

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)

Regional predictions of forest structure

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Regional predictions of forest structure

1. Introduction

1.1 Changes in regional forest structure

Regional changes in forest structure follow from natural processes acting on forests and the human forest management actions. Natural forests undergo continuous change that is characterized by the increase in plant size, consequent competition of space and growth resources, suppression and dominance of individuals and mortality of individuals. Mortality results either directly from competition or from biotic or abiotic factors leading to plant senescence. These biotic or abiotic disturbances, may be dependent on climatic factors, such as storms or fires, or they may be linked to forest structure. The abiotic disturbances may lead to large scale openings of tree canopies, while the biotic disturbances often concern only individual trees or groups of trees. The continuous chain of disturbance, recruitment and growth taking place at different temporal scale leads to variable forest structure which is spatially characterized as patches of widely different dimensions. At local scale it results into tree canopies that can be dominated by single cohorts or canopies with different size trees or multiple tree cohorts.

Increasingly, the forest structure results from man-made management where the biomass production of trees in a certain forest area is harvested and brought to human use. These practices alter mainly the disturbance process, influencing the size and quality of openings formed in the tree canopy and the age of the dominant trees. Silvicultural practices of soil scarification and artificial regeneration through sowing or planting and tree stand thinning aim at favoring selected species and individuals and increasing the value of growing trees.

Climate change influences practically all of the above processes and the resulting forest structure follows from a combination of climate change influences and alterations in forest management. In the boreal Fenno- Scandia temperature will rise faster than the global average, precipitation will increase somewhat along with the global increase in the CO₂ concentration. The changes will have impact on the frequency of natural disturbance factors, mainly windthrows (Peltola et al. 1999) and biotic causes that spreading of new species of animals and fungi and changes in the behavior of the existing ones will cause. However, as Finnish forests are predominantly managed, it is expected that the role of natural disturbance factors will also remain small in the future. This makes the estimation of changes very

challenging as one needs to account for changes in human preferences along with vegetation changes.

Natural vegetation change with climate is buffered as existing established populations tend to be able to resist out competition even in suboptimal conditions (Chapin et al. 2004). Forestry operations could actively introduce both new provenances and entirely new species as adaptive forestry (e.g. Kellomäki et al. 2005). From the forest management point of view the most important changes will be those related to the change and establishment of vegetation after the disturbance and the consequent competition between species, first between grasses, herbs and the trees, then between trees of different species and lastly the growth and development of established tree population (Nikinmaa et al. 2010).

1.2 The approach of the analysis

A number of Forest ecosystem and growth models have been developed that are applicable to Finnish conditions (Kellomäki et al. 2005, Koca et al. 2005) but their predictions, although qualitatively similar, are quantitatively different. Also the model behavior against results from experiments of long term exposure to elevated CO₂ concentration has not always been very good (Palmroth, personal communication). One aspect that makes the future prediction very difficult is connected to very variable level of information that we have on the physiology and structural development of different plant species. The information that a climate change sensitive prediction would need is very scarce with the ground vegetation but also with some tree species.

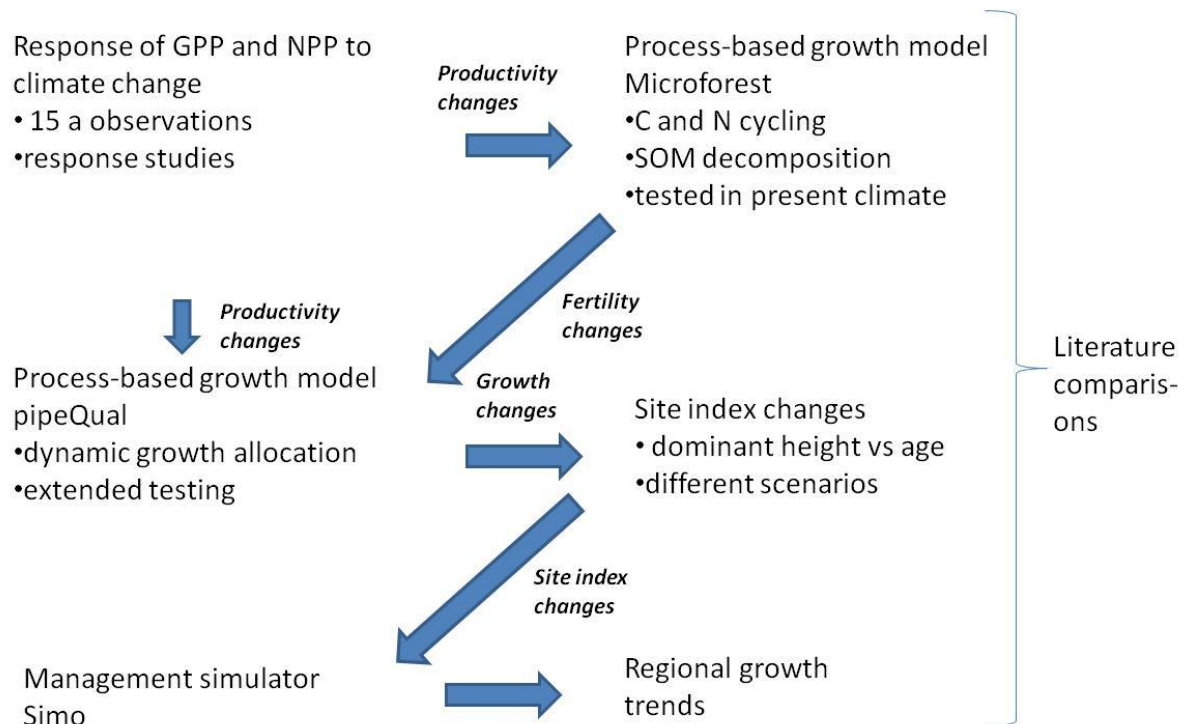


Figure 1. Schematic presentation of the used approach to analyze climate change impacts on forest productivity

For the reasons mentioned above, we chose a new and independent method from the previous modeling exercises to estimate the impact of climate change on forest growth. The approach is summarized in Figure 1. The basic idea of the approach is to use well known tree species as an indicator of the impact of climate change on the growth conditions and then use currently widely available data on the growth conditions on the performance of different tree species and ground vegetation. The analysis formed a chain in which long term, data intensive observations and short term exposures to elevated CO₂ concentrations were used to parameterize tested productivity model (SPP, Mäkelä et al. 2006) to estimate climate related changes in leaf and crown specific gross primary production (GPP), respiration and net primary production (NPP). This model was used in combination with climate change scenarios to estimate productivity changes. The productivity changes and climate change scenarios were used in combination of tested forest stand growth model MicroForest (Hari et al. 2008) that considered explicitly carbon and nitrogen cycles in forest, influence of climate to them and response of tree growth to changes in GPP and nitrogen availability. The simulation results from MicroForest were used to estimate soil fertility changes. The fertility and GPP changes were used to drive a widely tested PipeQual model (Mäkelä and Mäkinen 2003) that concentrates wide range of measurements of structural properties and regularities and derives the tree growth, growth allocation and dimensional development using the crown specific

GPP and soil fertility as driving variables. Model PipeQual was then used to simulate stand fertility change for the different climate change scenarios in terms of site index based on the dominant height of trees, a value that is used in management models to estimate tree growth using empirically derived growth relationships. The change of the site index based on Scots pine growth changes was then used together with empirical growth functions for different species to estimate potential for forest management and regional forest development with management model SIMO (Rasinmäki et al. 2009).

The main assumption of the last step in the approach was that the changes in the above and below growing conditions of trees is reflected on their dimensional development. Due to the functional- structural interactions within trees the development trends in the dimensional relationships remain the same independent of the driving conditions that have caused the changes and the relationship between the site index based on the dominant height and the tree growth at different ages remain the same. This assumption allowed us to use the very well known and widely distributed Scots pine as an indicator species for the expected changes and then rely on the ample data of empirical growth observations and models condensed out of those on predicting the expectable changes on other species.

