of
56 fossil-fuel intensive materials and energy with renewable forest biomass is a feasible
57 option in limiting the emissions of carbon dioxide (CO₂). In the forest ecosystem,
58 atmospheric carbon is sequestered by the growing trees, and the carbon stored in
59 biomass is released back to the atmosphere in the detritus cycle, where carbon in trees
60 is transferred to soil in the form of litter for decay. Similarly, carbon in forest biomass
61 used in the technosystem for materials and energy is emitted into the atmosphere
62 through the combustion and degradation in time perspective (i.e., residence time)
63 specific for different materials (Gustavsson et al. 2006; Kilpeläinen et al. 2013). The
64 amount of CO₂ in the atmosphere is, therefore, affected through a balance between
65 uptake and emission processes occurring in both the ecosystem and technosystem (e.g.,
66 Alam et al. 2013; Sathre et al. 2013; Kilpeläinen et al. 2013).

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

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

88 When evaluating climate impact for timber production and utilization, it is
89 important to consider factors such as net sequestration, degradation/combustion and
90 substitution effects of forest products as integrated. In this respect, carbon residence
91 time is a useful way to track and identify carbon bound in forest growth (Kellomäki et
92 al. 2013), but how long will carbon remain in the ecosystem and related technosystem
93 depend on the management of the forest ecosystem and the properties of materials in
94 use. Substituted materials, timing of substitution and life span of the biomass products
95 also affect climate impact calculation. Most studies are concentrated separately for
96 forest management (e.g., Klein et al. 2013) and biomass utilization (Buchanan et al.
97 1999, Hammond et al. 2008), and usually do not cover the carbon sequestration
98 combined with substitution effects of biomass under proper management.

99 In this context, we investigated the net climate impacts of the production and
100 use of timber in substituting fossil-fuel intensive materials and fossil energy. This was

done by comparing annual net CO₂ exchanges between the forest based bio-system 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 bio-system 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.

2. Methods, calculations and sensitivity analysis

2.1. Study approach

System boundaries and outlines of calculations

Bio-system included the forest production and the utilization chain for one hectare of forest land (Figure 1). Two consecutive rotations over 80 years were used. At the beginning of simulation, a stand with 2500 seedlings per hectare 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. Technosystem, included manufacturing, utilization of biomass products (pulp, sawn wood) and waste wood from milling processes for substituting fossil-fuel intensive materials and energy (plastic, concrete or steel, coal), and end-use of products.

In the analysis, the fossil- and bio-systems were compared, with the focus on (Figure 1):

- 126 (i) the substitution and climate impacts including dynamics of carbon flows in
127 ecosystems;
- 128 (ii) carbon balance in the ecosystem and technosystem;
- 129 (iii) retention of carbon in the ecosystem and technosystem; and
- 130 (iv) performance of carbon in the ecosystem and technosystem under varying
131 management regimes.

132

133 Place for Figure 1.

134

135 Both systems provided the same energy or material services. Therefore, the
136 substitution calculation for each category of forest products were used: (i) sawn wood
137 materials substituted concrete or steel with their equal share (for a square meter of wall
138 or apartment building with same thermal transmittance), (ii) pulp materials substituted
139 polyethylene (e.g., for disposable plastic items assuming that both are similar in
140 weight), and (iii) waste wood items substituted coal (for energy generation in same
141 unit, MWh). Based on this classification, we first calculated the embodied emissions
142 for each product (Table 1). Thereafter, this was scaled to our functional unit (i.e., tCO₂
143 emissions per ha of forest land). The scaling factor was specific for different materials
144 and fuel, and it ranged from 0.41 in coal to 3.82 in concrete (Sathre and O'Connor
145 2010; Cavalli 2015).

