NUMBER C 60 | DECEMBER 2014 | REPORT

Impacts of ozone on the carbon sequestration in Swedish forests

A modelling study

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Funded by: Swedish Environmental Protection agency
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Report number: C 60
Edition: Only available as PDF for individual printing

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Summary

Model simulations, based on empirical information about negative impacts of ozone on photosynthesis and leaf senescence (leaf aging) on young trees under experimental conditions, show that forest growth (Net Primary Production, NPP) is reduced by 4-16% and 1-4% for conifers and deciduous trees respectively under current, ambient ozone levels across Sweden, as compared to pre-industrial, low ozone levels. In general, these modelled ozone impacts are larger compared to growth reductions found for young trees under experimental conditions. The reduced NPP caused by current, ambient ozone levels was estimated to reduce the carbon sequestration for the living biomass in Swedish forests by 1.5 – 4.5 million tons of CO2 equivalents, corresponding to a reduction of 4-12%.

Extended Summary

Carbon sequestration by terrestrial vegetation is important for the budget of greenhouse gas (GHG) fluxes to and from the atmosphere, globally as well as for Sweden. The carbon sequestrations to Swedish forest ecosystems corresponded to approximately 38 M ton CO_2-e (CO_2 equivalents) while Sweden´s net emissions of GHG from all other sectors the same year 2011 corresponded to approximately 61 M ton CO_2-e. Most of the increase in the Swedish forest carbon stocks was in the living biomass. The high rates of carbon sequestration to Swedish forests depend on the fact the forests annual growth rates have been substantially exceeding annual harvest rates. Any factor that tends to reduce growth rates also potentially will reduce forest carbon sequestration rates. Ozone has the potential to negatively affect tree biomass increment growth.

The aim of this study was to estimate to what extent the occurrence of elevated ground level ozone concentrations will negatively affect the growth and carbon sequestration of Swedish forests. This was achieved by the following procedure:

- An assessment was made of which physiological processes influencing forest growth that could be particularly vulnerable to negative ozone impacts
- Ozone dose – response relationships were established for these vulnerable processes
- The occurrence of different ozone levels in each county of Sweden was mapped for a relevant time period
- The net primary production (NPP) for the Swedish forests was modelled with the 3-PG model for forest stand representative for six different geographical zones across Sweden, with or without the assumed negative ozone impacts derived for the dose – response relationships

- The modelled NPP for the forests in the different zones, with and without ozone, was used to estimate the ozone impacts on the carbon sequestration for the forest living biomass carbon stocks.

The results from the 3-PG model indicated that the biomass production (NPP) was reduced between 4-15% for Norway spruce in ambient ozone, as compared to the pre-industrial ozone scenario. The span of uncertainty reflects differences in the estimated impacts for the different zones across Sweden. Similar values (4-16%) were found in simulations for Scots pine. The reduction in biomass was less in Silver birch (1-4%). Biomass reductions were shown for all parts of Sweden, with the largest biomass reductions for the southern parts. In the future A2- and B2- climate scenarios, the ozone-induced biomass reductions were of similar magnitudes as compared to reference current climate.

The NPP was generally higher in the future A2- and B2 climate scenarios, as compared to the current climate, for all tree species and in all geographical zones across Sweden.

It was assumed that a change in growth rates, if not too large, will result in a proportional change in the carbon sequestration in the living biomass carbon stocks of forest ecosystems. The reduced NPP caused by current, ambient ozone levels was estimated to reduce the carbon sequestration for the living biomass in Swedish forests by 4-12%. The uncertainty range reflects the differences in the percent NPP reduction estimated for the different geographical zones.

The negative influence of current, ambient ozone levels on the forest growth simulated in this study was generally larger than the negative influence of ozone found for young trees under experimental conditions, where growth reduction for Norway spruce was 2% and growth reduction for Silver birch was 8%.