In this document we will briefly describe the main results at the different steps of the analysis but concentrate on the description of the regional analysis. A more detailed explanation of the results of the intermediate steps can be found on the earlier working papers of this life action (Nikinmaa et al. 2010, Kolari et al. 2011).

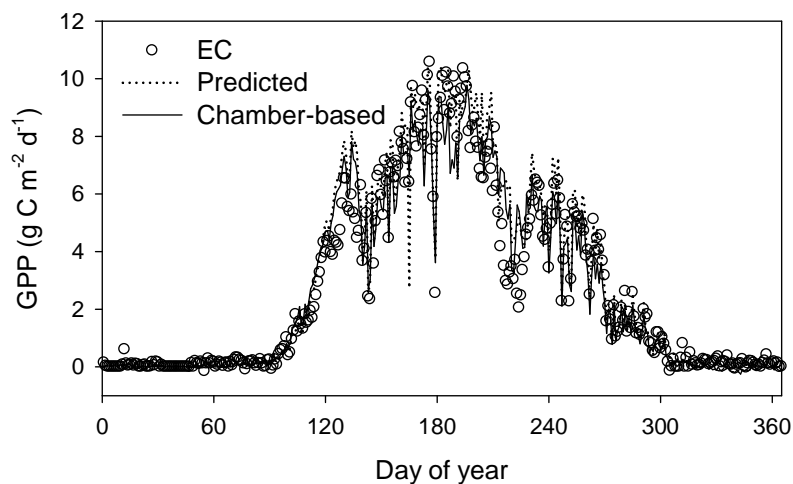
2. Process-based analysis of climate change impacts on site quality

2.1 Climate change impacts on GPP of pines (GPP)

We estimated the potential increase in photosynthetic productivity in Scots pine (*Pinus sylvestris*) due to direct effects of increasing temperature and CO₂. We calculated photosynthetic production of a single leaf in half-hourly time steps with leaf intercepted radiation, temperature, atmospheric vapor pressure deficit and CO₂ concentration and soil water status as variables driving the photosynthetic rate using a biochemical model of photosynthesis (Farquhar et al., 1980) along with a model of stomatal conductance (Leuning (1990)). 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).

Photosynthetic production of the trees was determined by integrating the instantaneous photosynthetic rate at shoot (pine) 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., 2007). In the model 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 2).



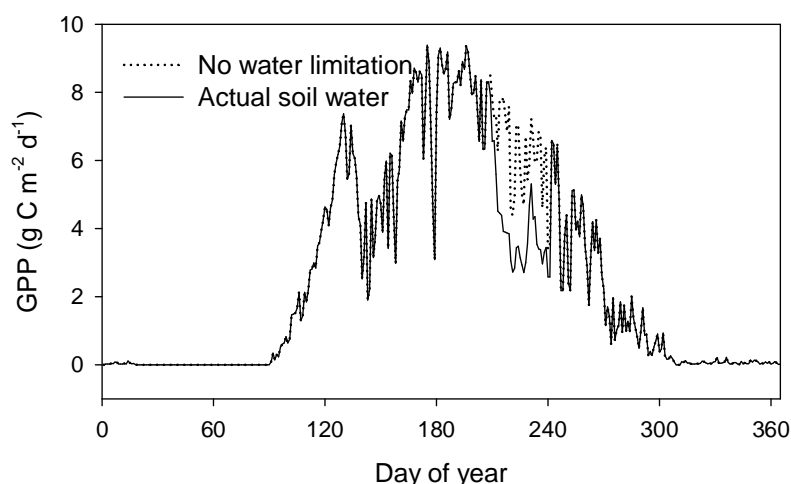


Figure 2. Daily photosynthetic production (GPP) of the stand during year 2006: a) GPP extracted from eddy covariance, upscaling directly from chamber measurements, and prediction with SPP (Kolari et al. 2009), b) predicted stand GPP with no soil water limitation on tree gas exchange and GPP with the 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 a climate change scenario (Jylhä et al., 2009) that corresponds to approx. 50% increase in the emissions of CO₂ from fossil fuel combustion by 2050 and a slow decline after that (scenario A1b, Table 1). Climate change modified weather data from Hyytiälä was used as the model input. All half-hourly records of air temperature and atmospheric CO₂ were increased by the mean annual temperature rise and CO₂ 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 CO₂ and mean annual temperature in Finland according to Jylhä et al. (2009).

Year	CO ₂ (ppm)	T increase (deg C)
2025	430	1
2055	540	2
2085	650	3

The analysis predicted that annual GPP will increase about 25% by 2100. 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 CO₂. The model predicts a decline in instantaneous transpiration rates in the mid-summer, but due to the longer growing season in the future, the annual cumulative transpiration will remain approximately at the present level. Increasing CO₂ enhances water-use efficiency as the stomata tend to open less at elevated CO₂ than in present CO₂. The free-air CO₂ enrichment studies have shown no significant change in the stomatal responses to CO₂ (Medlyn et al., 2001). Increasing stand foliage area, however, may partly offset the enhanced water-use efficiency.

Overall, drought will probably remain a minor risk for forest productivity in Finnish conditions in the future if the temporal distribution of precipitation over the growing season remains similar to the present conditions. The predictions done with SPP model assuming climate change scenarios and using known soil properties showed that the number of drought days (i.e. days when photosynthetic production drops below 50% of the potential) will slightly increase on average towards the end of the century, but the increase is just two to five days from the present (Mäkelä et al., 2010).

Responses to changing climate include also changes in net productivity (NPP) as changes will also influence the respiration rate. Experiments with long term exposure to elevated CO₂ in temperate climate have shown considerable increase in net primary production (NPP, i.e. photosynthetic production minus respiratory losses) (Franklin et al., 2009). Temperature increase will instantaneously influence respiration rate (eg. 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.

At leaf level, conifer productivity is expected to rise more than in broad leaved trees but at the canopy scale the differences are partially compensated by the relatively higher leaf area to present that the broad leaved trees are able to produce. Another factor influencing the productivity is enhanced nitrogen availability for trees that follows from accelerated nutrient turnover in the soil. This will potentially have a stronger influence on broadleaved than conifer trees (Ripullone et al., 2003). Higher nitrogen availability may increase the maximum photosynthetic rate particularly in

broadleaved trees. However, the additional nitrogen may also increase leaf growth. The results from long term CO₂ enrichment experiments would tend to suggest that in forests with rather low leaf areas the increased leaf area may be the dominating influence (Norby et al., 2005). Elevated CO₂ and nitrogen availability increase the leaf area duration (McCarthy et al., 2006). At higher leaf areas there also seems to be an enhancement in the light use efficiency of the leaves (Norby et al., 2005, McCarthy et al., 2006). Overall, the vegetation acclimation to new growing conditions will influence the predictions that are done assuming current response pattern to changing conditions. The elevated CO₂ concentration will most likely decrease the predicted difference between the conifer and broadleaved species but simultaneously the predicted increase in the nitrogen availability has an opposite effect.

2.2 Changes in tree growth including the changes in site fertility caused by climate change

Biomass production changes of pine forest was further studied with model 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 fine-roots from determined structural regularities between the wood dimensions and amount of foliage and from the requirement 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 in unshaded conditions, 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 CO₂ and temperature. The rate of decomposition was increased by 6% per °C rise in temperature. Nitrogen deposition was assumed to remain at the present level.