146 In the calculations, wood density of 400 kg m⁻³ and carbon content of 50%
147 were used for the dry wood (Lamlom and Savidge, 2003; Saranpää 2003). In using
148 biomass, 50% of the harvested pulpwood and sawlogs were converted into useable
149 pulp and sawn wood products (the rest being waste wood). The embodied carbon
150 emissions in materials (products) include all the emissions in different phases, from

151 producing and providing raw material and manufacturing raw material to materials in
152 terms of carbon dioxide (CO₂). In estimating embodied emissions, the productivity and
153 fuel consumption of necessary machines are based on the available literature (Table 1).
154 With regard to reabsorption of CO₂ during the life span of concrete, 8% of that emitted
155 in the production was re-fixed by carbonation (Gajda 2001; Gustavsson et al. 2006;
156 Dodoo et al. 2009).

157

158 Place for Table 1.

159

160 **Net climate impacts (*I*)**

161 The difference in net CO₂ exchange between fossil-system (*I_{FOS}*) and bio-system (*I_{BIO}*)
162 gives an annual value indicating the net climate impact, *I* (Equation 1) (Kilpeläinen et
163 al. 2011; 2013; 2015). The value of the net climate impact can be positive or negative.
164 The negative net climate impact indicates that the bio-system is producing lower
165 emissions compared to its corresponding fossil-system, while a positive impact means
166 that produced emissions are higher for the bio-system.

167

168 *Net climate impact (I) = Bio-system (I_{BIO}) – Fossil-system (I_{FOS})* (1)

169

170 To calculate the net climate impacts (*I*), we estimated the annual net CO₂ exchange for
171 both bio-system (*I_{BIO}*) and fossil-system (*I_{FOS}*), including the flow of carbon in an
172 ecosystem (*NEE*) and technosystem (*NTE-B or NTE-F*). The equations are provided in
173 Table 2 for bio- and fossil-system.

174

175 Place for Table 2.

176

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

182

183 **2.2 Computations for annual net CO₂ exchange (I_{BIO} and I_{FOS})**

184 **Net ecosystem CO₂ exchange (NEE) for alternative and reference management**

185 A gap-type forest ecosystem model (SIMA) (Kellomäki et al. 1992a, b; Kellomäki et
186 al. 2008) was used to calculate the net ecosystem CO₂ exchange (NEE) (see equation 3,
187 6). The growth of trees in plantation or as established naturally is controlled by the
188 temperature conditions, the availability of light, soil water and nitrogen and the CO₂
189 concentration in the atmosphere. The risk of trees to die in a given year is related to the
190 competition between trees reducing growth. Trees may further die randomly. Organic
191 matter in litter and dead trees ends up in the soil, and decays, releasing CO₂ and
192 nitrogen. Management controls the ecosystem dynamics including regeneration
193 (natural regeneration, planting of given species in a desired spacing), frequency and
194 intensity of thinning, and final felling at the end of selected rotation. For more details
195 of the model and its performance, see Kellomäki et al. (1992a, b); Kellomäki et al.
196 (2008); Routa et al. (2011).

197 The simulations were done for Norway spruce grown on a site of medium
198 fertility (*Myrtillus* site type (MT)) in the boreal conditions (central Finland, Joensuu
199 region: 62°39'N, 29°37'E, temperature sum 1150–1200 degree-days). The initial
200 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 the diameter at the breast height of 2.5 cm. The stand density 2500 seedlings per hectare was used in planting.

The simulations were extended over 160 years including two 80-year rotations, which represented the same management. The management 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). At the end of both 80-year periods, all the timber (pulpwood and sawlogs) were 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, coarse and fine roots. The decomposition of soil organic matter (C_{decomp}) includes CO₂ emissions from litter and humus layer of the forest floor. The annual difference between sequestration and emissions indicates the net ecosystem CO₂ exchange (NEE).

