Vulnerability assessment of ecosystem services for climate change impacts and adaptation (Vaccia)

ACTION 9: *Assessment of impacts and adaptation measures for forest production; Case study at Northern Häme and Lapland* *(Short name: Forest Production)*

Impact of changing climate on optimal silviculture

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Pasi Kolari, Lauri Valsta, Tianjian Cao, Eero Nikinmaa, Annikki Mäkelä, Pertti Hari, Teemu Hölttä

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1. Introduction

Silviculture aims at directing growth of forest trees in order to achieve development that produces wished end products, out of which different timber products are currently in most cases the most valuable outcome. Silviculture that aims at most valuable timber production controls both the establishment of new forest stands and the disturbances acting on the stands. In establishment phase sufficient measures are taken to guarantee the establishment of wished tree stock and during the forest development trees are removed and the stand is harvested before the natural senescence of trees would occur. The final harvest of the stand occurs to optimize the value of timber production and it occurs normally well before the biological maximal age of the forest stand is reached. In this kind of scheme, competition between individuals determine the mortality and the dimensional development of tree stock. Competition, on the other hand can be controlled at practical scale with intermediate harvesting operations.

Despite of the high degree of control that forest management has on forest stand development, there are only limited possibilities to influence the actual growth rate of trees. There silviculture relies on the natural processes driving the primary productivity of the forest. In the boreal forests of Finland, most upland sites are nitrogen limited and fertilization could be used to enhance productivity. It is, indeed, rather commonly used, but it is economically viable only when the growth addition it introduces produces most valuable sawn wood dimensions. Therefore fertilization is used normally only in mature forests rather close to the final harvest of the stand. In countries like Finland that has long tradition of forest management, the research has produced quite good understanding of the timber growth rate in different kind of soils in current climatic conditions. Therefore the whole silvicultural chain and the required management inputs and production outputs are relatively well known.

Changing climate will influence factors influencing both the establishment and the disturbance but also the primary productivity. For the latter influence we do not any more have history of direct observations of tree growth and development. It can be assumed that by controlling the rotation and competition we can still keep the natural disturbance factors mostly in minor role in forest management and by increasing the establishment effort we can still establish the forest stands. Under such premises the questions that arise are then how much is productivity enhanced, how much more effort we need to use for stand establishment and how do we need to accommodate the tree removals to control the competition in an optimal way and to harvest the stock when it is economically most valuable.

In this document, we concentrate on studying how primary productivity and tree growth changes as a response to changing climate using the process based approach described in the first technical report of this VACCIA action 9 and how the ground vegetation competition changes based of the meta-analysis of the same report (Nikinmaa et al. 2010). We use these productivity changes to estimate how they influence the economics of silviculture. The possible intensification of natural disturbances and their influence is left outside the scope of this analysis.

2. Forest growth scenarios

1. Photosynthetic production of trees

We estimated the potential increase in photosynthetic productivity in Scots pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) due to direct effects of increasing temperature and CO_2. The model of photosynthesis calculates the light driven biochemical processes that bind CO_2 into sugars and the diffusive influx of carbon dioxide into the leaf from the atmosphere resulting from the concentration gradient that photosynthesis establishes. The biochemical activity of leaves depend on the radiation that they receive, the leaf nutrient status (here estimated with nitrogen (and thus protein) concentration) and the temperature and the seasonal cycle in it. The carbon dioxide influx depends on the steepness of the concentration gradient and the conductivity of the diffusive pathway from atmosphere into internal air spaces in leaves. The former depend on the net rate by which photosynthesis minus respiratory processes consume CO_2 in leaf and the atmospheric CO_2 concentration. The conductivity of the diffusive pathway is mainly controlled by the degree of opening of the leaf stomata. Between species important changes in the leaf boundary layer and within leaf diffusive pathway conductivity exist as well. The stomatal conductivity depend on rate of leaf CO_2 gain and leaf water loss, that inevitably takes place.

Depending of the growing conditions the photosynthetic production of leaves respond to predictable manner to variations in the atmospheric and soil conditions. This response can be estimated from field observations. Once established as a model, it can be used to calculate how photosynthetic production varies with measured or predicted changes in these driving conditions. We calculated photosynthetic production of a single leaf in half-hourly time steps with leaf intercepted radiation, temperature, atmospheric vapor pressure deficit and CO_2 concentration and soil water status were variables driving the photosynthetic rate using biochemical model of photosynthesis (Farquhar et al. 1980) along with stomatal conductance model of Leuning (1995). The seasonality of photosynthetic capacity and quantum yield in conifer pine were described as delayed temperature response (Mäkelä et al. 2004).

The model parameters were estimated from multiannual time series of shoot and leaf gas exchange in pine shoots in Hyytiälä, Southern Finland (Kolari et al. 2007). CO_2 response of photosynthesis was determined from campaign-wise response measurements of increased CO_2 on Scots pine needles in the summer of 2010 (unpublished data).The CO2 acclimated trees have normally somewhat lower values for Farquhar photosynthesis model parameters (VC_{max} and J_{max}) than instantaneous response to elevated concentration would give but as Nowak et al (2004) argue, this down-regulation occurs in low nitrogen conditions. Juurola (2003) did not observe large down-regulation of photosynthetic parameters in Scots pine. As nitrogen availability is predicted to increase with climate change, we believe that the use of instantaneous response is justified. Also, our field determined response of photosynthetic rate with CO_2 was similar as used before for Scots pine (Wang et al. 1996)

For deciduous birch, the annual cycle model was replaced by simple temperature-driven model of leaf unfolding and day-length-triggered leaf senescence that determined the seasonal development of the leaf area index of the stand. The parameters of the photosynthesis model were estimated from gas exchange of birch leaves (Juurola 2003).