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 3). This largely resulted from lower allocation below ground. Average growth increment in closed-canopy stands with CO₂ scenario B1 and mean annual temperature rise of 2°C was 16% and 31% in southern Finland and in Lapland, respectively. The extreme CO₂ 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 (Strömberg 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 CO₂ are certain to produce growth acceleration as predicted (Magnani et al. 2007)

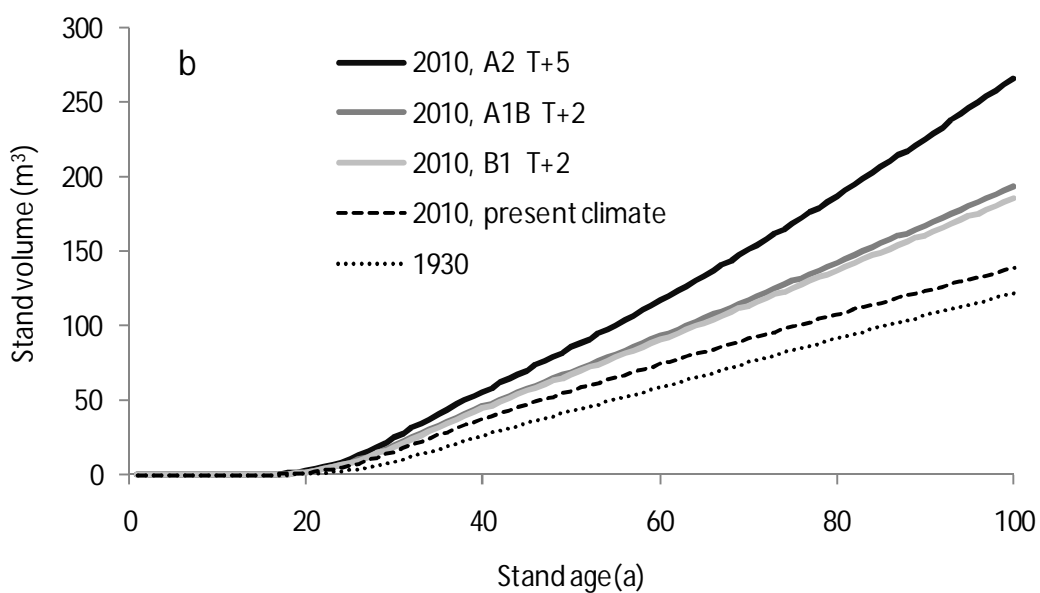
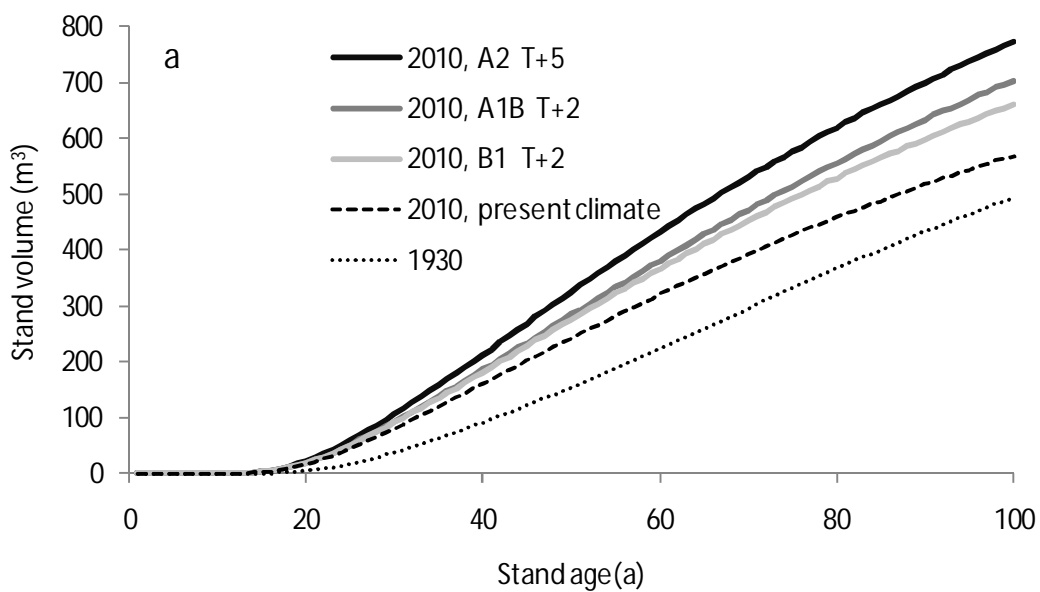


Figure 3. Projected development of stand volume in Scots pine stands in southern Finland (a) and in eastern Lapland (b). The simulated stands were established in 1930 (actual climate and nitrogen deposition history) and in 2010 with different CO₂ and temperature rise scenarios and assumption of nitrogen 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 CO₂. 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 CO₂ (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).

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 slight decrease in both pine and spruce growth during dry years (Yrjönen 2008). 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. 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 for possible soil- drought combinations and occasional severe drought that will then kill the ill suited trees.

Bearing in mind the uncertainty involved in the scenarios and possible other factors concerning the vegetation response the conservative assumption that the current productivity relationships between species at different site fertility classes are maintained, is justified. As the literature review showed, the direct and indirect influences of elevated CO₂ and temperature cause opposing response patterns between conifers and broadleaved trees that may cancel each other out.

3. Climate change impacts on site fertility changes

We use the stand growth simulator Pipe Qual (Mäkelä and Mäkinen 2003) to analyse the impact of higher productivity on the pine stand growth and development of stand dimensions. This model was used rather than MicroForest because its simulation time requirement was much shorter than in MicroForest and the development of tree dimensions and particularly the height over the stand development, which is critical for the site quality estimations, has been more widely tested in PipeQual than in MicroForest. Model PipeQual is a process based model that is based on carbon balance and dynamic allocation of growth. The latter is derived from functional balance considerations that assume that the structural growth of tree compartments needs to match their functional capacity. The model considers the nitrogen influences by parameter describing the nitrogen uptake by unit carbon used for roots and the nitrogen concentrations in different plant biomass compartments. The dimensional development and allocation to stem and branch growth is derived from large data-set of observations of structural regularities that are also physiologically justified. The model has been tested widely against observations and it has been able to reproduce well the observed trends (Mäkelä and Mäkinen 2003)

To simulate the climate change impacts with model PipeQual, the same changes in specific photosynthetic and respiration rates were used as in MicroForest. To account for the changes in the soil fertility the model MicroForest was run with constant 2100 climate for the different scenarios. The parameter describing soil fertility in the model PipeQual was then varied to produce same forest biomass production as obtained with model MicroForest. In these simulations both models assumed pine monocultures without between species competition. This way we obtained the productivity parameters for 2100 climate for the different scenarios. As the used scenario changes and changes in GPP, NPP and soil changes in MicroForest were linear in time, we also assumed and that the soil changes in PipeQual take place linearly from now to 2100. The used parameters are given in Table 2. Subsequently the model PipeQual was used to simulate the stand development assuming constant parameter values for every scenario and year between 2000 and 2100. This gave the site quality value of that year expressed with site index using dominant height at 50 years.

Table 2 Parameter values that were varied in the model PipeQual

Modification in leaf specific photosynthesis rate

Scenario	B1	A1b	A2
in 100 years	16%	31%	41%

annual increase from 2000	0.16% $2*0.16/100=0.0032$	0.31% $2*0.31/100=0.0062$	0.41% $2*0.41/100=0.0082$
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Modification in respiration rates

Scenario	B1	A1b	A2
in 100 years	16%	31%	41%
annual increase from 2000	0.16%	0.31%	0.41%
leaves	$0.2*0.16/100=0.00032$	$0.2*0.31/100=0.00062$	$0.2*0.41/100=0.00082$
stem	0.000024	0.000046	0.00006
roots	0.00024	0.00046	0.0006

Modification in root parameter

Scenario	B1	A1b	A2
increase in available N	14%	31%	54%
new alfa in 100y	$1/(1.14*1/x)$	$1/(1.31*1/x)$	$1/(1.54*1/x)$
VT 0.56	0.49	0.43	0.36
MT 0.43	0.38	0.33	0.28
OMT 0.22	0.19	0.17	0.14

Figure 4 shows how the site fertility is expected to change in the basic scenario (A1) and Figure 5 shows what is the annual change in the site fertility as a function of year 2000 site index (H_{100}) in different scenarios. From both of the pictures can be seen that the change in fertility is highest on the poorer sites and from Figure 5 that the pattern is clearer the higher temperature and CO₂ scenarios used. Empirical models derived in the current climate give about equal increase in site index when going from northern Finland to south, however, direct comparison is difficult with climate change. Smaller increase with higher site index is logical in that sense that in

fertile stands the growth is closer to the absolute limit that radiation interception sets on productivity than on more infertile areas.