220

221 **Net technosystem CO₂ exchange (NTE)**

In the *bio-system*, net technosystem CO₂ exchange ($NTE-B$) was calculated following the Equations (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 for 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., the diameter of stem part >17 cm indicates sawlogs and the diameter 6.5–17 cm of stem part pulpwood. The rest of stem < 6.5cm of 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 biomass-based products (C_{bio}) were calculated by applying Equation (8) adopted from Karjalainen et al. (1994):

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

where PU is the fraction of products in use; a (120), b (5), d (120) are dimensionless fixed parameters regardless of the product's life span; c (year^{-1}) is the life span of a product. The c value is dependent on the utilized life span, e.g., from 0.65 for short-life up to 0.0275 for long-life; and t (year) is time. The half-life values were used in such a way that short-life corresponds to the use pulp and long-life was for sawn wood (Table 2). 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 net technosystem CO_2 exchange ($NTE-F$) followed the Equation (7), where $C_{seq-con}$ 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 the Equation 8. For simplification, the

250 life span of fossil-fuel intensive materials was assumed similar as in biomass based
251 products.

252

253 **2.3 Retention and stocks of carbon in forest ecosystem and technosystem**

254 During sequestration, carbon enters into the *forest ecosystem* and may retain there for
255 several decades depending, e.g., on frequency and intensity of thinning, rotation length
256 and the decomposition rate of litter and humus (Kellomäki et al. 2013). Similarly, the
257 carbon in biomass used in the *technosystem* may be retained from a year to several
258 decades depending on the timing of the harvest and the life span of the products. The
259 duration of carbon retention in the ecosystem or technosystem is referred to as the
260 residence time (τ) (Equation 9). The residence time is obtained by dividing the stock
261 of carbon (e.g., t CO₂.ha⁻¹) in the ecosystem or technosystem by the emission rate (q,
262 e.g., t CO₂ ha⁻¹.year⁻¹) from a system:

263

264
$$\tau = \frac{\text{Capacity of a system to hold carbon}}{\text{Rate of carbon flowthrough a system}} = \frac{\text{Stock}}{q}$$

265 (9)

266

267 Carbon stocks refer to the carbon in stems, branches, leaves and the stump-roots
268 system in growing trees, dead trees including decaying wood, and litter and humus in
269 the forest floor. In the simulation, the initial values of the humus layer was estimated
270 123 t CO₂.ha⁻¹, based on the amount of litter and humus related to the site type and
271 temperature sum (Kellomäki et al. 2008). Technosystem carbon stock refers to the
272 carbon bound in stem wood that was moved from the ecosystem to the technosystem
273 for utilization.

274

2.4. Sensitivity analysis

Sensitivity analysis was done in order 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 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 sensitivity 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 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 to 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 5–7 times, with a 70% collection rate of original fibers (Finnish Forest Industries 2015).

Place for Table 3.

3. Results

3.1 Net ecosystem CO₂ exchange (*NEE*)

299 In general, CO₂ emissions from ecosystem exceeded the sequestration in the very early
300 phase of the stand development (seedlings stage, < 10 years), resulting in the net CO₂
301 increase in the atmosphere regardless of management (Figure 2). In the next phase
302 (10–60 years), the CO₂ sequestration substantially exceeded the CO₂ emission. This
303 also held for the mature phase (60–80 years) regardless of the management. Over the
304 whole simulation period (160-year), forests sequestered more carbon than released.
305 The mean net ecosystem CO₂ exchange (*NEE*) ranged from -468 to -658 g CO₂.m⁻².
306 year⁻¹ during the simulation period. The sequestration was the largest under the
307 thinning with increased stocking. The sequestration exceeded substantially that under
308 the baseline thinning, and further under the thinning with decreased stocking.
309 Similarly, the increased stocking through rotations indicated an increasing time of
310 carbon residence in the ecosystem.

