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Regional effects of alternative climate change and management scenarios on timber production, economic profitability and carbon stocks in Norway spruce forests in Finland

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25 ABSTRACT

26 We studied regional effects of alternative climate change and management scenarios on
27 timber production, its economic profitability (NPV with 2% interest rate) and carbon stocks
28 over a 90 years simulation period in Norway spruce forests located in southern, central and
29 northern Finland. We also compared the results of optimised management plans (maximizing
30 incomes) and fixed management scenarios. Business-as-usual (BAU) management
31 recommendations were used as basis for alternative management scenarios. The forest
32 ecosystem model SIMA together with a forest optimisation tool was employed. To consider
33 the uncertainties related to climate change, we applied two climate change scenarios (SRES
34 B1 and A2) in addition to the current climate.

35 Results showed that timber production, NPV and carbon stocks of forests would reduce in
36 southern Finland, opposite to northern Finland, and especially under the strong climate
37 change scenario (SRES A2) compared to the current climate. In central Finland, climate
38 change would have little effect. The use of optimised management plans also resulted in
39 higher timber yield, NPV and carbon stock of forests compared to the use of a single
40 management scenario, regardless of forest region and climate scenario applied. In the future,
41 we may need to modify the current BAU management recommendations to properly adapt to
42 the changing climatic conditions.

43

44 **Keywords:** climate warming; carbon balance; forest production; forest optimisation;
45 economic profitability.

46

47 **INTRODUCTION**

48 Nowadays, short growing season, low summer temperatures and lack of available nitrogen
 49 limit the productivity of boreal forests. However, the global climate is expected to warm
 50 substantially in the future due to the rapid increase of greenhouse gases and especially carbon
 51 dioxide in the atmosphere (IPCC 2013). Under the gradually changing climate, carbon
 52 sequestration and productivity of managed boreal forests are, in general, expected to increase
 53 in Finland due to longer growing seasons and increase of temperature, atmospheric CO₂
 54 concentration and precipitation (Kellomäki et al. 2008; Zubizarreta-Gerendiain et al. 2015a).
 55 Under the warming climate, the increased decomposition rate of soil organic matter may also
 56 increase the nitrogen availability for forest growth (Jarvis et al. 2005). On the other hand,
 57 productivity of Norway spruce (*Picea abies*) with shallow rooting may suffer from drought on
 58 soils with relatively low water holding capacity, especially in southern Finland (Ge et al.
 59 2011, 2013a, 2013b; Kellomäki et al. 2008).

60
 61 In addition to climatic and site conditions, forest structure as controlled by forest management
 62 also affects forest productivity (growth and timber yield) and carbon sequestration and stocks
 63 of forests (Garcia-Gonzalo et al. 2007a; Pyörälä et al. 2014; Zubizarreta-Gerendiain et al.
 64 2015b). Forest productivity and carbon stocks could be increased for example, by using less
 65 intensive thinnings and by maintaining growing stock volumes higher and applying longer
 66 rotation lengths (e.g. Liski et al. 2001; Pukkala et al. 2011). However, this may decrease the
 67 economic profitability of forestry due to the delayed harvesting, especially if a high interest
 68 rate is used in calculation of the net present value. Under the changing climate, currently
 69 applied business-as-usual management practices (e.g. forest regeneration, thinning and
 70 rotation length) may need to be modified to fully utilise the increased productivity and
 71 decrease the negative effects of climate change (Garcia-Gonzalo et al. 2008; Pukkala and

Kellomäki 2012; Zubizarreta-Gerendiain et al. 2015a; Torssonen et al. 2015). Forest landscapes should also consist of a mosaic of stands with different development stages to maintain sustainable timber production and carbon sequestration and stock of forests over time (Garcia-Gonzalo et al. 2007a). This is because newly regenerated sites and over mature forests (latter ones having high carbon stocks) may act even as sources of carbon instead of sinks opposite to young and medium age stands (Jarvis et al. 2005).