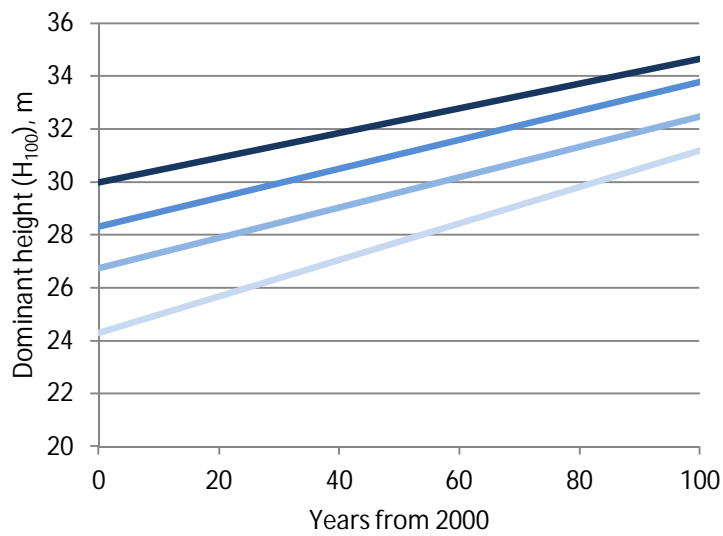


Figure 4. The predicted change of site index (H_{100} , stand dominant height at 100 years) in the average climate change scenario (A1b)

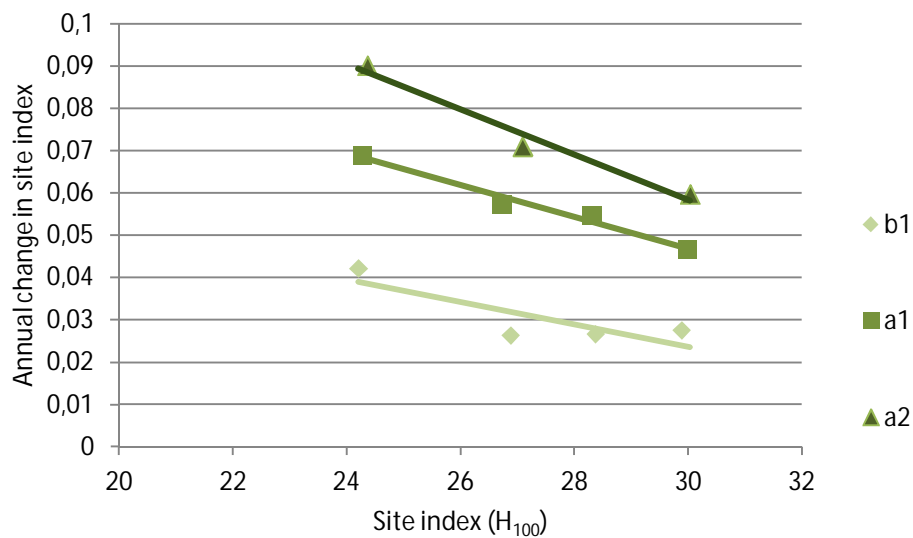


Figure 5. Annual change of site index as a function of initial site index values for different climate scenarios (b1 (light green), A1b (medium green) and A2 (dark green)).

4. Regional changes in forest structure

To study the impacts of climate change on regional forest structure and forest management potential the site quality change that was derived in the previous analysis using Scots pine as an indicator species was used in an adaptable simulation framework for multiscale forest resource data SIMO (Rasinmäki et al. 2009). Table 3 represents the annual change of site quality as a function of the initial site quality index for the different climate change scenarios that were used in the simulations.

Table 3. Annual change of site index (Hdom100) as a function of initial site index by different scenarios. The used equation was $d(\text{site index})/dt = \alpha \text{SI}(\text{initial}) + \beta$

Scenario	α	β
b1	-0.0026	0.1024
A1b	-0.0038	0.1598
A2	-0.0053	0.2186

The simulations were done for the VACCIA action 9 case study region of Häme from where the forest data from 25km radius around the university of Helsinki forestry station Hyytiälä was used. The data came from the Finnish forest research institute's multisource inventory (Tomppo et al).

Figures 6 and 7 present the current situation in the forest. As can be seen from Figure 6, the better the size class the higher the stand volume but there are no differences between the two most fertile size classes. The actual average stand volumes are also much lower than would be for single fully stocked stands resulting from management activities at the site. Most of the forests are also very young, about 65% are less than 60 years old and most of them are growing on medium fertile site class 3 (Myrtillus-type forests). The age distribution of the forests is younger the better the fertility class. This reflects the management activities. The better is the site type, the higher is the average forest growth and the younger it pays off to regenerate the stand (see Figure 8).

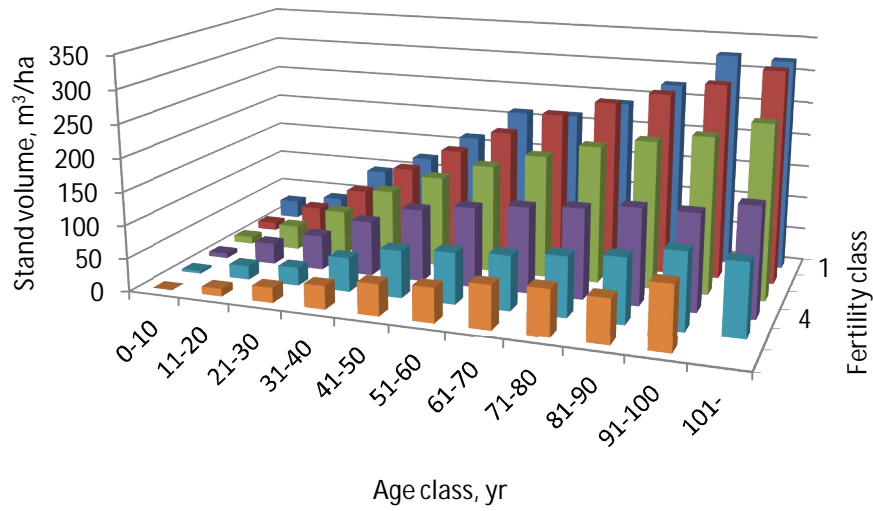


Figure 6. The average stand volume by age and fertility classes in the forests of the VACCIA action 9 case study area of Häme.