The results from this simulation can to some extent be regarded as an independent confirmation of the ozone impacts of growth, especially for Norway spruce, where the measurements of ozone impacts on photosynthesis, senescence and growth originates from different experiments.

The results described in this report have been published in a scientific article (Subramanian et al., 2014).

Sammanfattning

Modellsimuleringar baserat på tillgänglig information om ozonets negativa inverkan på fotosyntes och bladåldrande hos unga träd under experimentella förhållanden visade att skogens tillväxt, uttryckt som nettoprimärproduktion, har minskat mellan 4 och 12 % på grund av nu förekommande nivåer av ozon över Sverige, i jämförelse med de låga ozonnivåer som förelåg före industrialiseringen. Denna simulerade inverkan av ozon på skogens tillväxt är större än de beräkningar av ozonets negativa inverkan som gjorts baserat på tillväxtmätningar på unga träd under experimentella förhållanden. Skogens minskade tillväxt beroende på förekommande ozonhalter beräknas medföra en minskad kolinbindning till den svenska skogen på runt 1,5-4,5 miljoner tons CO_2-e, vilket motsvarar 4-12 %.

1 Introduction

1.1 The importance of terrestrial carbon sequestration

Carbon sequestration by terrestrial vegetation is important for the budget of greenhouse gas (GHG) fluxes to and from the atmosphere, globally (Canadell et al., 2007, Pan et al., 2011) as well as for Sweden (Sweden NIR, 2011, Lundblad et al., 2013). For the year 2011, the carbon sequestration to Swedish forest ecosystems corresponded to approximately 38 M ton CO_2-e (CO_2 equivalents) while Sweden´s net emissions of GHG from all other sectors the same year corresponded to approximately 61 M ton CO_2-e. Hence, at least for the next decades to come, it is important to maintain these high rates of carbon sequestration to northern European forests.

Most of the increase in the forest carbon stocks was in the living biomass (Sweden, NIR 2011). The high rates of carbon sequestration to Swedish forests depend on the fact the forests annual growth rates have been substantially exceeding annual harvest rates (Figure 1).

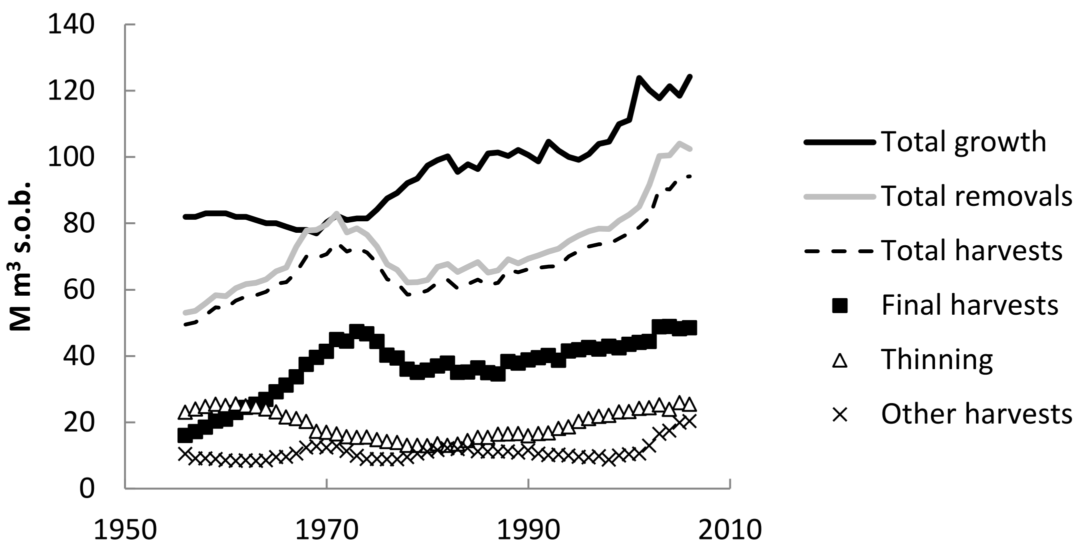


Figure 1. Annual national values for total growth (including trees that are harvested later the same year) and yearly fellings divided into different categories of fellings for the time period 1956-2006. Values are running five-year means averaged over all tree species. Source: Swedish National Forest Inventory.