Forest ecosystem models offer useful means to study the sensitivity of forest growth, timber production, economic profitability of forestry and carbon sequestration (and stocks) of forests to changes in environmental conditions (e.g. climate and site fertility) and forest management (Kellomäki et al. 2008; Matala et al. 2003, 2005, 2006). The outputs of forest ecosystem model simulations can also be used as inputs for forest optimisation tools to solve forest planning problems. The integrated use of forest ecosystem model simulations and optimisation techniques allow identifying adaptive measures, which could increase forest production and/or forest carbon stocks in a sustainable and cost-efficient way (e.g. Garcia-Gonzalo et al. 2014). So far, only few attempts exist to optimise forest management under changing climatic conditions (e.g. Nuutinen et al. 2006; Garcia-Gonzalo et al. 2008, 2014; Pukkala and Kellomäki 2012; Zubizarreta-Gerendiain et al. 2015a,b). Furthermore, these studies have typically considered only one climate change scenario despite of uncertainties of the future climate projections.

In this work, we employed the forest ecosystem model SIMA (Kellomäki et al. 1992a, 1992b, 2008) together with a forest optimisation tool to study the regional effects of different climate change and management scenarios on timber production, its economic profitability (NPV with 2% interest rate) and carbon stocks over a 90 years simulation period in Norway spruce

97 forests located in southern, central and northern Finland. We also compared these results to
 98 those of optimised management plans, in which different management alternatives could be
 99 applied simultaneously in a forest region. Business-as-usual (BAU) Finnish forest
 100 management recommendations were used as a basis for alternative management scenarios in
 101 forest ecosystem model simulations. Their outputs were further on used as inputs for a forest
 102 optimisation tool. In order to consider the uncertainties related to the projected climate
 103 change, we applied two different climate change scenarios (SRES B1 and SRES A2) in
 104 addition to the current climate. The main hypothesis of our work was that different
 105 management and climate change scenarios could even have opposite effects on timber
 106 production, its economic profitability and carbon stocks of forests, depending on regions of
 107 Finland. Furthermore, we expected that the results of optimised management plans differ from
 108 those of using the same fixed management scenarios.

109

110 MATERIAL AND METHODS

111 Outlines for the simulations and optimisation

112 *Outlines for SIMA model simulations and optimisation.* The SIMA gap-type forest ecosystem
 113 model (Kellomäki et al. 1992a, 1992b, 2008) was used to predict forest productivity and
 114 carbon stocks in Norway spruce forests from southern to northern Finland under alternative
 115 forest management and climate change scenarios over a 90-year simulation period. The
 116 outputs of simulations (i.e. timber production, economic revenues and carbon stocks of
 117 forests) were used as inputs for a linear programming model to find out the maximum
 118 sustainable timber yield for each simulation cases.

119

120 In the SIMA model, the regeneration, growth and mortality of tree stands are affected by
 121 following environmental factors: temperature sum, availability of light and nitrogen, soil

moisture and atmospheric CO₂ (Kellomäki et al. 2008). In addition, they are affected by forest management, which affects the availability of resources for growth. Management control includes natural and artificial regeneration with desired spacing and selected tree species, control of stand density by tending of seedling stand and thinning, nitrogen fertilisation, and choice of rotation length based on tree age or alternatively basal area weighted mean diameter of trees at breast height (1.3 m above stem base). The simulations are carried out on an area of 100 m² with a one-year time step. The simulations are based on the Monte Carlo technique to take into account stochastic events (i.e. such as birth and death of trees) and therefore, each simulation is repeated many times (20 times in this work) and only their mean tendency of output variables are used in data analyses, as was done before in the work of Torssonen et al. (2015), for example.

The SIMA model has been parameterised for Norway spruce, Scots pine (*Pinus sylvestris*), silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) growing throughout Finland (latitudes N 60° and N 70° and longitudes E 20° and E 32°). Previous predictions of the SIMA model have shown good agreement with measured volume growth on permanent sample plots of the National Forest Inventory (NFI) throughout Finland, parallel simulations made by empirical growth model Motti (see Hynynen et al. 2002; Matala et al. 2005, 2006), and measured growth response of trees to nitrogen deposition (see e.g. Mäkipää et al. 1998; Matala et al. 2003; Routa et al. 2011a, 2011b).