Photosynthetic production of the trees was determined by integrating the instantaneous photosynthetic rate at shoot (pine) or leaf (birch) level over the whole stand. The integration was done with SPP (Stand Photosynthesis Program, Mäkelä et al. 2006) that combines a model of shoot photosynthetic production with the model of light interception in the canopy (Stenberg 1996) and soil water limitation to gas exchange (Duursma et al. 2008). The soil water starts to limit the transpiration rate as soil water content drops below 40% level of the total potential plant available water in the soil (which is defined as the difference in soil water content at field capacity (i.e. when freely draining water has drained from soil pores) minus that at the plant wilting point) and decreases henceforth rather linearly with decrease in the plant available water. In SPP, photosynthetic production is modelled at tree level. Trees of different species, size, leaf area density or physiology are represented as size classes. Each size class may have its own photosynthetic parameters, canopy shape and dimensions. The individual crowns consist of a homogeneous medium. The trees are assumed to be randomly distributed in the stand. When calculating the light environment inside the crowns, shading by the neighboring trees is taken into account in addition to within-crown shading.

In the present climate the model can explain the seasonal pattern of photosynthetic production very well, including drought-induced decline (Figure 1).
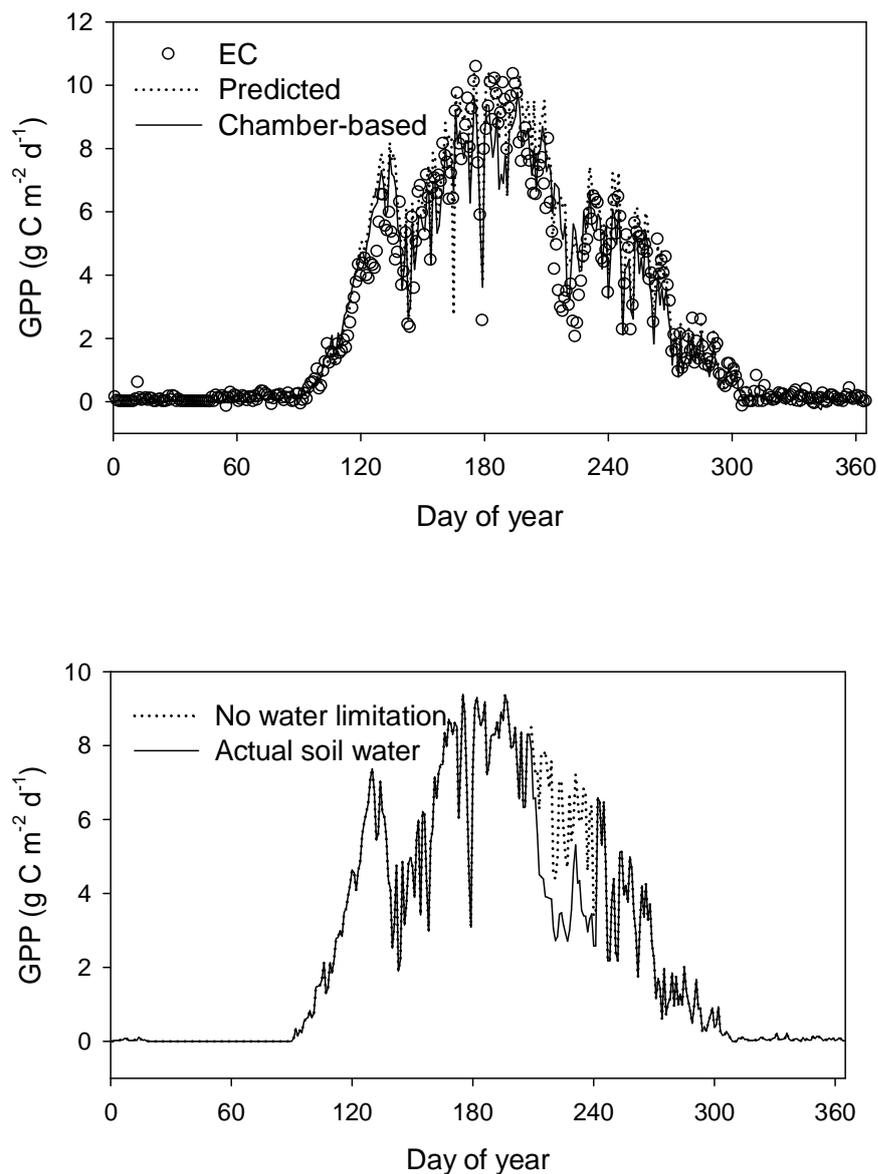
Figure 1. Daily photosynthetic production (GPP) of the stand during year 2006: a) GPP extracted from eddy covariance, upscaling directly from chamber measurements, and prediction with SPP (Kolari et al. 2009), b) predicted stand GPP with no soil water limitation on tree gas exchange and GPP with the actual soil water status