Forests that are actively managed generally sequester carbon at higher rates as compared to non-managed forests (Eriksson et al., 2007, Hyvönen et al., 2007, Pingoud et al., 2010). Any measure that increases the productivity of a temperate or boreal forest, such as e.g. fertilization or a more favourable climate, is likely to increase the forest carbon sequestration (Hyvönen et al., 2007, Eggers et al., 2008).

1.2 The role of ozone in carbon sequestration

Short Lived Climate Pollutants (SLCP) have recently appeared on the agenda within the Climate convention (FCCC). Ozone is one of the SLCP and it has both a direct and an indirect effect on radiative forcing. It has been estimated that the indirect effects on radiative forcing through reducing forest carbon sequestration through reduced growth rates may be as large as the direct effect on radiative forcing (Sitch et al., 2007).

It is well established that ozone has the potential to negatively affect tree biomass increment, at least for young trees. Wittig et al. (2009) recently published a meta-analysis of the impacts of current and future ozone levels on the growth of northern hemispheric tree species. They concluded that current ozone levels (mean exposure concentration 40 ppb, as compared to charcoal filtered air) reduce tree biomass on the average by 7%.

2 Aim of the study

The aim of this study was to estimate to what extent the reductions of ozone concentrations near the ground can improve the growth and carbon sequestration in Swedish forest ecosystems.

The results described in this report have further been published in a scientific article (Subramanian et al., 2014).

3 Approach

The aim of this study was achieved by the following procedure:

- An assessment was made of which physiological processes influencing forest growth that could be particularly vulnerable to negative ozone impacts.
- Ozone dose – response relationships were established for these vulnerable processes.
- The occurrence of ozone levels in different parts of Sweden was mapped for a relevant time period.

- The NPP for the Swedish forests was modelled for representative forest stands in each of six geographical zones in turn representative for the different ozone exposure across the country.
- The NPP was modelled separately with three different ozone exposure scenarios and under three different climate scenarios.
- The negative ozone impacts were derived for the dose - response relationships based on AOT40 from the EMEP model.
- The modelled NPP for the six forest zones under different climate and ozone scenarios were used to calculate the impact of ozone molecule on carbon sequestration of Swedish forests at a national scale based on the total carbon sequestered in the year 2011

4 Methodology

4.1 Geographical resolution

The assessments were divided into six geographical zones in Sweden (Figure 2, Table 1). The zones were selected based on the assumption that the area within each zone will have nearly similar ozone concentrations.

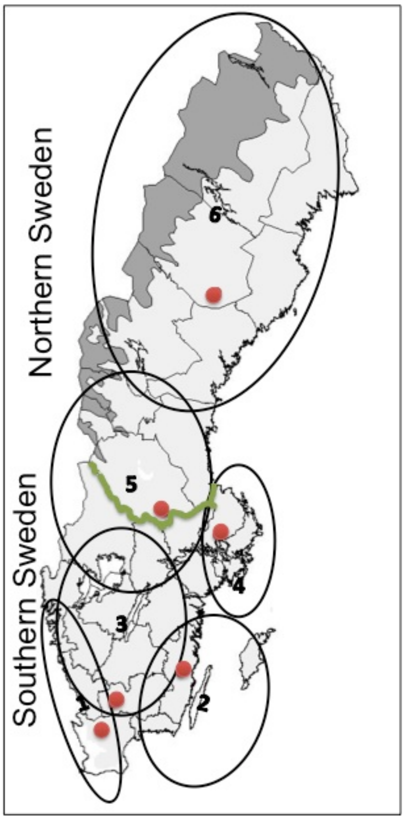


Figure 2. The six geographical zones and the representative stand in each zones used for the analyses in this study. The green line depicts the boundary between northern and southern Sweden.