Description of model forest areas. In this work, model stand data was used to generate three artificial pure Norway spruce forests (areas of 1000 ha each) located in southern (60°N, Helsinki), central (62°N, Kuopio) and northern (66°N, Rovaniemi) Finland on medium fertile (MT) site types. The model stand data for analysis consisted of 9 model stands, representing

an age class range from 5 to 85 years (ten year interval). The amount of initial soil organic matter and initial tree stand characteristics for the 9 stands representing different age classes were created using current climate and business-as-usual Finnish forest management (Äijälä et al. 2014). Forest ecosystem carbon stock included carbon in soil and trees (stem, branches and foliage and coarse and fine roots). In the simulations, an annual nitrogen deposition of 10 kg ha⁻¹ was used. In order to generate forest areas with an even age-class distribution (four age classes), different age classes were further grouped into age class groups, each representing 25% of the total area of 1000 ha (Table 1).

Table 1

Forest management scenarios. The development of each Norway spruce stand was simulated for the period 2010-2100. Stands with a dominant height ≥ 12 m were thinned from below and a basal area was reduced to the given target level. In order to generate a set of management alternatives, the basic thinning regime (business-as-usual management, see Äijälä et al. 2014) was varied by changing the upper thinning threshold (-10, +10 and +20%) and the percentage of basal area removal in the first thinning (50 and 65%) and in the following thinnings (20, 30 and 40%). In addition, stands could have the final cut at ages of 60, 70, 80 or 90 years (see table 2). All these different possibilities provided a total of 96 management alternatives for each climatic condition and forest region. After clear-cutting, the regeneration area was planted with an initial stand density of 2500 Norway spruce seedlings ha⁻¹ and simulation continued until the end of the 90 years planning period. Trees cut in thinning and final cut were considered as saw logs, pulpwood or logging residuals depending on their dimensions. The minimum tree diameter was 15 cm for sawlogs and 6 cm for pulpwood. Smaller stems were treated as logging residuals (with no monetary value).

The outputs of all simulations were used as inputs for the optimisation. The optimisation finds the best management plan fulfilling the optimisation targets, by employing a combination of different management alternatives over the region (i.e. the selection of one management alternative for each stand to be applied over the whole planning horizon). Furthermore, a subset of six management alternatives was selected (Table 2) to study more in details how the results of optimised management plans differ compared to those applying fixed management scenarios over the whole forest region and 90 years simulation period.

Table 2

Climate scenarios. In addition to the current climate, two different climate change scenarios were used for the simulations. The current climate represented the monthly mean values of temperature and precipitation and the annual mean CO₂ of the years 1961-2000. The current climate data were interpolated onto a 10 km x 10 km grid based on mean monthly values (Venäläinen et al. 2005). Climate change scenarios used were the IPCC SRES A2 (strong climate change) and B1 (mild climate change) emission scenarios as calculated based on monthly mean output data from 19 global climate models of the CMIP3 multi-model dataset (Meehl et al. 2007). Their predicted changes in temperature and precipitation were interpolated onto a 50 km x 50 km grid (Jylhä et al. 2009). According to these scenarios, winter and summer temperatures (T) will increase in Finland by 4–7°C and 2–3°C, precipitation (P) by about 14–30% in winter and by about 8–10% in summer and the atmospheric CO₂ to about 540 (B1) and 840 ppm (A2) by 2100 from the current value of 360 ppm, respectively. The closest grid point to each forest area was used in the simulations under the current climate and changing climate scenarios. The elevation of T, atmospheric CO₂ and P changes observed for the SRES B1 (the CMIP3 climate projection) correspond well the

RCP4.5 of the new CMIP5 database (Taylor et al., 2012), whereas the SRES A2 shows 1.3–1.5 smaller temperature increase in summer from southern to northern Finland compared to the RCP8.5 (Taylor et al., 2012).

Costs of forest operations and prices of different assortments used in NPV calculation. The calculated forest value included the net present value (NPV, with 2% interest rate) of forest revenues over the planning horizon (90 years). The prices used for different assortments were based on the average stumpage prices (41 € m⁻³ for saw logs 15 € m⁻³ for pulp wood, according to the Finnish Statistical Yearbook of Forestry (Metla, 2010)).