312 Place for Figure 2.

314 **3.2 Carbon stocks in ecosystem and technosystem**

315 **Ecosystem carbon stocks**

316 Over the 160-year simulation period, the average CO₂ stocks in trees and soil were the
317 highest (445 and 197 t CO₂.ha⁻¹) in the stand without management, while under the
318 baseline thinning the average CO₂ stock in trees was 191 and 111 t CO₂.ha⁻¹ in soil
319 (Figure 3a). Compared to baseline thinning, the increased stocking enhanced the
320 average ecosystem carbon stocks (both in tree and soil) by 17%, while the decreased
321 stocking reduced by 21% the average CO₂ stock in the ecosystem.

323 Place for Figure 3a.

324

325 **Technosystem carbon stocks and emissions**

326 The gross increase of carbon stocks ($\text{t CO}_2\cdot\text{ha}^{-1}$) in cumulative values is shown in
327 Figure 3b (panel a). Over two rotation periods (160-year), the highest total carbon in
328 timber yield ($734 \text{ t CO}_2\cdot\text{ha}^{-1}$) was gained in baseline thinning. The corresponding value
329 in cubic meter was $1003 \text{ m}^3\cdot\text{ha}^{-1}$. Compared to baseline thinning, the timber yield was
330 reduced by 11% under the thinning with decreased stocking, and 4% under the
331 increased stocking in thinning (Figure 3b). This was mainly due to the lower yield of
332 sawlogs, while the pulpwood yield increased by 3% and 10% compared to baseline
333 thinning for the corresponding management regimes. Under the thinning with
334 decreased stocking, the flows of CO_2 to the technosystem started one year (year 31)
335 earlier than under the baseline thinning. Similarly, the carbon stock in the
336 technosystem started to accumulate five years later than under the baseline thinning,
337 when the thinning with increased stocking was used. Under no management, all of the
338 biomass were left in the ecosystem.

339

340 Place for Figure 3b.

341

342 Over the simulation period, the average carbon stocks in the technosystem were 39, 38,
343 $33 \text{ t CO}_2\cdot\text{ha}^{-1}$ under the baseline thinning, and under thinning with decreased stocking
344 and increased stocking, if the emissions from waste wood (Figure 3b, panel b) and
345 wood products (Figure 3b, panel c) were taken into account in the calculation. During
346 the first rotation, the highest average CO_2 stocks in the technosystem were for the
347 management with decreased stocking ($15 \text{ t CO}_2\cdot\text{ha}^{-1}$) representing more frequent of
348 thinnings than the other management regimes. However, this was not the case for the

349 second rotation, where carbon stocks decreased by 12 and 11% for increased stocking
350 and decreased stocking, respectively, compared to that under the baseline thinning. At
351 the end of the simulation period carbon stocks were 152, 115, 160 t CO₂.ha⁻¹ for
352 baseline thinning and the thinning with decreased and increased stocking, respectively.
353

354 **3.3 Residence time of carbon in ecosystem and technosystem**

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

362

363 Place for Table 4.

364

365 In the ecosystem, the mean carbon residence time over the whole simulation period
366 increased by about 11% for management with increased stocking and decreased by
367 about 18% for decreased stocking compared to baseline thinning. In the technosystem,
368 the carbon residence time was the highest for the decreased stocking in the ecosystem
369 due to higher intensity of biomass flow from the ecosystem to the technosystem.
370 Compared to baseline thinning, the mean residence time of carbon in the technosystem
371 decreased by about 24% under the increased stocking in the ecosystem and increased
372 by about 4% under the decreased stocking in the ecosystem.

373

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

Comparing to 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 (Figure 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 to 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 upto 47 and 62% respectively, but slightly increased the technosystem emissions (upto 4%) compared to 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 (Figure 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.

Place for Figure 4.

3.5 Net CO₂ exchange of the bio-system (I_{BIO}) and fossil-system (I_{FOS})

399

400 Figure 5 shows the annual cumulative net CO₂ exchanges of the fossil-system (I_{FOS})
401 and bio-system (I_{BIO}) and the values shown at the end of line corresponded the sum of
402 I_{BIO} and I_{FOS} values over the 160-year period.