Table 1. Specification of the different geographical zones and the counties represented in each zone.

Zone		**Counties represented**
1	South-west	Skåne, Halland,
2	South-east	Blekinge, Kalmar, Gotland
3	South-central	Kronoberg, Jönköping, Västergötland, Östergötland
4	East	Stockholm, Södermanland, Uppland
5	Mid	Värmland, Örebro, Västmanland, Dalarna, Gävleborg
6	North	Jämtland, Västernorrland, Västerbotten, Norrbotten

4.2 Ozone scenarios

Ozone impacts on vegetation were based on the AOT40 concept (Fuhrer et al., 1997). AOT40 can be used as the ozone dose concept to assess ozone impacts on vegetation in certain climate regions, especially when the dose – response relationships for ozone impacts have been derived in the same region (UNECE, 2004). This was the case in this study.

Values for AOT40 were obtained from EMEP (D. Simpson, personal communication) for the years 2005, 2006, 2008 and 2009 for each EMEP grid over Sweden. Each EMEP grid was assigned as relevant for one of Sweden´s counties. Then, an average value for AOT40 for each county was calculated across the four years. This AOT40 was then used in ozone dose – response relationships to calculate an ozone-modifying factor for each growth and physiological process considered, relevant for forest growth (see further below).

We considered three different ozone scenarios:

- A low, pre-industrial ozone scenario, AOT40 = 0 (i.e. the ozone concentrations never exceeded 40 ppb)
- Current ozone levels in Sweden (from EMEP).
- A doubling of the current ozone levels in Sweden (EMEP * 2).

Table 2. The mean ozone exposure as expressed as AOT40 (ppm h) for the different regions and for the current ozone level scenario.

Zone		AOT40 (ppm h)
1	South-west	13.8
2	South-east	13.0
3	South-central	11.8
4	East	10.5
5	Mid	8.2
6	North	3.7
Entire country		7.1

4.3 Climate scenarios

We considered three different climate scenarios:

- Current climate
- 2100 A2 scenario
- 2100 B2 scenario

4.4 Experimental studies

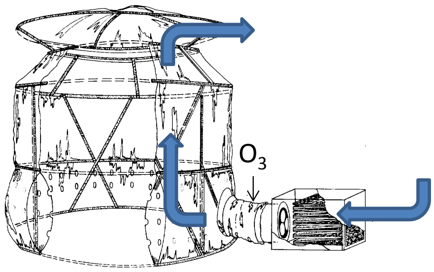
In order to have some relevance for ozone impacts on mature forest trees under stand conditions, data from young trees under experimental conditions have to be selected with care. The selection was based on the following criteria:

- Only multi-year experiments were used;
- Experiments should be made with well established, relatively large tree saplings, avoiding experiments with small seedlings;
- Data from the last year(s) of the experimental periods were used, as ozone impacts could be expected to be more close to equilibrium with regard to tree adaptation to the ozone exposure;
- Total biomass (including roots) or stem increment growth data were used as the response parameter for growth

Results from ozone impact studies on perennial plants involve a time component over which effect estimates have to be integrated. The dose-response relationships to be used have to be applicable for the metrics used for forest increment growth, which is generally m^3 yr^{-1}, i.e. a growth rate over a longer time period. Many studies report only the percent reduction of biomass caused by ozone at the end of the experiment and do not provide information on the biomass at the start of the experiment, hence impacts on growth rates cannot be calculated. The significance of this problem increases at low growth rates in relation to the size of the ozone effect.