Mathematical formulations for the optimisation

Timber yield, revenues and carbon stocks for all management alternatives applied to each stand and climatic conditions were used to develop the mathematical formulation of the planning model (i.e. the coefficients for all the equations below). For the optimised plan, the objective was to maximise net incomes (i.e. maximisation of net present value using a 2% discounting rate) ensuring a non-declining timber yield over the years. Non-declining yield constraints were applied to avoid over-cutting the forest. The study considered a 90-year planning horizon and three alternative climates. In order to assess the impacts of climate change on net revenues, timber production and carbon stocks, the model included several accounting variables. A Model I type formulation described by Johnson & Scheurman (1977) was used. The test problem may be described as:

$$\text{Max FV} = \sum_{i=1}^N \sum_{j=1}^{M_i} f_{ij} x_{ij} A_i \tag{1}$$

Subject to:

$$\sum_{j=1}^{M_i} x_{ij} = 1, i = 1, \dots, N \tag{2}$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} w_{ijt} x_{ij} A_i = W_t, t = 1, \dots, T \quad (3)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} carb_{ijt} x_{ij} A_i = CARB_t, t = 1, \dots, T \quad (4)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} npv_{ijt} x_{ij} A_i = NPV_t, t = 1, \dots, T \quad (5)$$

$$\sum_{i=1}^N \sum_{j=1}^{M_i} nr_{ijt} x_{ij} A_i = NR_t, t = 1, \dots, T \quad (6)$$

$$W_{t+1} \leq (1 + \alpha) \cdot W_t, t = 1, \dots, T - 1 \quad (7)$$

$$W_{t+1} \geq W_t, t = 1, \dots, T - 1 \quad (8)$$

$$0 \leq x_{ij} \leq 1, \forall i, j \quad (9)$$

where, FV is total net present forest value (includes value of the ending inventory), N is number of stands, A_i is area of the stand I , x_{ij} is the decision variable and defines the proportion of the stand i that is assigned to management alternative j (the values range between 0 and 1), T is number of periods during the planning horizon (90), M_i is number of prescriptions for stand I , fv_{ij} is forest value per ha associated with prescription j and stand I (forest value includes the value of the ending inventory), w_{ijt} is harvested timber flow per ha in period t that results from assigning prescription j to stand I , $carb_{ijt}$ is average carbon stock per ha in stand i in period t if prescription j is selected, nr_{ijt} is net revenue per ha in period t associated to prescription j in stand I , npv_{ijt} is discounted net revenue per ha in period t associated to prescription j in stand I , and α is deviation allowed from target level (e.g. 15% variation).

Equation (1) defines the objective of maximising FV. Equation (2) ensures that one and only one prescription is assigned to each stand. Equations 3, 4, 5 and 6 account for timber yield, average carbon stock, net revenue and discounted revenue in each planning period. Equations 7 and 8 force timber yield levels to meet the flow targets in each period. They reflect concerns with the sustainability of timber supply where timber harvested in successive periods can increase up to 15% but cannot decrease. Equation 9 ensures that the decision variables take a value between 0 and 1.

RESULTS

Carbon stock of forests

The total carbon stock of forest (in soil and trees) was clearly affected by climatic conditions (Fig 1). Compared to the current climate, total carbon stock of forest in southern Finland was up to 15-23% lower under the B1 and A2 scenarios than under the current climate, depending on the applied management scenario (Fig1, Table3). In central Finland, total carbon stock was slightly lower under both climate change scenarios (up to 10% less) compared to the current climate. This was opposite to northern Finland, where carbon stock of forests increased under both climate change scenarios (up to 8% higher).

Table 3

When heavy thinnings were applied, the carbon stock of the forest was lower than with baseline and light thinning, regardless of the forest region, rotation length and climate applied (Fig 1). Management scenarios with long rotation length (90 years) also resulted in higher carbon stocks compared to those with shorter rotation length (70 years). Optimised

management plans, in general, resulted in higher carbon stocks of forests than the base-70 management alternative.

The carbon stock in soil was lower under both climate change scenarios than under the current climate regardless of region and management applied. Similarly, the carbon stock in trees was lower in southern Finland under both climate change scenarios than under the current climate. In central Finland, the carbon stock in trees was similar under the current climate and B1 scenario, while it was slightly lower under the A2 scenario. In northern Finland, the carbon stock in trees was higher under both climate change scenarios than under the current climate, regardless of management scenario.

Fig 1.