In the simulations tree dimensions, leaf area index and tree density were typical for an established tree stand in a self-thinning phase well after canopy closure. The model was run with different climate change scenarios (Jylhä et al. 2009) that correspond to different future development in the emissions of CO_2 from fossil fuel combustion (Table 1). The CO_2 increase and the climatic feedback mechanisms lead to temperature rise of 2–5°C by the end of 21st century. Climate change modified

weather data from Hyytiälä was used as the model input. All half-hourly records of air temperature and atmospheric CO_2 were increased by the mean annual temperature rise and CO_2 increase, respectively. Water vapor concentration in the air was altered so as to keep relative humidity of air unchanged (Dessler and Sherwood 2009; Kimmo Ruosteenoja, personal communication).

Table 1. Projected increase in atmospheric CO_2 according to Jylhä *et al.* (2009)

Year	CO_2 (ppm)		
	B1	A1B	A2
2025	420	430	430
2055	490	540	550
2085	540	650	710

Annual photosynthetic production will increase more in birch due to steeper instantaneous temperature response and higher temperature optimum of photosynthesis than in pine (Figure 2). Most of the increase can be attributed to longer growing season, in midsummer the simulated momentary photosynthetic rates in 2085 are only 10–15% higher than in the present climate. The summertime enhancement in photosynthetic production is almost exclusively caused by the increase in atmospheric CO_2. By 2100, CO2-induced increase in annual photosynthetic production in pine will be 10%, 19% and 23% in scenarios B1, A1B and A2, respectively. The direct effect of temperature rise on productivity is smaller, approx. 3% per °C increment. The production increase is well in line with results from various free-air CO2 enrichment (FACE) studies where the NPP increase in forest stands with 550 to 700 ppm increase in CO2 has been about 20% (Nowak et al. 2004, Norby et al. 2009). Proportional increase in NPP and GPP can be assumed as the respiration rate has been observed to increase in proportion to GPP.

The model predicts a decline in instantaneous transpiration rates in both pine and birch. Due to the longer growing season in the future, however, the annual cumulative transpiration will remain approximately at the present level.
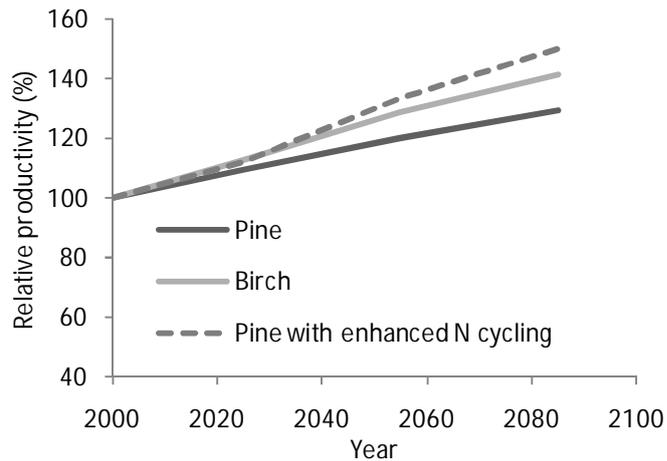
Figure 2. Predicted relative (year 2000 = 100) annual photosynthetic production in middle-aged pine and birch stands (only direct effect of temperature and CO_2 considered) and in the stemwood production of pine (enhanced N cycling and changed allocation patterns taken into account) until year 2085. The simulations were done with CO_2 scenario A1B and linear temperature rise of 3°C by year 2100.