403 Until year 20, both bio- and fossil-systems were a source of carbon due to a
404 higher decay rate of soil organic matter. The bio-system gained the substitution
405 benefits from the initiation of the first thinning regardless of the management regimes.
406 In the regimes using baseline and increased stocking, I_{BIO} was always lower with
407 respect to that of I_{FOS} (Figure 5, a, b). Under the decreased stocking regime, the I_{BIO} did
408 not completely overtake the corresponding fossil-system (Figure 5, c). When the
409 unmanaged stand was used as a reference (Figure 5, d), the fossil-system benefitted
410 mainly from the higher rate of carbon sequestration until the unmanaged stand became
411 mature. Thereafter, the benefit decreased substantially as indicated by the sum of I_{BIO}
412 and I_{FOS} calculated for different components in bio-system and fossil-system (Figure
413 6).

414

415 Place for Figure 5.

416

417 Place for Figure 6.

418

419 **3.6 Net climate impact of the bio-system**

420 Difference in net CO₂ exchange between bio-system and fossil-system (net climate
421 impact, I) and separately for ecosystem (net ecosystem impact) and technosystem (net
422 technosystem impact) part are shown in Figure 7. Net ecosystem impact was the
423 highest for the increased stocking benefiting the bio-system. The technosystem impact

were always negative and bio-system gained benefits due to substitution. The net climate impacts ranged from -2 to -332 t CO₂.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 (Figure 7).

Place for Figure 7.

In Figure 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 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 CO₂.ha⁻¹ during the first rotation, and from 18 to -371 t CO₂.ha⁻¹ for the whole study period (1–160 years), depending on the management regime.

Place for Figure 8.

4. Discussion and conclusions

This study investigated the net climate impacts when forest biomass (bio-system) was used to substitute fossil-fuel intensive materials and energy (fossil-system). The net climate impact was calculated by comparing the net CO₂ exchange between the fossil- and the bio-system, where both the systems produced similar output in terms of materials and energy. The net CO₂ 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 to account the net climate impacts for biomass against alternative references (i.e., unmanaged and baseline) (Alam et al. 2013; Kilpeläinen et al. 2013; Hoover et al. 2014; Skog et al. 2014; Røyne et al. 2016). Again, alternative forest management used in the bio-system enabled to assess 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 use of forest products against the use of fossil-fuel intensive materials with respect to substitution and climate change mitigation.

Carbon sequestration into ecosystem, carbon emissions from soil, and amount of harvested biomass were simulated using a forest ecosystem model over two consecutive rotations (2 x 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 stand compared to 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 unlimited mass of carbon (Karjalainen 1995). This is because after the mature phase of stand development, forests reach an equilibrium between

474 regeneration, growth, and mortality (e.g., Eriksson et al. 2007; Lundmark et al. 2014)
475 in the time perspective of 120 to 140 years in boreal conditions. In our case, the
476 equilibrium was reached even earlier between systems, when unmanaged regime was
477 used in the reference fossil-system, due to the combined effects of two reasons:
478 diminishing rate of carbon sequestration and the emissions from the use of fossil
479 materials. Temporal aspects, both the starting point and the duration of study periods,
480 was also crucial in net climate impact calculations. The reference fossil-system (with
481 unmanaged) overtook the corresponding net CO₂ exchange in the bio-system (with
482 baseline thinning), which in turn, increased the negative net climate impacts in the bio-
483 system. According to the results the unmanaged forests provided only limited
484 possibilities for climate change mitigation compared to the possibilities to store carbon
485 in wood based materials and to substitute materials and fuels in energy production. Our
486 results support earlier studies (Klein et al. 2013, Krug et al. 2012) and indicated that
487 drawing a system boundary excluding carbon storage and substitution effects of
488 harvested biomass may produce variable results as seen, for example in Naudts et al.
489 (2016).