Timber yield and NPV

In southern Finland, under both climate change scenarios the total timber yield over the 90 years simulation period was lower compared to the current climate, regardless of management scenario applied (Fig 2). Under the A2 and B1 climate change scenarios, harvested timber yield was 26-43% and 13-19% lower than under the current climate, depending on the management scenario used (Table 3). Also for the optimised management scenario, it decreased by 36 and 11% under the A2 and B1 scenarios, compared to the current climate. Shorter rotation lengths also showed smaller decrease than longer ones, especially under the A2 scenario. In central Finland, the total timber yield reduced slightly under the A2 scenario (decrease 3 to 5%) for different management scenarios, while under the B1 scenario was similar to that under the current climate (table 3). For the optimised management plan, timber yield reduced 4% under the A2 scenario compared to the current climate, while under the B1

scenario no change was observed. In northern Finland, timber yield increased for all management scenarios 21-26% under the A2 scenario and 19-23% under the B1 scenario compared to the current climate. (Fig. 2) This increase was higher with shorter rotation lengths. In the optimised management, timber yield increased 22 and 20% under the A2 and B1 scenarios compared to the current climate (Table 3).

Fig 2.

Under the current climate, the use of business-as-usual management (70-base) provided the highest timber yield over the 90 years simulation period in southern and central Finland, if not considering the optimised management (Fig 2). Furthermore, under both climate change scenarios, the 70-base management was among those providing the highest timber yield, regardless of forest region. In the optimised management plan (i.e. a combined use of different management scenarios over the region), the harvested timber yield was, in general, considerably higher than with any fixed management scenario, regardless of climate scenario and forest region considered, except under the A2 scenario in southern Finland (Fig. 2, table 3). In southern Finland, when applying the optimised management plan instead of a fixed one, such as business as usual (70- base), the harvested timber yield over the 90 years simulation period increased 7 and 13% under the current climate and the climate change scenario B1, respectively. For the A2 scenario, the timber yield of optimised plan did not differ (0.6% lower) from that of the 70-base management scenario (table 4). In central and northern Finland the optimised management plan showed 6 to 8% higher timber yield than the 70-base management scenario regardless of climate applied.

Table 4.

In southern Finland, shorter rotation lengths clearly provided higher timber yield than longer rotation lengths regardless of climatic conditions, and especially under the A2 scenario (Fig 2). In central Finland, shorter rotation lengths resulted in slightly higher timber yield. In northern Finland the harvested timber yield was not clearly affected by rotation length, regardless of climate applied. But if the standing volume of growing stock at year 90 was also considered, the total timber volume (standing and harvested) was higher for longer rotations, in all other simulation cases except in southern Finland under the A2 climate change scenario (Table 5). The optimised management plan also resulted in considerably higher total timber volumes (standing and harvested volume) regardless of the applied climate and region. In the optimised plan, long rotation lengths were in general more common (80-90 years) and shortest ones (60 years) were not used. Considering the intensity of first thinning, 50% of the removal was more usual compared to the 65%, regardless of the region and climate applied.

Table 5.

Net present value (NPV) over the planning horizon (90 years) was in southern Finland lower under both climate change scenarios compared to the current climate, regardless of management scenario applied (Fig 3). For instance, under the 70-base management, NPV was 12 and 20% lower under the B1 and A2 scenarios, compared to the current climate (Table 3). For the optimised management, it was 7 and 30% lower under the B1 and A2 scenarios, respectively. In central Finland, climate change did not largely affect NPV (difference up to 2.5% compared to the current climate). In northern Finland, NPV was depending on management scenario 13-20% higher under the B1 and A2 scenarios compared to the current

climate. For the optimised management plan, the NPV was 18-19% higher under the B1 and A2 scenarios, compared to the current climate.

Among different fixed management alternatives in southern Finland the highest NPV values were obtained with 70-base and 70-heavy management scenarios, regardless of the climate scenario applied (Fig 3). The use of light thinnings and/or longer rotations resulted in lower NPV. In central Finland, the general trend was the same as in southern Finland. In northern Finland, management scenarios applying heavy thinnings and long rotation lengths (90-heavy) provided similar NPV values than 70-base and 70-heavy management scenarios. In general, the NPV for the optimised plan was considerably higher than for other fixed management scenarios, regardless of forest region and climate applied. However, in southern Finland under the A2 scenario, several fixed management alternatives such as 70-heavy management resulted in a higher NPV than the optimised scenario (Fig.3).