The ozone dose-response relationships used in this study were derived mainly from three different, multi-year experiments with open-top chambers (OTC, Figure 2, Table 3). OTCs are in principle circular greenhouses without roofs. A fan will distribute air into the OTC continuously. This air can either be left untreated (NF, non-filtered air, ozone concentrations close to ambient air) or it can be filtrated to remove ozone (CF, charcoal filtered air, low ozone concentrations resembling pre-industrial levels) or it can be added extra ozone (NF+, ozone concentrations elevated above ambient). The fans are turned off and the chamber walls are removed during wintertime. Thus, the winter conditions that the tree saplings experience are realistic. The saplings are either planted in the ground or grown in 120 litre barrels merged into the soil. Water and nutrients are provided daily through an irrigation system. Nutrients are only provided during the growing season. Overall in the GOSP project, over 800 Norway spruce saplings were harvested including the roots.

A



B

C

Figure 3. An illustration of a typical open-top chamber (OTC, A), equipped with a roof to prevent precipitation. The OTC is approximately 3 m in diameter and 3 m high. The walls are of transparent soft poly-ethylene and the lower walls are double, with perforations on the inside distributing air around the inside of the OTC. The air can be either charcoal filtered to remove ozone or extra ozone can be added. The major OTC facility at Östads Säteri (B), 45 km northeast of Gothenburg, operated 42 OTCs 1992-1996 for the GOSP experiment and 1997-1998 for the Ozone-Birch experiment. Norway spruce saplings in the GOSP experiment (C) after the third year of exposure, 1994.

The early OTC experiment at Rörvik, 1985-1989 was slightly different. In this experiment rigid walls were used which were not removed during wintertime, only the fans were turned off and the chamber doors were left open. In this experiment there were only two Norway spruce saplings in each OTC and they were planted directly in the soil in the OTC. The main aim with this experiment was to study ozone impacts on physiological processes, such as photosynthesis and not on growth. The conditions for the different OTC experiments used in this study are summarized in Table 3.

Table 3. Conditions for the different OTC experiments used in this study.

Site/ exp	Type of OTC/experimental conditions	Period of exposure	Reference
Rörvik	Permanent walls, Ozone treatments: CF/ NF/ NF+. Replicate OTCs, n=2. Planted into the soil. Two trees/OTC. Plant material: One clone (Poland) of Norway spruce (cuttings from 30-year-old tree, grafted 1981). Tree height at the end: ~2m	1985-1989 (5 seasons)	Wallin et al., 1990, Skärby et al., 1995.
Östad/ GOSP	Walls removed during winter, Ozone treatments: CF/ NF/ NF+. Replicate OTCs, n=6. Planted into 120 liter barrels, roots harvested. From the beginning 18 or 24 trees/OTC. Tree height at the end: ~2 m Plant material: One clone (Minsk) of Norway spruce, grafted 1989.	1992-1996 (4 seasons)	Wallin et al., 2002. Karlsson et al., 2002. Ottosson et al., 2003.
Östad/ birch	Conditions as with Östad/GOSP, but: Ozone treatments NF/ NF+/NF++. Replicate OTCs, n=6. Tree height at end: ~3.5 m Plant material: a half-sib family of Silver birch, *Betula pendula* Roth., obtained from the clone S21K883060. Seeds cultivated Jan 1997.	1997-1998 (2 seasons)	Karlsson et al., 2003.

4.5 Ozone sensitive physiological processes

From experimental data published in the literature as well as experiments performed in Sweden we identified the following processes, important for forest growth, and particularly sensitive to ozone impacts:

1. Relative growth. Based on total biomass, including roots. [(biomass 2 – biomass 1)/biomass 1].
2. The maximum photosynthetic capacity of the entire tree canopy.
3. Leaf/ needle senescence. Decrease in photosynthetic capacity over time.
4. Allocation of carbon within the tree. Shoot/root ratio.
5. Allocation of carbon within the tree. Stem height/volume ratio.
6. Increase tree water use, due to higher stomatal conductance caused by ozone.