490 When reference fossil-system (with unmanaged regime) were compared with
491 bio-system (with baseline thinning), the average avoided emissions over the study
492 period was estimated 0.38 tCO₂m⁻³ (avoided emissions per utilized m³ of timber). Our
493 value is lower compared to a range of 0.47 - 0.72 in earlier studies (Werner et al. 2010;
494 Lundmark et al. 2014; Braun et al. 2016). The variability in the results occurred due to
495 variations in system boundaries and assumptions made between these studies. Another
496 reason, may be even more important, is the use of consequential life cycle approach in
497 our analysis (i.e., difference in sequestration/emissions between alternative systems)
498 resulted a value lower to them. When baseline thinning was used in reference fossil-

499 system, the highest net climate benefits were gained for the bio-system that used the
500 increased stocking regime, while a decreased stocking regime appeared to give lower
501 net climate benefit than in the baseline. This is caused by a higher number of thinning
502 in decreased stocking regime compared to others, thus reduced the production potential
503 of forests and on-site carbon storage, especially during the last part of the rotation
504 (Liski et al. 2001; Kaipainen et al. 2004; Alam et al. 2012).

505 Our results showed that the decrease in carbon residence time in ecosystem
506 caused by extracting timber from forests could be compensated for by increasing
507 carbon stocks in the technosystem carbon pools. The highest mean carbon residence
508 time in the ecosystem was found under the unmanaged regime, while in the
509 technosystem it was the highest under the decreased stocking regime, because carbon
510 flow increased from the ecosystem to the technosystem in this regime due to increased
511 intensity and number of thinnings. Nevertheless, decreased stocking regime could not
512 increase the net climate impact mainly due to the fact that development of carbon stock
513 based on long-life products (i.e., sawn wood) was reduced in this regime unlike other
514 studied managed regimes. However, assessing the technosystem and the ecosystem
515 together, carbon residence time increased substantially in managed stands (Skog et al.
516 2014), mostly under the baseline thinning regime. If the temporal aspects are taken into
517 account, the climate benefits due to substitution started to gain after the first thinning
518 (time taken 31-37 year since stand establishment), which continued to increase over
519 time due to accumulated utilization of harvested biomass, in line with the studies
520 published earlier (see e.g., Sathre et al. 2013; Haus et al. 2014). However, the major
521 share of benefits was obtained mainly during the second rotation if the substitution
522 benefits gained during the first rotation were accumulated for the whole study period
523 (160-year). But, the benefits may be realized more quickly if the analysis were

524 extended to a regional or national level with constant biomass supply and carbon
525 sequestration (Kilpeläinen et al. 2015).

526 Our analysis at stand level fits well the objective of the study since it could
527 follow the difference in carbon dynamics between the fossil- and the bio-system as
528 well as identify emissions those were sourced from the production phase of materials
529 to the phase until their end use. There can be used other materials from forest biomass
530 than the ones used in our study, but drawbacks to this are to define equivalent in
531 functionality for alternative materials replaced and lack of comparative studies that
532 include complete material information (Smyth et al. 2014). Our use of alternative
533 materials for sawn wood (in concrete and steel) and pulp (e.g., in disposable plastic
534 cups or packaging) seem reasonable (Hocking 1994; Sathre and O'Connor 2010;
535 Werner et al. 2010; Dahlgren et al. 2015), but an alternative use for pulp products can
536 be at the end of their life span replacing, for example fossil-fuel intensive energy (e.g.,
537 coal). When replacing coal, additional substitution benefits are gained in the bio-
538 system since emissions for pulp products are already counted earlier and at this point
539 of their use they can be assumed carbon neutral. Our sensitivity analysis also revealed
540 that efficient use of wood products could gain substantial benefits given that they retain
541 carbon longer over time in the biosphere, from 14–20 years in the reference life span
542 up to 32–40 years in the long-life span, resulting an increased net climate benefits. But
543 all these affects are strongly linked with forest management activities and its further
544 effect on carbon sequestration capacity of forest ecosystem. In order to realize their
545 positive impacts on climate there is a need for development in both forest management
546 and timber utilization activities (Soimakallio et al. 2016).