Fig 3.

DISCUSSION AND CONCLUSIONS

In this work, we studied regional effects of different climate change and management scenarios on timber production, its economic profitability (NPV with 2% interest rate) and carbon stocks over a 90 years simulation period in Norway spruce forests located in southern, central and northern Finland. We also compared these results to those of optimised management plans, in which different management alternatives could simultaneously be applied in a forest region. Business-as-usual Finnish forest management recommendations were used as a basis for alternative management scenarios in forest ecosystem model SIMA simulations. In order to consider the uncertainties related to the projected climate change, we

applied two different climate change scenarios (SRES B1 and SRES A2) in addition to the current climate. The outputs of the model were further on used as inputs for a forest optimisation tool. Altogether, we used 96 different management cases for each forest region and climatic condition as inputs for the optimisation tool to maximise the NPV, ensuring simultaneously a non-declining timber yield over the simulation period. However, based on preliminary analyses (not shown in details in this work), we selected six representative management alternatives to demonstrate the main patterns of findings (see Table 2). This was done because it would have been too complex to show all the results for each 96 management cases separately.

Our results demonstrated that climate change will, in different ways, affect timber yield, its NPV and carbon stocks of Norway spruce forests in different forest regions in Finland. It also affected total carbon stock of forests via changes in soil carbon and tree carbon, respectively. Regardless of the management scenario, total carbon stock of forest decreased in southern Finland under the changing climate (especially under A2) due to decrease in tree growth and increase in decomposition of the soil organic matter. On the contrary, in northern Finland climate change increased tree growth and thus carbon stock in trees. However, total carbon stock of forest varied also largely depending on the management scenario used. In our study as well as in previous ones (e.g. Garcia-Gonzalo et al. 2007b), lower thinning intensity and longer rotation lengths resulted in, on average, higher carbon stocks of forests.

Timber production decreased considerably in southern Finland under both changing climate scenarios, and especially under the stronger A2 scenario. These results can be explained by the fact that the growth of Norway spruce is expected to suffer drought in southern Finland especially on sites with low water holding capacity (Kellomäki et al. 2008; Ge et al. 2013a). Thus, if strong climate change occurs, tree species more resistant to drought, such as Scots pine, should be preferred in cultivation on such soils in Finland (Kellomäki et al. 2008).

392 According to our results, in central Finland timber yield was not largely affected by the
393 changing climate. In northern Finland timber yield increased clearly, which could be
394 explained by the fact that low summer temperatures are currently limiting forest growth there
395 (Briceño-Elizondo et al. 2006; Ge et al. 2013b). Our findings are in line, for example, with the
396 study of Coomes et al. (2014), who suggested that climate change effects on timber
397 production vary also depending on the forest region and its environmental conditions.

398
399 Even if our results showed that the studied management alternatives could not fully
400 compensate the loss of timber production under the strong climate change (the A2 scenario),
401 some of them showed a lower production decrease. In general, heavier thinnings and shorter
402 rotation lengths should be preferred especially in southern Finland to reduce competition
403 among trees for growth resources and to moderate the mortality of trees under the strong
404 climate change. Fortunately, the most drastic effects of climate change are expected later in
405 this century and we have, in this sense, some time to gradually adapt our forest management
406 to these conditions. Nonetheless, the expected impacts also differ depending on the projected
407 climate change as we demonstrated in this work.

408
409 Usually in unthinned or slightly thinned forests the total carbon stock is higher than in more
410 heavily managed ones (with earlier and/or more intensive thinnings), opposite to the NPV
411 (Garcia-Gonzalo et al. 2007b). In our study, NPV showed in general a decreasing tendency
412 from heavy to light thinning, and from shorter to longer rotation lengths (Fig 3). This was
413 opposite to the total carbon stock of forest (Fig 2). So, there is a trade-off between the NPV
414 and carbon stock of forests. Nonetheless, our optimisation results showed that it is also
415 possible to increase simultaneously the NPV and average carbon stock of forest over 90 years
416 simulation period compared to the use of one fixed management scenario. However, to study

more in details these trade-offs among multiple criteria, multi-objective optimisation techniques should be applied in future studies.