Increasing CO_2 enhances water-use efficiency as the stomata tend to open less at elevated CO_2 than in present CO_2 (Figure 3). The free-air CO2 enrichment studies have shown no significant acclimation in the stomatal responses to CO2 in comparison to instantaneously determined response (Medlyn et al. 2001). Increasing stand foliage area, however, may partly offset the enhanced water-use efficiency as the average leaf shading will increase with consequent decrease in WUE.
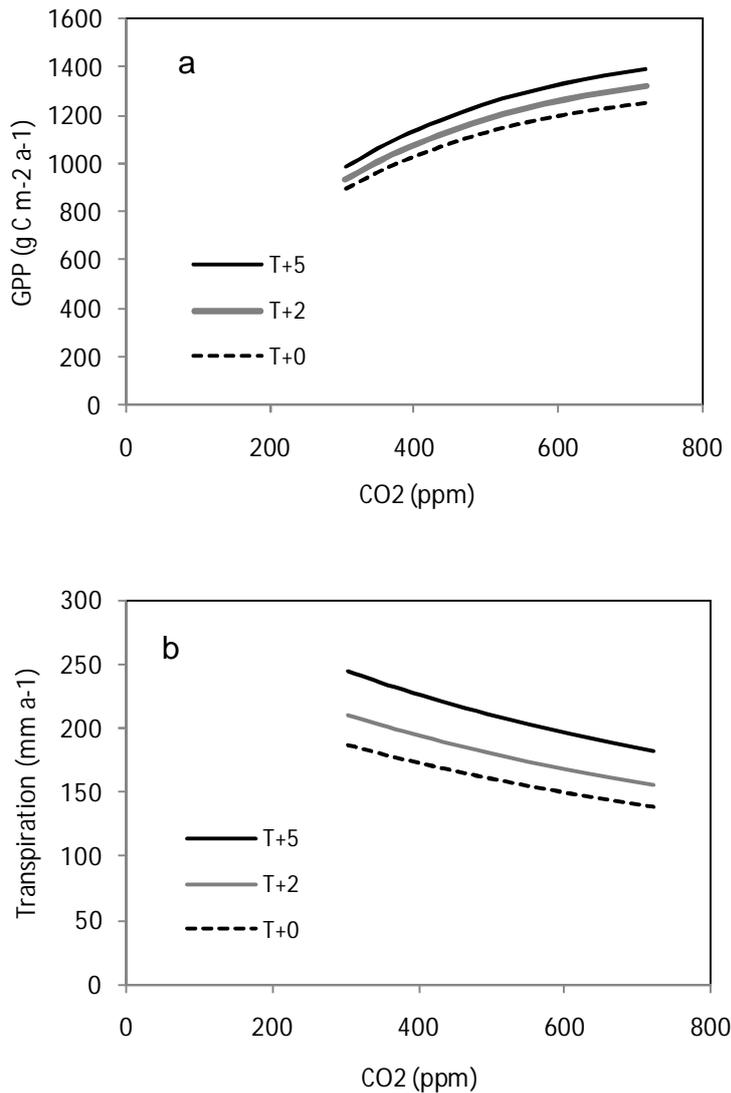
Figure 3. Variation in a) photosynthetic productivity and b) transpiration at different atmospheric CO_2 concentrations and average temperature rises in a typical middle-aged southern Finnish Scots pine stand. Stand foliage area remained constant in all simulations and there was no feedback from enhanced nutrient cycling.

2. Tree Growth

Changes in photosynthetic productivity (GPP) is but one of the response to changing climate and long term response includes changes in net productivity (NPP) as changes will also influence the respiration rate, changes in resource allocation to different biomass compartments, changes in their size that will have feedback to productivity as shown before and changes in the senescence. Experiments with long term exposure to elevated CO_2 in temperate climate have shown considerable increase in both net primary production (NPP, i.e. photosynthetic production minus

respiratory losses) and growth allocation between leaves, wood and fineroots (Franklin et al. 2009). Temperature increase will instantaneously influence respiration rate (e.g. Kolari et al. 2009) but there is a lot of evidence that it will tend to balance with the production rate (Malhi et al. 1999, Saxe et al. 2001, Körner 2006) so that increased GPP will also be associated with proportional increase in the net productivity (NPP).

Biomass production changes of pine was further studied with MicroForest (Hari *et al.*, 2008) that incorporates soil nitrogen (N) cycling and changing allocation into foliage, wood and roots. It calculates the allocation between the leaves, wood and fineroot from determined structural regularities between the wood dimensions and amount of foliage and so that the resource uptake and the resource use for growth will match each other (Hari *et al.*, 2008). The key parameters of the model that change with climate are annual photosynthetic production per unit leaf area in unshaded conditions, annual maintenance respiration of different plant tissues, decomposition rate of proteins in the soil, and nitrogen deposition. For the productivity simulations the annual photosynthesis was obtained from the previously presented simulations with increased CO_2 and temperature. Annual maintenance respiration was assumed to increase proportionally to photosynthesis. The rate of decomposition was increased by 6% per °C rise in temperature based on observed temperature response of soil CO_2 efflux (Kolari et al. 2009) and increase in active growth and decomposition period (temperature >5°C) length (Körner 2006). Nitrogen deposition was assumed to remain at the present level in the future. No thinnings were performed in the simulations, only natural mortality was considered.

Simulations with just increased photosynthetic productivity resulted in relatively smaller growth enhancement than increase in annual photosynthesis because soil nutrients were depleted. However, enhanced N cycling and change in within-tree biomass allocation along with productivity changes allowed for increment of approximately 8% per °C temperature rise in pine stemwood production in mature stand (Figure 4). This largely resulted from lower allocation below ground. Average growth increment in closed-canopy stands with CO_2 scenario B1 and mean annual temperature rise of 2°C was 16% and 31% in southern Finland and in Lapland, respectively. The extreme CO_2 scenario A2 and temperature rise of 5°C resulted in growth enhancement of 40% in southern Finland and 80% in the north. In this scenario climate in Lapland eventually becomes warmer than the present climate in southern Finland. However, wood production will remain at a lower level as the initial pools of soil organic matter and correspondingly organic nitrogen are smaller in the north (Jari Liski, personal communication).