547 To summarize, we found that decrease in carbon stocks in ecosystem caused by
548 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 to 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 ecosystem and builds up the carbon stocks in various parts of 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 $0.24 - 0.28 \text{ t CO}_2\text{ha}^{-1}\text{.year}^{-1}$ 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 to the baseline thinning. The study suggests that future climate mitigation strategies should obtain the benefits from forest management and forest biomass to encourage changes in forest management to mitigate carbon emissions.

567

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Table 1. Embodied emission value of carbon utilized in this study. Values were converted into $\text{t CO}_2\text{.t}^{-1}$ 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.t^{-1} .

Materials	Emission value, $\text{t CO}_2\text{.t}^{-1}$	References
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 2010a
Sawn wood	0.15	UPM 2010b

Table 2. Equations used in bio- and fossil-system for net climate impact calculations. For explanations, see the legends below the Table.

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

Legends:

NEE = Net ecosystem CO_2 exchange;

NTE-B = Net technosystem CO_2 exchange in bio-system;

NTE-F = Net technosystem CO_2 exchange in fossil-system;

C_{seq} = Sequestered 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;

$C_{\text{seq-con}}$ = Sequestered carbon in concrete.

Table 3. Summary of reference situation and factors that were changed for the purpose of the sensitivity analysis in order to manage carbon in the ecosystem and technosystem. Results were presented in all combinations of 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 to baseline thinning
Thinning with decreased stocking	Thinning thresholds decreased by 20% (decreased stocking) compared to baseline thinning

Technosystem	
Life time of products, years	Share of biomass in products, %
Reference life <ul style="list-style-type: none">• Pulp or plastic, 6• Sawn, 35	Reference share <ul style="list-style-type: none">• Pulp/sawn, 50• Waste, 50
Long life <ul style="list-style-type: none">• Pulp or plastic, 12• Sawn, 70	Higher share <ul style="list-style-type: none">• Pulp/sawn, 70• Waste, 30
Short life <ul style="list-style-type: none">• Pulp or plastic, 3• Sawn, 17	Lower share <ul style="list-style-type: none">• Pulp/sawn, 30• Waste, 70

Table 4. Mean residence time (in years) of carbon over rotations at the ecosystem and technosystem as a function of varying management regimes. Percentage (%) changes are shown in parentheses when various management options are compared to 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.

	Rotation 1 (1–80 years)	Rotation 2 (81–160 years)	Both rotations (1–160 years)
Management regimes	Mean carbon retention, years (% changes)		
<i>Ecosystem</i>			
• 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)
<i>Technosystem</i>			
• 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 (-)
<i>Eco- and technosystem</i>			
• 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)

819

820 Figure legends:

821

822 Figure 1. Broken lines define the system boundary for the bio-system and the reference
 823 fossil-system considering various management options in both systems. The difference
 824 between the systems are calculated for (i) net ecosystem CO₂ exchange (*NEE*) refers to
 825 Net ecosystem impact, (ii) net technosystem CO₂ exchange (*NTE*) refers to Net
 826 technosystem impact, and (iii) net CO₂ exchange ($I_{BIO} - I_{FOS}$) indicates Net climate
 827 impact (*I*). In the analysis, unmanaged regime in reference fossil-system was compared
 828 with baseline management in bio-system (see asterisk sign *). Baseline management in
 829 reference fossil-system was compared with all management options utilized in bio-
 830 system (see dagger sign †). In the technosystem, substitution occurred as follows: pulp
 831 for plastic; sawn wood for concrete and steel; and waste wood for coal. Forest
 832 management regimes were defined in Table 3.

833

834 Figure 2. Net ecosystem CO₂ exchange, *NEE* (i.e., difference between sequestration
 835 and decomposition) under different management regimes. Values in parentheses beside
 836 the Figure legend indicate mean net ecosystem CO₂ exchange, *NEE* (g CO₂.m⁻².year⁻¹)
 837 over the simulation period.