Our results showed, that the business as usual management used nowadays in Finland (Äijälä et al. 2014) is competitive in terms of timber yields under the current climate, unlike under the strong climate change (A2 scenario). However, the use of the same fixed management scenario over a whole forest region may result in heavy fluctuations of timber yields and unprofitable cuttings over time. Therefore, optimisation can be used to find the best combination of management alternatives over the forest region, when considering certain management objectives (e.g. NPV, carbon stock) and constraints (e.g. non-declining timber yield, revenues). In the present study, when management was optimised for the whole forest region, it gave higher NPV for all study cases and climatic conditions, except in southern Finland under the A2 scenario with substantially lower timber yield. Furthermore, in the optimisation we tried to satisfy the non-declining timber yields over time, which maintained the volume of growing stock higher over the planning period and resulted in lower amount of harvested timber compared to the use of fixed single management scenarios.

To conclude, in general our optimised management plan resulted in a more profitable forest management with a sustainable harvest and incomes during the planning horizon, which is important for forest owners. Longer rotation lengths were also more common in central and northern Finland. This was opposite to the southern Finland where shorter rotations were more often used. Considering the intensity of the first thinning, 50% of the volume removal was more recurrent compared to 65%, regardless of the region and climate applied. Based on our findings, the current Finnish management practices may need to be regionally modified in the future to properly adapt to the changing climatic conditions. However, possible increase

of abiotic risks to forests, for example, by wind, may also influence these needs, which should be studied more in details in the future.

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TABLES

Table 1: Generated forest areas with an even age-class distribution (four age classes).

Initial age class (years)	Age class group (years)	Area represented (ha)	Total area (ha)
5	0-20	125	
15	0-20	125	250
25	21-50	83.3	
35	21-50	83.3	
45	21-50	83.3	250
55	51-70	125	
65	51-70	125	250
75	>70	125	
85	>70	125	250

595 **Table 2:** Simulation layout.

	All simulated	Selected management		
Management	management	alternatives for comparison		
	alternatives	Heavy	Baseline	Light
Rotation length (years)	60, 70, 80, 90	70 or 90	70 or 90	70 or 90
Upper thinning threshold change (%)	-10, 0, 10, 20	-10	0	20
First thinning, basal area removed (%)	50, 65	65	50	50
Other thinnings, basal area removed (%)	20, 30, 40	40	30	20

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Table 3. Change (%) of total carbon stocks (trees+soil), timber production (i.e. sum of harvested timber volume (m³ ha⁻¹) at year 90) and net present value (NPV) for different management scenarios under the climate change (B1 and A2 scenarios) compared to the current climate in different regions (i.e. southern, central and northern Finland).

	South		Central		North	
	A2	B1	A2	B1	A2	B1
Carbon stocks, % change						
70-heavy	-18.5	-15.4	-5.5	-4.9	0.1	0.3
70- base	-16.8	-10.7	-8.0	-5.8	8.0	6.9
70-light	-18.3	-11.7	-6.6	-4.1	7.8	7.5
90-heavy	-14.6	-12.3	-8.9	-6.7	4.1	3.4
90-base	-15.5	-12.0	-10.4	-4.5	6.5	5.3
90-light	-23.2	-11.0	-6.7	-3.6	2.7	3.9
Optimised	-16.2	-8.5	-4.3	-3.6	2.2	2.3
Timber, % change						
70-heavy	-26.4	-13.2	-4.2	-0.9	22.3	19.4
70-base	-30.5	-17.0	-4.7	-2.4	24.2	19.9
70-light	-31.7	-18.6	-2.8	0.6	25.6	21.7
90-heavy	-38.6	-13.8	-4.5	-2.6	26.1	23.3
90-base	-43.0	-18.1	-2.9	2.7	21.3	20.9
90-light	-30.7	-19.2	-3.9	0.9	24.0	20.8
Optimised	-35.6	-11.0	-4.2	-0.1	21.8	20.0
NPV, % change						
70-heavy	-16.1	-9.0	-2.2	-1.2	17.0	15.4
70- base	-19.6	-12.0	-1.0	-0.5	17.2	14.1
70-light	-20.6	-14.6	-0.1	0.1	19.6	16.6
90-heavy	-22.9	-9.2	-1.0	-0.7	17.2	16.7
90-base	-20.6	-10.9	-2.3	-0.6	20.3	15.5
90-light	-19.1	-11.6	1.5	2.1	13.4	15.0
Optimised	-30.1	-6.8	-2.5	0.0	19.1	17.5

Table 4. Timber yield ($\text{m}^3 \text{ ha}^{-1}$) for 10 years periods and in total over 90 years in the optimised management and its difference (%) with the 70-base management in different regions (i.e. southern, central and northern Finland) under the current climate (CU) and A2 and B1 climate change scenarios.