The experimental results from the large scale CO2 enhancement experiments have produced similar results (Oren et al. 2001) in terms of elevated CO2 while soil warming experiments produced similar outcome in terms of enhanced nitrogen availability (Strömgren and Linder 2002). The fate of nitrogen quantitatively upon the enhanced decomposition is not certain as part of it may be immobilized within the soil microbial communities. However, combined influence of continuous nitrogen deposition and elevated temperatures and CO_2 are certain to produce growth acceleration as predicted (Magnani et al. 2007)
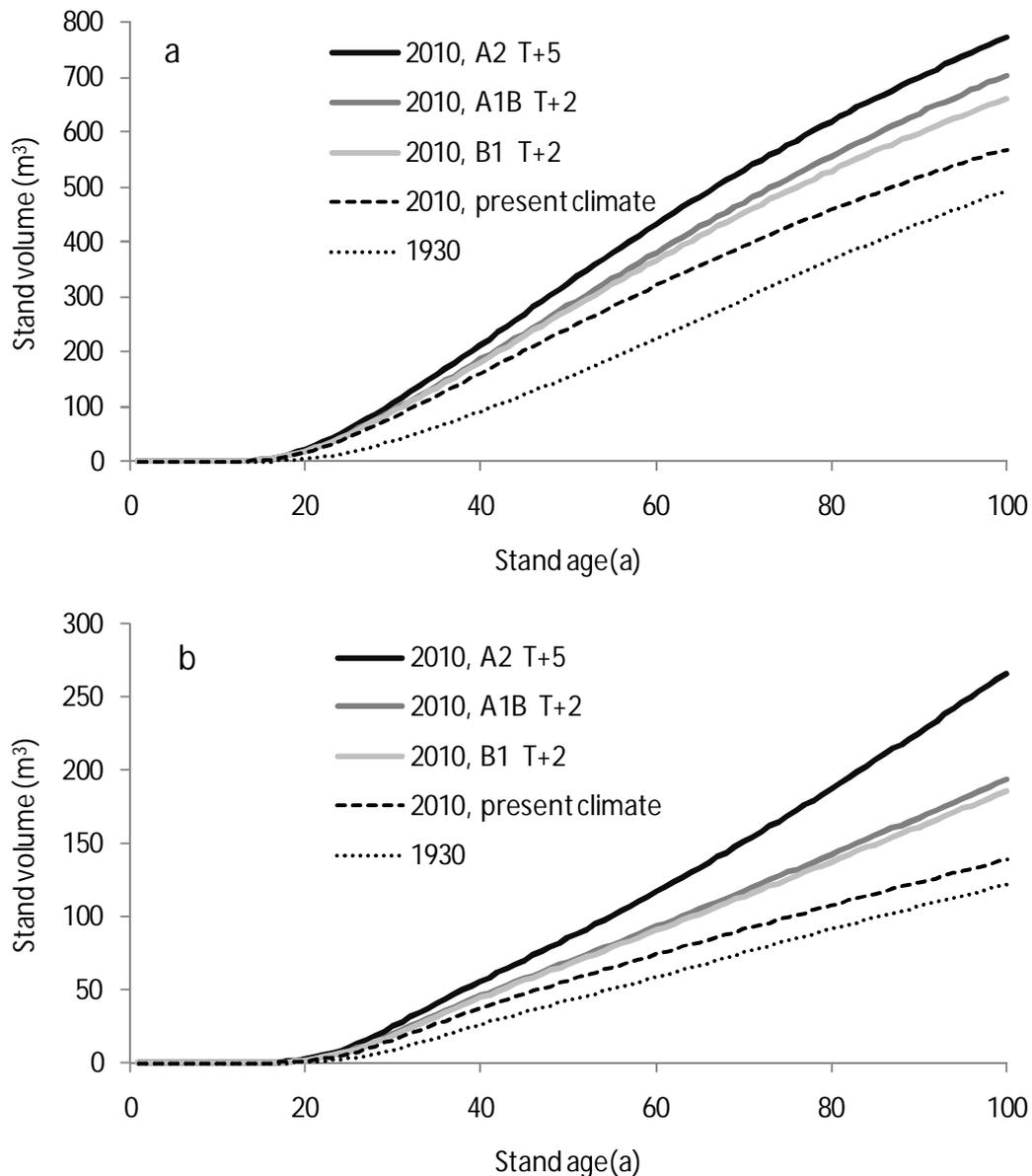

Figure 4. Projected development of stand volume in Scots pine stands in southern Finland (a) and in eastern Lapland (b). The simulated stands were established in 1930 (actual climate and nitrogen deposition history) and in 2010 with different CO_2 and temperature rise scenarios and assumption of

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nitrogen deposition remaining at present level of 0.5 g N m^{-2} a^{-1} in southern Finland and 0.2 g N m^{-2} a^{-1} in the north.

Tree species seem to have different response pattern in growth allocation as regards to the enhanced production in elevated CO_2. The nutrient use efficient conifers seem to allocate relatively more to stem while the broadleaved species had much higher allocation to fine root under elevated CO_2 (Delucia et al. 2005). Franklin et al. (2009) attributed these changes to different turnover rates of the fine roots which imposes large differences in the nitrogen usage for root growth. Due to this difference the broadleaved species that have generally more rapid root turnover rate would be more susceptible to low soil nitrogen availability than pines. However, if indeed the nitrogen availability increases in soil due to climatic warming and enhanced decomposition, it may be that the broadleaved trees may invest more of their growth to stems than pines (McCarthy et al. 2006). This is also seen in the Finnish growth and yield tables of Scots pine with saturating stem yield with the highest soil fertilities (Koivisto 1959). Some of those allocation changes are considered in the modeled response but they may be slight overestimations as not all the changes e.g. in branchiness that are associated with higher productivity are considered. We could thus suspect that the gain in stem growth may be slightly lower than predicted in the simulation for Scots pine and about the same or higher for birch.