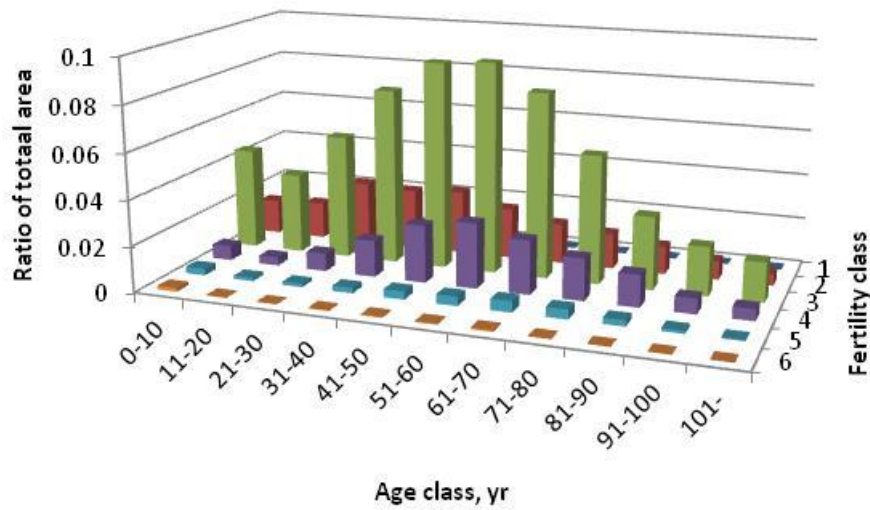


Figure 7. Proportion of forest stands in different age and fertility classes in the forests of the VACCIA action 9 case study area of Häme.

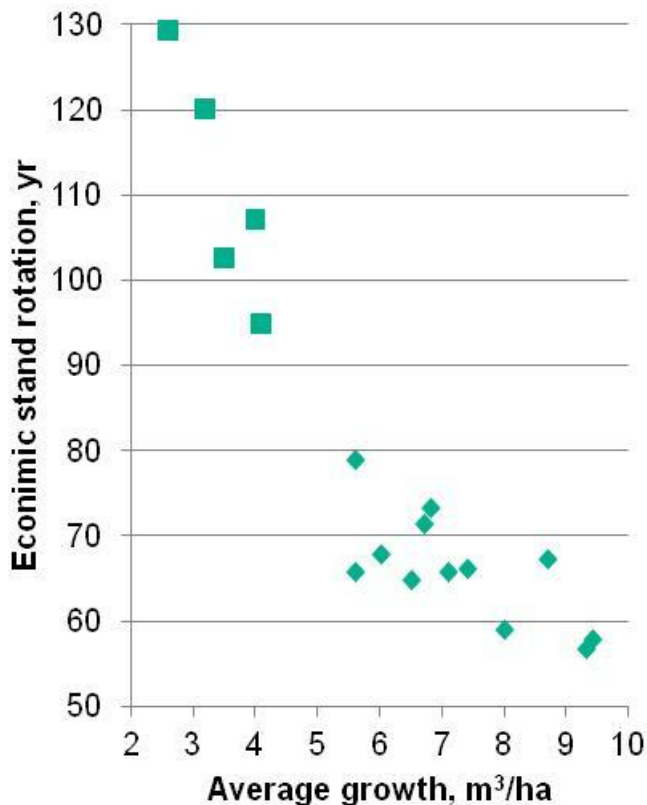


Figure 8. The relationship between the length of economic stand rotation length and the average growth during the rotation length.

With climate change the stand productivity will change. This means that even in the basic scenario, all the forests will be by 2100 in the fertility class 2 or better. Also the combination of elevated temperature and CO₂ will further increase the forest productivity by about 20% even in the most fertile classes. It would seem that the average stand volume would thus increase considerably during the next 100 years, increasing simultaneously the carbon storage in trees. Simultaneously, the organic matter turnover in the soil would increase, suggesting a decrease in the soil carbon storage. Simulations with the model MicroForest have suggested though that the increased nitrogen availability to vegetation that results from the more rapid organic matter turnover would facilitate so much higher vegetation growth and litter input to soil, that it would compensate for the increased turnover rate and no decrease in soil carbon storage would follow (Hari et al. 2008).

Although the fertility change would suggest higher average stand volumes in the future, it would also mean that the average rotation length would reduce. So even if the stand productivity would increase, the average stand volume in the area might not. However, the annual drain of timber from the area would increase substantially.

It is clear that the fate of the regional forest structure will depend on the adaptation of forest management to the changing conditions. Its prediction is somewhat difficult as both the optimal forest management strategy is very much dependent on the stand conditions and also the forest owners preferences may value also other aspects than just optimizing economic returns. One aspect that will influence the situation is carbon trade and if carbon stored in forests will have commercial value.

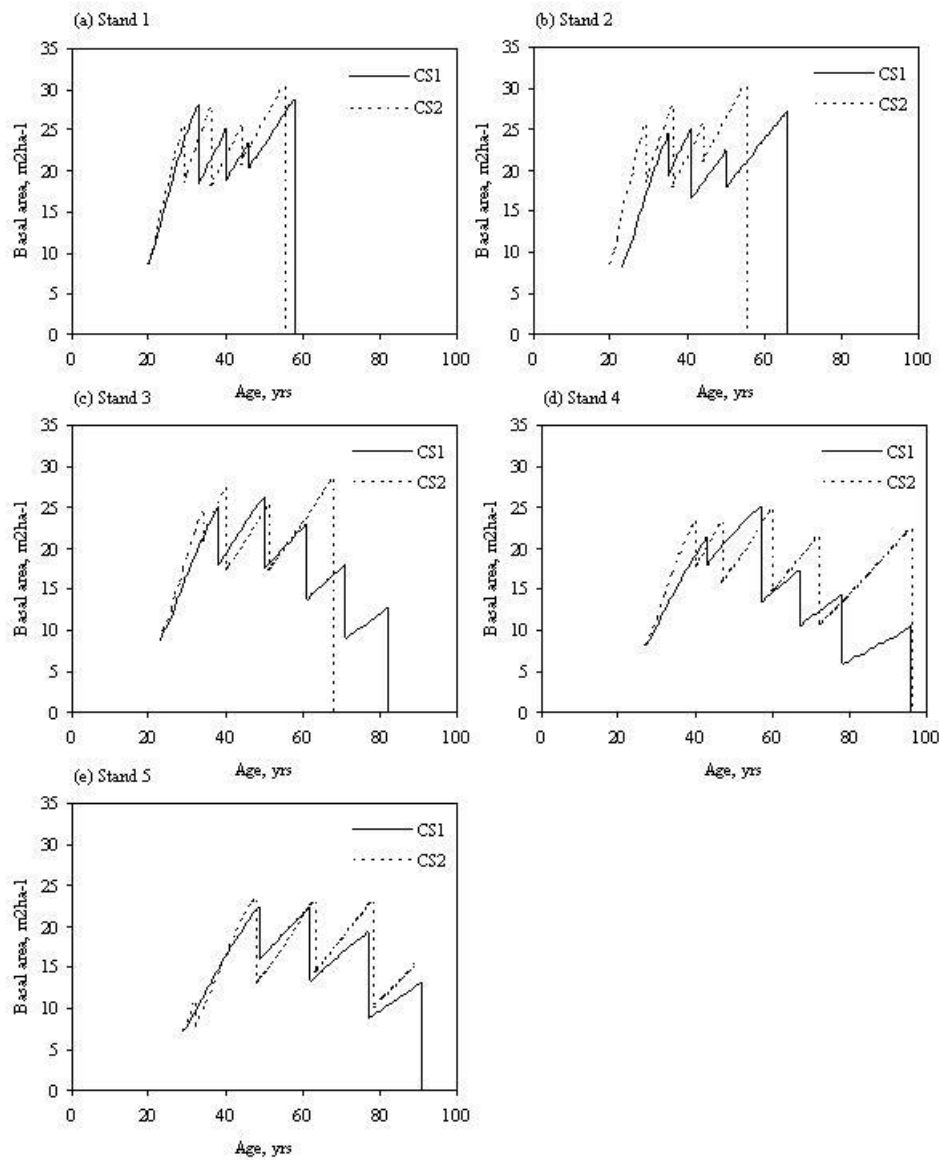


Figure 9. Economically optimal management scenarios for current (continuous line) and changed (A1b scenario, dotted line) climate for fertile (a and b, *Myrtillus*-type), medium fertile (c and d, *Vaccinium*-type) and poor (d, *Calluna*-type) stands.