Years	1-10	11-21	21-30	31-40	41-50	51-60	61-70	71-80	81-90	total timber yield	% change to 70-base
South											
CU	64	64	64	64	64	64	64	64	73	588	7
A2	43	49	49	49	49	43	43	43	11	378	-0.6
B1	58	58	58	58	58	58	58	58	58	524	13
Central											
CU	62	62	65	65	65	65	65	65	65	579	6
A2	62	62	62	62	62	62	62	62	62	554	6
B1	63	63	63	63	63	63	63	63	72	578	8
North											
CU	49	49	49	49	49	49	49	49	53	441	7
A2	54	54	54	54	59	63	63	63	72	537	6
B1	51	51	51	58	62	62	62	62	71	529	6

Table 5. Sum of harvested timber and standing volume of growing stock ($\text{m}^3 \text{ha}^{-1}$) at year 90 for forests located in southern, central and northern Finland under current climate (CU) and A2 and B1 climate change scenarios. Differences in % between optimised management plan and single fixed management scenarios within the same climate and region.

	CU		A2		B1	
South	$\text{m}^3 \text{ha}^{-1}$	%	$\text{m}^3 \text{ha}^{-1}$	%	$\text{m}^3 \text{ha}^{-1}$	%
70-heavy	599	-14.2	398	1.3	500	-14.8
70- base	630	-9.7	389	-1.0	516	-12.1
70-light	630	-9.7	381	-3.1	502	-14.5
90-heavy	638	-8.6	331	-15.8	530	-9.7
90-base	666	-4.6	359	-8.7	541	-7.8
90-light	659	-5.6	316	-19.6	517	-11.9
Optimised	698		393		587	
Central						
70-heavy	592	-14.5	565	-14.0	586	-15.4
70- base	625	-9.7	587	-10.7	618	-10.8
70-light	615	-11.1	584	-11.1	614	-11.4
90-heavy	638	-7.8	592	-9.9	624	-10.0
90-base	647	-6.5	615	-6.4	659	-4.9
90-light	661	-4.5	603	-8.2	657	-5.2
Optimised	692		657		693	
North						
70-heavy	463	-14.6	574	-15.6	551	-14.7
70- base	475	-12.4	599	-11.9	577	-10.7
70-light	467	-13.8	601	-11.6	577	-10.7
90-heavy	493	-9.0	601	-11.6	577	-10.7
90-base	519	-4.2	642	-5.6	620	-4.0
90-light	514	-5.2	650	-4.4	619	-4.2
Optimised	542		680		646	

FIGURE CAPTIONS

Fig1. Average carbon stock (soil, trees and total carbon) of forests ($\text{Mg ha}^{-1} \text{ year}^{-1}$) over 90 years simulation period under the current climate and climate change scenarios A2 and B1 in southern, central and northern Finland. In addition to optimised management, six-fixed management scenarios were applied with rotation length of 70 or 90 years, and heavy, baseline or light thinnings (see Table 2).

Fig2. Timber yield (harvested log and pulp wood, $\text{m}^3 \text{ ha}^{-1}$) under the current climate and climate change scenarios A2 and B1 in southern, central and northern Finland. In addition to the optimised management, six fixed management scenarios were applied with rotation length of 70 or 90 years, and heavy, baseline or light thinnings (see Table 2).

Fig3. Net present value (NPV, euros ha^{-1}) over 90 years simulation period under the current climate and climate change scenarios A2 and B1 in southern, central and northern Finland. In addition to optimised management, six-fixed management scenarios were applied with rotation length of 70 or 90 years, and heavy, baseline or light thinnings (see Table 2).

641 **FIG1 (excel)**

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FIG2 (excel)

FIG3 (excel)