Increase of drought days was not predicted to cause any significant reduction in the plant productivity but it may have direct influence to growth. In the long term historical growth data there was a decrease in both pine and spruce growth during dry years (Yrjönen 2008). The growth influence of drought results from the growth process itself. Trees use water pressure to expand the newly differentiated cells to the size of mature cells that are then lignified in the cell wall formation process. The water pressure is created osmotically and trees use sugars for that. If they are under water stress more sugars are needed to just maintain the cell turgor not to mention the cell expansion. If drought is persistent, the achievable final cell size remains smaller. However, if the drought is reversed also growth may resume and rather rapid expansion may follow. This naturally depends if the phase of the annual cycle still allows it. Figure 5 shows results of a modeling study that predicts how much earlier the growth starts to react to decrease in soil moisture compared to photosynthetic productivity.
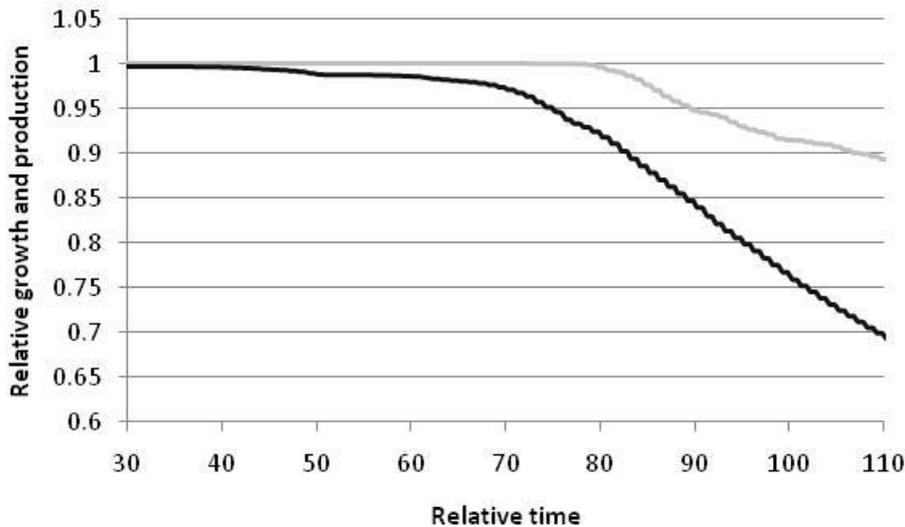
Figure 5. Relative decrease in modeled cumulative photosynthetic production (grey line) and modeled cumulative growth (black line) during 2006 drought year vs. no drought conditions.

Although the average number of drought day does not increase considerably, the climate change may imply occasional more severe drought periods that may severely influence growth and enhance leaf turnover and increased mortality. Simulation study (Mäkelä et al. 2010) showed that the number of drought days would be about double to that of 2006 with similar rainfall pattern in the new climate with elevated temperature. This would be extremely stressful for trees and almost certainly lead to increased tree mortality. The severity and extension of the drought period depend on the soil water storing capacity. The main problem in the future may follow from the combination of favorable growth years that may allow establishment of trees with too large foliage fine-root ratio and occasional severe drought that will then kill the ill suited trees.

3. Influence of climate change on the stand establishment

Open conditions after final harvest favor initially photosynthetically efficient, fast growing species. Grasses and herbs that allocate their production predominantly to productive and reproductive organs quickly conquer the space. Elevated temperature, CO_2 concentration and more rapid turnover rate of soil organic matter that releases more nitrogen to plant use will lead to eutrofication of the sites. This will favor more rapid post disturbance development of grasses and herbs (Theurilat and Guisan 2001, Manninen et al. (in print)). Also comparable size seedlings of broadleaved species such as birches are better competitors for resource capture in high resource availability during early development in comparison to conifers (e.g. Dehlin et al., 2004).

Figure 6 presents the calculated variation of grass and herb biomass both as a function of fertility class and annual temperature sum according to a model based on large forest inventory database (Muukkonen and Mäkipää 2006). The current temperature sum variation between 500 to 1300 dd is predicted to change to be between 900 to 2400 dd in 100 years in Finland. Southern Finland corresponds to current weather in Southern UK while that of Lapland corresponds to southern Finlnd. In Southern UK Ford and Newbound (1970) observed about triple the biomass of herbs and grasses 2 years after clear-cutting compared to the values of the most fertile sites in South Finland currently. On the other hand, according to Palviainen et al. (2005) the maximum ground vegetation biomass occurs 5 years after clear cutting in the current 1000 dd climate conditions. This means that both the ground vegetation competition intensifies and the opportunity window for stand regeneration becomes much shorter than currently.
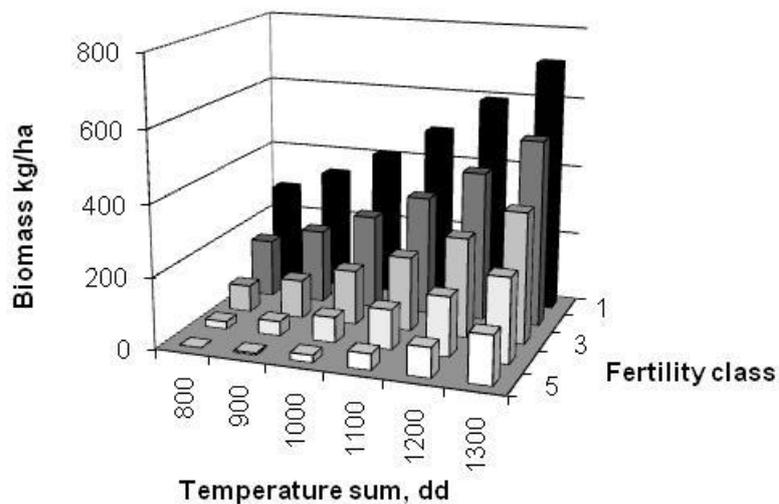