Figure 9 presents how the climate change according to the basic scenario influences optimal management regime on fertile, medium fertile and poor site types. There is a tendency that slightly higher growing stock and shorter rotation length would be optimal but there is a lot of variation depending on the site (see Table 4 for stand properties). If the price of carbon stored in the forests could be considered as an income to the forest owner, then the rotation length would be influenced by the price-level of carbon. Figure 10 shows that the influence may be of the order of 30 years in the present conditions and the influence would be the strongest as the price of carbon rises from 20 to 40 euros per ton. In the EU carbon trade, the price fluctuated between 20 to 30 euros per ton in 2005 to 2008. Since then the price level has come down for various reasons, being now close to 10 euros per ton.

Table 4. Initial stand states of five Scots pine stands for which the optimal management scenarios were calculated. BA = stand basal area, m²/ha, Hdom = dominant height, m, H100 = Site index, ST = Site type, TS = Temperature sum (degree days)

Stand	Age	#tree	BA	Hdom	H100	ST	TS
1	20	2000	8.6	7.8	27.9	MT	1300
2	23	2000	8.1	7.8	25.4	MT	1300
3	23	2000	8.8	7.8	21.9	VT	1100
4	27	2000	8.2	7.7	18.4	VT	1100
5	29	2000	7.3	7.7	17.6	CT	1300

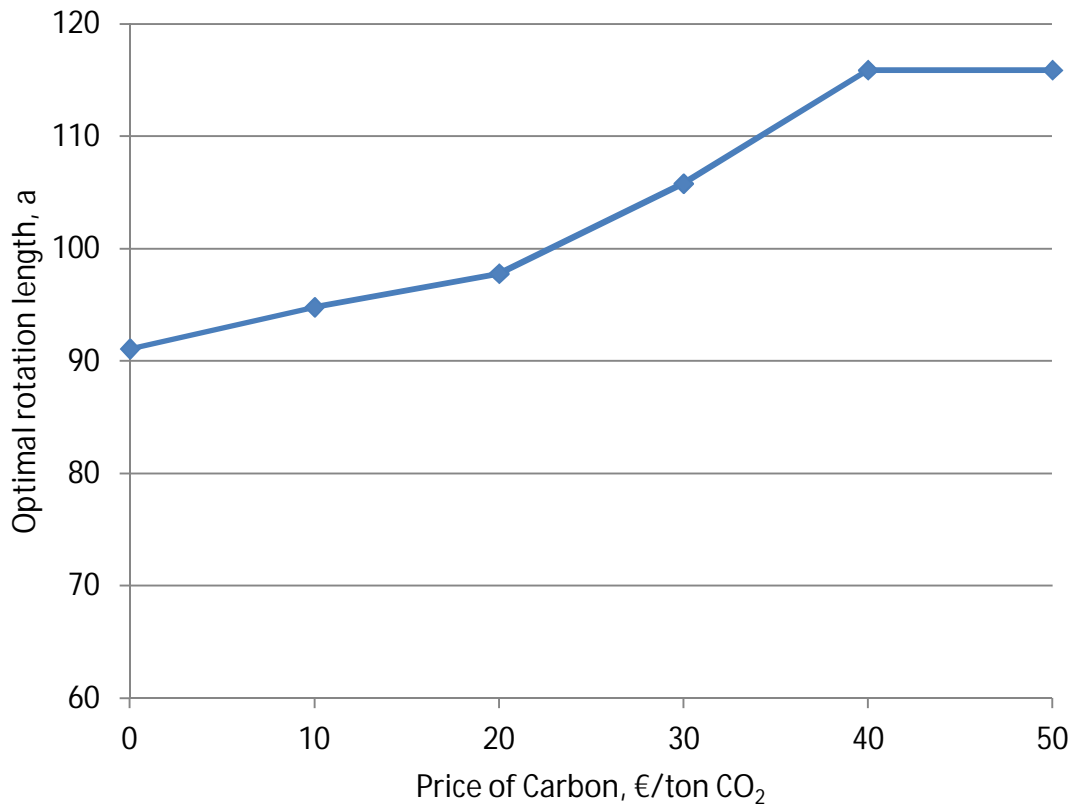


Figure 10. Optimal rotation length as a function of price of carbon.

Climate change has been predicted to favor broadleaved trees over the conifers in the Scandinavia (Kellomäki et al. 2005, Koca et al. 2005). Also our analysis predicted that elevated temperature and CO₂ and better nitrogen availability would favor broadleaved trees over the conifers (Nikinmaa et al. 2010). One important factor in that trend is due to the much better ability of broadleaved trees to compete against the much more vigorous ground vegetation in the changing climate conditions (Nikinmaa et al. 2010, Kolari et al. 2011). The same tendency would seem to follow judging from the observed species distribution at the case study area (see Figure 11). The broadleaved trees become more abundant as the site fertility is increasing while the pine and spruce become less common. In earlier analysis predictions have shown spruce to be particularly sensitive to climate change in southern Finland (Kellomäki et al. 2005). However, in our case study area droughts are not predicted to become much more common while there would be general eutrofication of the growing sites. This would mean that pine might suffer more than spruce in its abundance. The commonness of species naturally depend on the intensity of silviculture. The economic analysis indicated that the improved tree growth would allow more intensive treatments at forest regeneration phase that would enable both pine and spruce regeneration. Both these species are currently

avored over the broadleaved trees in their respective growing sites (spruce from fertile to rich and pine from medium fertile to poor) as their economic value growth is better. This situation may change as trees are being used to different purposes (such as energy and biofuels). This would naturally directly influence also the expected species distribution in the future forests.

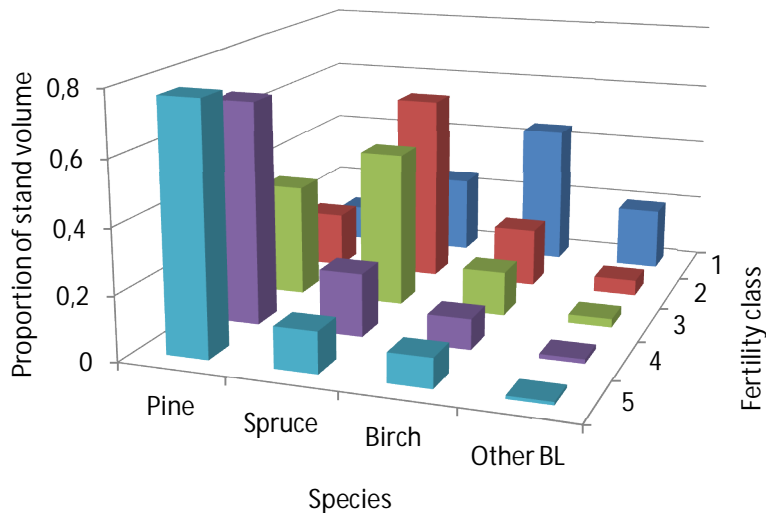


Figure 11. The species distribution (proportion of stand volume) at different stand fertility classes.

In reality the changes take place gradually over the years and forests of different ages have different response to improved growing conditions. Figure 12 shows the changes in the total growing stock over the next 100 years at our case study area of Häme as simulated with the model SIMO (Rasinmäki et al 2009) assuming present conditions and the mild climate change scenario (B1). In the model the climate change influence was estimated using the before presented changes in the site index over the year but it was assumed that the relationship between the site index and the growth would remain the same. The site index values for Scots pine were used and it was assumed that the relationships between the dominant height based site index values between tree species would remain constant.