838

839 Figure 3a. Development of ecosystem carbon stocks (t CO₂.ha⁻¹) in trees (panel a) and
 840 in soil (panel b) under different management regimes. Each reduction in tree carbon
 841 stocks corresponds to the harvesting of timber from ecosystem and mobilized to the
 842 technosystem. Values in parentheses beside the Figure legend indicate mean carbon
 843 stock (t CO₂.ha⁻¹) over the simulation period. Scales are different for panels a and b.

844

845 Figure 3b. Panel a: Increase of carbon stocks ($\text{t CO}_2\text{.ha}^{-1}$) in the technosystem due to
846 accumulation of harvested pulpwood and sawlogs excluding the decrease in stock due
847 to the emissions. Panel b: the CO_2 emission ($\text{t CO}_2\text{.ha}^{-1}\text{.year}^{-1}$) from the waste wood
848 (i.e., 50% of total harvested timber) for energy. Panel c: the CO_2 emission ($\text{t CO}_2\text{.ha}^{-1}\text{.year}^{-1}$) from degradation of pulp and sawn wood products.

850

851 Figure 4. Sensitivity of carbon stocks, carbon emissions and carbon residence time in
852 the ecosystem (panel a) and technosystem (panels b1 and b2) under varying
853 management regimes, product's life span, and share of wood. Management regimes,
854 product's life span, and share of wood are defined in Table 2.

855

856 Figure 5. Annual cumulative net CO_2 exchange for bio-system (I_{BIO}) and fossil-system
857 (I_{FOS}) under various forest management regimes for 160-year. Calculations were made
858 according to the various management options, including emissions from the sawn
859 wood, pulp and combustion of waste wood and net ecosystem CO_2 exchange (NEE).
860 For the I_{FOS} , NEE of baseline management was used in the panels a, b and c, and the
861 same energy and services was produced as in baseline, increased stocking and
862 decreased stocking, respectively. In the panel d, I_{FOS} used NEE of unmanaged regime
863 and materials and energy was produced as in baseline management.

864

865 Figure 6. Total net CO_2 exchange ($\text{tCO}_2\text{.ha}^{-1}$) of bio-system (I_{BIO}) and fossil-system
866 (I_{FOS}) divided into different components over a 160-year period. Calculations were
867 made according to the various management options, including emissions from the pulp
868 and sawn wood and combustion of waste wood from pulpwood (Waste P) and sawlogs

(Waste S) and net ecosystem CO₂ exchange (*NEE*). For the *I_{FOS}*, *NEE* of baseline and unmanaged regimes were used, and the same energy and materials services was produced as in baseline (see ‘1’), increased stocking (see ‘2’) and decreased stocking (see ‘3’), respectively.

Figure 7. Net CO₂ exchange calculated as a difference between bio-system and fossil-system over the 160-year period. Net ecosystem impact = Bio-system (*NEE*) – Fossil-system (*NEE*); Net technosystem impact = Bio-system (*NTE-B*) – Fossil-system (*NTE-F*); Net climate impact (*I*) = Bio-system (*I_{BIO}*) – Fossil-system (*I_{FOS}*). In the *I_{FOS}*, reference management was either baseline or unmanaged regime as indicated in the Figure 1 and 6. Negative values indicate that *I_{BIO}* produces less emissions compared to the *I_{FOS}* and vice versa.

Figure 8. Net climate impacts (t CO₂.ha⁻¹) of the timber harvesting and utilization under alternative forest management regimes and varying life span of products during the first (upper panel), and the both rotations (lower panel). Management regimes and products’ life span are defined in Table 2.

Figure 1

Figure 2.

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905 Figure 3a.
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Figure 3b.

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916 Figure 4.

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Figure 5.

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Figure 7.

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954 Figure 8.