Figure 6. The post harvest biomass of herbs and grasses as a function of site temperature sum and fertility class (1 rich, 5 poor) according to Muukkonen and Mäkipää (2006)

For Southern Finland we may assume that in 2100 the peak biomass of herbs and grasses on the fertile MT site will double that of rich OMT site currently and it will be about the level in current rich OMT site on poor CT site. This will mean that eventually the stand establishment requires planting immediately after clear-cutting with rather intensive management of herb layer. Soil scarification will not be sufficient to control the ground vegetation but special treatment of herbs need to be done during the second year after planting. Also at least two treatments of the competing broadleaved trees are required. Alternatively pre-harvesting treatment of the broadleaved trees may be necessary to control the sprouting. Silviculture using coppicing and species that are suitable for it could be another alternative. In

Northern Finland the situation will correspond closely to current situation in South Finland and most likely also the recommendations currently used there could be adapted. Increasing CO2 concentration may mean, though, somewhat higher competition than presently experienced in South Finland.

4. Economic considerations

Simple optimality criterion for final harvest is that the forest stand should be regenerated when the interest expenses of land and standing stock of the forest exceed the value growth of the standing stock. The value growth consists of volume increment of trees and the transition of timber to more valuable timber assortment classes following from size growth of trees. In the complete scheme, it is normally assumed that there is an infinite number of rotation periods and the silvicultural treatments are selected that maximize the value of bare land, i.e. the amount of money one could use on purchasing land that would still pay off when considering the expected costs and revenues to establish, manage and harvest timber stock over infinity. The selected scheme is influenced by the used interest rate.

Present silvicultural recommendations for private forest owners reflect the optimality criteria, but are also influenced by other factors not always explicitly stated. They tend to recommend longer rotation times than optimality consideration with normally used interest rates that the economy nowadays would suggest. Due to high variation in the market price of timber, extending the rotation period may be rational behavior as in that way the forest owner has more options to optimize the timber price when selling the standing stock. Apart from the timber price, a number of other values influence the harvesting decision, such as scenery and recreational value of forests.

The current silvicultural recommendations for private forest owners suggest a rotation period of 80 to 100 years for a forest in medium fertile site type in South Finland and 100 to 130 years in similar conditions for the Lapland. These stands correspond to the simulated development in Figure 4. Figure 7 shows what is the standing stock at 100 years old forests in 2030 to 2110 and how much faster the standing stock would reach the volume presently harvestable at the lower age of current harvest recommendations. Both in South Finland and in Lapland the previous harvestable volume would be reached about 30 years earlier in the most extreme scenario. Assuming harvesting value of 17200 euros for the South Finland case and 5160 for North Finland case the net present value of the harvest in the previous case would increase from 1394 to 3698 euro´s and for Lapland from 360 to 1109 euro´s using a 3% interest rate. With higher interest requirement the relative effect would be even stronger.