As can be seen from the Figure 12 the climate change impacts at regional level are much more modest than they are at single stand level. The stand regeneration criteria were assumed the same as used in the current forest practices. The present forest structure naturally reflects very strongly on the development of the forest and as the current, predominantly middle aged forest reach the maturity, they are regenerated and the total standing stock starts to reduce in the simulations between 2020 and 2030. At around 2070 the standing stock starts to grow rapidly and the clear differences between current and changed climate can be seen, so that by 2100 the standing stock is about 10 % higher in the changing climate than it would be in the current. This is about half of the increase estimated for a single stand. Although there was no big change in the growing stock in the next 50 years, the changed climate allowed higher annual harvest (Figure 13).

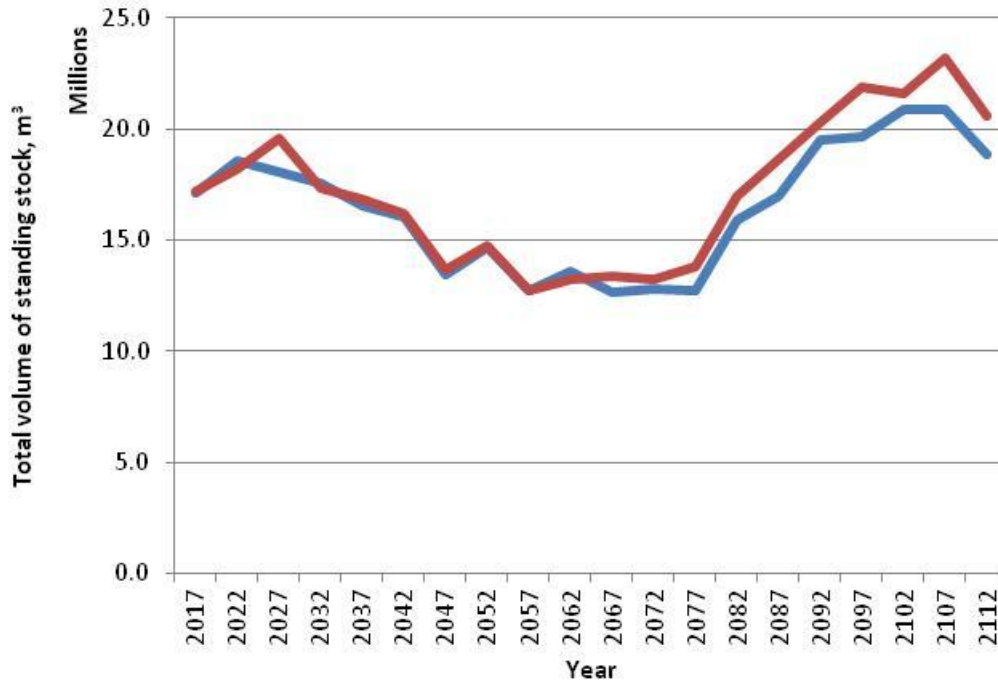


Figure 12. The simulated development of total standing stock (m³) at the case study region of Häme for current climate (blue line) and assuming a climate change scenario B1 (red line).

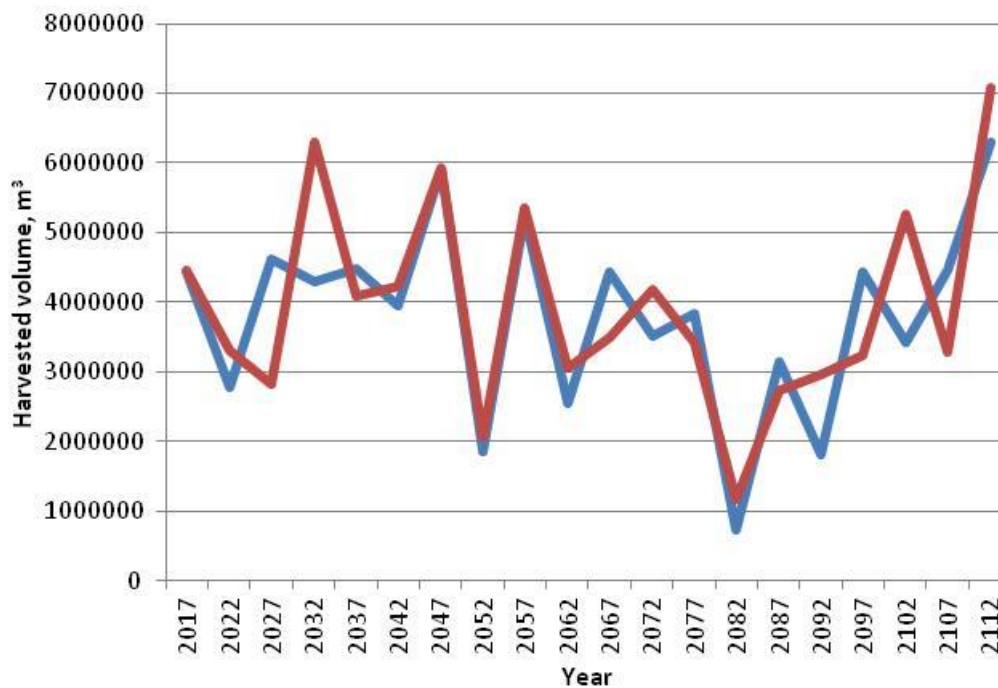


Figure 13. The simulated development of annual harvest (m³) at the case study region of Häme for current climate (blue line) and assuming a climate change scenario B1 (red line).

The above analysis does not consider other disturbance factors than management. The position of the case study region and fertile site types suggest that drought related questions will not be significant in this region. Simulation results presented in earlier Vaccia action 9 working papers (Nikinmaa et al. 2010) showed that on average there will not be drought problem on such soils as there are in this area. Global fire risk analysis (Petchony & Schindel, 2010) also suggest that there is not higher risk of forest fires in this region either. As Peltola et al. (1999) suggested, the milder winter may increase the risk of wind-throws. Also increasing winter precipitation may signify occasional heavy and wet snowfall that can cause increasing snow damage. During the recent years the region has seen both heavy summer storms and snow breaking tree crowns at large areas. The biotic stress from insects and pathogens will increase with longer growing season but simultaneously tree growth becomes more vigorous and the rotation lengths get shorter that can compensate for this increasing biotic stress. Its consideration in the management decisions will be, nevertheless, more important than currently.

5. Conclusions

Higher forest growth and standing stocks can be expected at regional level, but the changes are smaller than would be expected based on simulations of single monoculture stands of Scots pine. The current forest structure and the adapted silvicultural regime will have a major impact on the expected outcome. Increased fertility will enhance productivity but is associated with lower longevity of trees due to silviculture, species changes and disturbance frequency.

6. Cited literature

Chapin, III, F.S., Callaghan, T.V., Bergeron, Y., Fukuda, M., Johnstone, J.F., Juday, G and S. A. Zimov. 2004. Global Change and the Borea Forest: Thresholds, Shifting States or Gradula Change? *Ambio* Vol. 33 No. 6:361-365.

DeLucia EH, Moore DJ, Norby RJ. 2005. Contrasting responses of forest ecosystems to rising atmospheric CO₂: implications for the global C cycle. *Global Biogeochemical Cycles*, 19, 1–9.

Dessler A.E. & Sherwood S.C. 2009. A matter of humidity. *Science* 323:1020–1021.

Duursma R.A., Kolari P., Perämäki M., Nikinmaa E., Hari P., Delzon S., Loustau D., Ilvesniemi H., Pumpanen J., Mäkelä A. 2008. Predicting the decline in daily

maximum transpiration rate of two pine stands during drought based on constant minimum leaf water potential and plant hydraulic conductance. *Tree Physiology* 28, 265-276.

Ellsworth DS, Reich PB, Naumburg ES, Koch GW, Kubiske ME, Smith SD. 2004. Photosynthesis, carboxylation and leaf nitrogen responses of 16 species to elevated pCO₂ across four free-air CO₂ enrichment experiments in forest, grassland and desert *Global Change Biology* 10: 2121–2138.