As the simulations show, the growth in the most extreme scenario case (800 ppm CO_2 + 5 degrees increase in temperature) continues to increase linearly until 2110 so that the 100 years old forests then have more than double the volume when compared as old stands in 2030. However, the net present value of harvest at 100 years in 2110 would be only 2685 euro's and the difference is relatively even bigger for the North Finland.
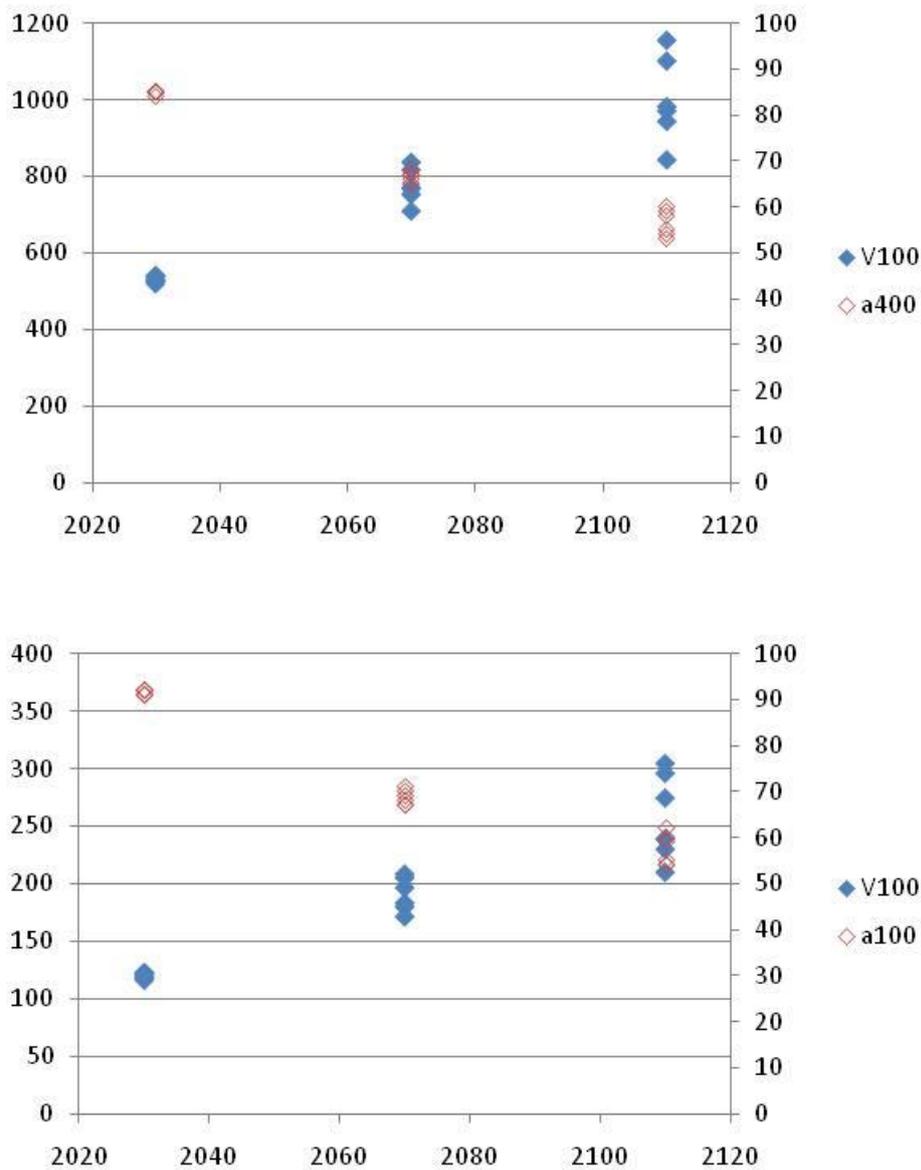

Figure 7. The growing stock of 100 years old forest under different climate scenarios (CO_2 400 to 800 and temperature +5 decrees at 2110) (blue marks) and the age at which the forest volume is 400 m^3 (South Finland, upper picture) and 100 m^3 (North Finland, lower picture)(red marks) .

This simple analysis shows that the net present value of the harvest can more than double for the South Finland and triple for the north. In this analysis we did not consider the effect of thinning. In this transient phase, the increased growth is decoupled from the need for increased effort in stand establishment as the forests have been regenerated in the current climate but the growth benefits from the improving growth conditions. However, in the long term optimization of the rotation also the establishment costs of new tree generations need to be considered. The higher the cost and the higher the growth the earlier it pays off to change the tree generation into a new one in the future climate.

5. Final remarks

The simulated climate impacts on forest productivity are in line with the experimental manipulations where the CO_2 concentration has been increased artificially at forest stand level (FACE- experients). The growth model also responds to increased rate of soil organic matter decomposition that will take place with increasing temperature and will release nitrogen for tree growth. However, quantitatively these values are still uncertain as there may be both immobilization and priming impacts that influence the nitrogen release rate. On the other hand, the analysis suggested that drought should not be a major factor influencing growth on majority of soil types.

Despite the lower growth increases than have previously been predicted for Scots pine, the analysis showed that considerable increase in the profitability of silviculture can be expected, such that northern Finland reaches similar levels as currently enjoyed in southern Finland and doubling the net present value of harvest from the present in South Finland.

In reality these values probably indicate the upper limit as it was assumed that different disturbance factors do not increase and the forest mortality is similarly related to forest density as currently. Warmer climate will expose forests to new, harmful insects and pathogens and even some of the currently harmless ones may become problematic. Although, on average, drought will not be a major factor decreasing growth, it may have an important role in triggering mortality in combination of different biotic vectors. Also climatic change will expose the forests more to the storms.

The analysis used Scots pine as indicator for expected development. Given the predicted change of higher temperatures with not much higher drought risk would favor broadleaved trees more than pine. The predicted 60% higher growth increase

in birch relatively to pine would make it a better alternative for silviculture than currently. The higher productivity will eventually allow sufficient protection of saplings in their early development. This applies also to other broadleaved trees such as oak.

In our analysis we also studied spruce behavior but did not find any drastic difference from the behavior of pine. If water stress or warm winter induce accelerated defoliation that prevent it from developing large foliage mass, it will lose in its competitive ability. Overall, the climate change impacts for spruce management can be expected similar to pine. We may expect shorter rotation but more difficulties in stand establishment. However, similar problem with wood quality as there is for pine should not concern spruce. The drought problem will be stronger than for pine and attention should be paid not to establish spruces on too coarse soils with inadequate water holding capacity. The adequate timing of thinning will be equally or more important than for pine relative to drought years.

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