Farquhar, G.D., S. von Caemmerer and J.A. Berry (1980). A biochemical model of photosynthetic CO₂ assimilation in leaves of C₃ species. *Planta* 149, 78.

Franklin, O., McMurtrie, R.E., Iversen, C.M., Crous, K.Y., Finzi, A.C., Tissue, D.T., Ellsworth, D.S., Oren, R. and R.J. Norby. 2009. Forest fine-root production and nitrogen use under elevated CO₂: contrasting responses in evergreen and deciduous trees explained by a common principle. *Global Change Biology* 15:132-144.

Hari, P., M. Salkinoja-Salonen, J. Liski, A. Simojoki, P. Kolari, J. Pumpanen, M. Kähkönen, T. Aakala, M. Havimo, R. Kivekäs and E. Nikinmaa (2008). Growth and development of forest ecosystems; The MicroForest Model. In: Hari, P. and L. Kulmala (eds.) Boreal forest and climate change. Advances in Global Change Research, Vol. 34 (Springer Verlag), 433.

Jylhä, K., K. Ruosteenoja, J. Räisänen, A. Venäläinen, H. Tuomenvirta, L. Ruokolainen, S. Saku and T. Seitola (2009). Changing climate in Finland: estimates for adaptation studies. Finnish Meteorological Institute, Reports 2009: 4.

Kellomäki, S., Strandman, H., Nuutinen, T., Peltola, H., Korhonen, K.T. and Väisänen, H. 2005. Adaptation of forest ecosystems, forests and forestry to climate change. FINADAPT Working Paper 4, *Finnish Environment Institute Mimeographs* 334, Helsinki, 50 pp.

Koca, D., Smith, B. and M.T. Sykes. 2006. Modelling regional climate change effects on potential natural ecosystems in Sweden. *Climatic Change* 78: 381–406

Koivisto, P. 1959. Kasvu- ja tuottotaulukoita. Summary: Growth and yield tables. *Communicationes Instituti Forestalis Fenniae* 51.8. 1–49 s.

Kolari, P., Valsta, L., Nikinmaa, E., Cao, T., Mäkelä, A., Hari, P. and Hölttä, T., 2011. Impact of Changing Climate on Optimal Silviculture. Technical report, ACTION 9: Assessment of impacts and adaptation measures for forest production; Case study at Northern Häme and Lapland. Vulnerability assessment of ecosystem services for climate change impacts and adaptation (Vaccia)

Kolari P, Kulmala L, Pumpanen J, Launiainen S, Ilvesniemi H, Hari P, Nikinmaa E 2009. CO₂ exchange and component CO₂ fluxes of a boreal Scots pine forest. *Boreal Environment Research* 14, 761-783.

Kolari, P., Lappalainen, H.K., Hänninen, H. & Hari, P. 2007. Relationship between temperature and the seasonal course of photosynthesis in Scots pine at northern timberline and in southern boreal zone. *Tellus* 59B, 542–552.

Körner C. 2006. The significance of temperature in plant life. In: Morison J.I.L. & Morecroft M.D. (eds.) *Plant growth and climate change*. Wiley-Blackwell.

Leuning, R. 1995. A critical appraisal of a combined stomatal-photosynthesis model for C₃ plants. *Plant, Cell and Environment* 18, 339-355.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J.B., Rayment, M., Tedeschi, V., Valentini, R., and Grace, J. 2007. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* 447: 848–850.

Mäkelä A and Mäkinen H. 2003. Generating 3D sawlogs with a process-based growth model. *Forest Ecology and Management* 184:337-354

Mäkelä, A., P. Hari, F. Berninger, H. Hänninen and E. Nikinmaa 2004. Acclimation of photosynthetic capacity in Scots pine to the annual cycle temperature. *Tree Physiology* 24, 369.

Mäkelä, A, P. Kolari, J. Karimäki, E. Nikinmaa, M. Perämäki and P. Hari 2006. Modelling five years of weather-driven variation of GPP in a boreal forest. *Agricultural and Forest Meteorology* 139, 382.

Mäkelä A, Pulkkinen M, Kolari P, Lagergren F, Berbigier P, Lindroth A, Loustau D, Nikinmaa E, Vesala T, Hari P 2008. Developing an empirical model of stand GPP

with the LUE approach: analysis of eddy covariance data at five contrasting conifer sites in Europe. *Global Change Biology* 14:92-108

Malhi Y., Baldocchi D.D. & Jarvis P.G. 1999. The carbon balance of tropical, temperate and boreal forests. *Plant, Cell and Environment* 22:715–740.

McCarthy HR, Oren R, Finzi AC, Johnsen KH. 2006. Canopy leaf area constrains [CO₂]-induced enhancement of productivity partitioning among aboveground carbon pools. *Proceedings of the National Academy of Sciences, USA* 103: 19356–19361.

Medlyn BE, Barton CVM, Broadmeadow MSJ, Ceulemans R, de Angelis P, Forstreuter M, Freeman M, Jackson SB, Kellomäki S, Laitat E, Rey A, Roberntz P, Sigurdsson BD, Strassemeier J, Wang K, Curtis PS, Jarvis PG. 2001. Stomatal conductance of European forest species after long-term exposure to elevated [CO₂]: a synthesis of experimental data. *New Phytologist* 149: 247–264.

Nikinmaa, E., Kolari P., Hari P., Hölttä T. & A. Mäkelä 2010. Process based model analysis of pine and spruce growth to predict climate change impacts. Technical report, ACTION 9: Assessment of impacts and adaptation measures for forest production; Case study at Northern Häme and Lapland. Vulnerability assessment of ecosystem services for climate change impacts and adaptation (Vaccia)

Norby RJ, DeLucia EH, Gielen B, Calfapietra C, Giardina CP, King JS, Ledford J, McCarthy HR, Moore DJP, Ceulemans R, De Angelis P, Finzi AC, Karnosky DF, Kubiske ME, Lukac M, Pregitzer KS, Scarascia-Mugnozza GE, Schlesinger WH, Oren R. 2005. Forest response to elevated CO₂ is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences, USA* 102: 18052–18056.

Oren, R., Ellsworth, D.S., Johnsen K.H., Phillips N., Ewers B.E., Maier C., Schäfer K.V.R., McCarthy H., Hendrey G., McNulty S.G. & G.G. Katul. 2001. Soil fertility limits carbon sequestration by forest ecosystems in CO₂ –enriched atmosphere. *Nature* 411:470-472.

Pechony O. & D.T. Schindell 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. *PNAS* 107(45): 19167–19170

Peltola H., Kellomäki S. & H. Väisänen 1999. Model computations of the impact of climatic change on the windthrow risk of trees. *Climatic Change* 41: 17–36,

Ripullone, F., Grassi, G., Lauteri, M. and M. Borghetti. 2003. Photosynthesis–nitrogen relationships: interpretation of different patterns between *Pseudotsuga menziesii* and *Populus × euroamericana* in a mini-stand experiment. *Tree Physiology* 23:137-144

Rasinmäki, J., Kalliovirta, J. & Mäkinen, A. 2009. SIMO: An adaptable simulation framework for multiscale forest resource data. *Computers and Electronics in Agriculture* 66: 76–84.

Saxe H., Cannell M.G.R., Johnsen Ø., Ryan M.G. & Vourlitis G. 2001. Tree and forest functioning in response to global warming. *New Phytologist* 149: 369–400.

Strömgren M, Linder S. 2002. Effects of nutrition and soil warming on stemwood production in a boreal Norway spruce stand. *Global Change Biology* 8: 1194–1204.

Yrjönen J. 2008. Mitä proveniensiikokeet kertovat puiden sopeutumisesta ilmastonmuutokseen? Pro gradu -tutkielma. Helsingin yliopisto, metsäekologian laitos. (MSc-Thesis, Department of Forest Ecology, University of Helsinki).