All these processes were not applicable to include in the 3-PG model. Only ozone impacts on processes 2 and 3, the maximum photosynthetic capacity and leaf/needle senescence, could be included in the 3-PG model. Ozone impacts on processes included in the 3-PG model are described below, together with the ozone impacts on growth, which is used to compare with the NPP calculated using the 3-PG model.

Ozone impacts on Scots pine were assumed to be similar to the impacts on Norway spruce.

4.5.1 Impacts on Norway spruce

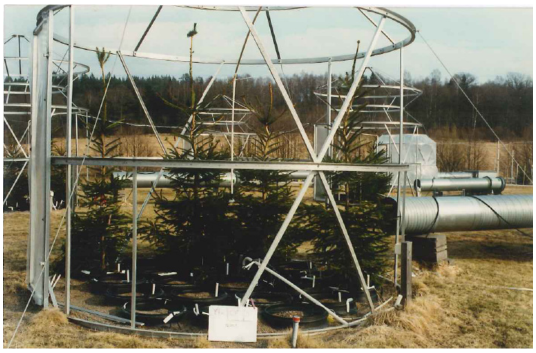
4.5.1.1 Relative growth

Direct ozone impacts on growth could not be incorporated in the 3-PG-model. However, there exists a close link between the ecosystem NPP, the output of the 3-PG model, and the stem growth (Landsberg and Waring, 1997). Hence, experimental studies on ozone impacts on growth could be used for comparisons of the output from the 3-PG model, since the input to the 3-PG model was results from partly independent empirical studies on physiological processes such as photosynthesis and senescence.

The Östad/GOSP experiment was particularly designed to investigate ozone impacts on the growth of young trees. The experimental period lasted 4 years and the experiment was divided into two separate experiments, with a slightly different design and separate statistical treatments. The main experiment included three ozone treatments CF, NF and NF+ in combination with optimum water and nutrient supply as well as two ozone treatments CF and NF+ in combination with a phosphorous supply deficit treatment. In the second drought experiment, two ozone treatments, CF and NF+ were either well supplied with water and nutrients or subject to 8-week drought periods during the growth seasons 2, 3 and 4, respectively.

Approximately 800 spruce saplings were harvested and measured in the experiment. Overall, the statistical result from the experiment confirmed a negative impact of the ozone exposure on total biomass growth (Karlsson et al., 2002, Ottosson et al., 2003). However, the maximum ozone impacts on growth were detected after the experimental third year. Careful analysis indicated that the experimental system (i.e. the chambers and the 120 litre growth pots) most likely started to restrict growth towards the end of the experiment (Wallin et al., 2002). Therefore, we used the ozone impacts on stem increment between the end of experimental year 2 and end of experimental year 3 in this analysis. Values for stem volumes were used for all spruce saplings present at the time of measurement and calculations were made across all combination treatments (drought and phosphorous deficiency) since there were no statistical evidences for interactions between ozone and the combined treatments (Karlsson et al., 2002, Ottosson et al., 2003). The stem increments of Norway spruce saplings during the experimental year 3 were lower for the high ozone treatments (Figure 4).

A



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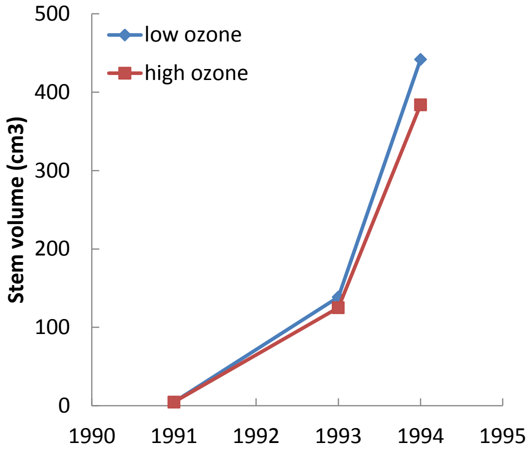


Figure 4. The Norway spruce saplings in the GOSP experiment at the end of the third experimental year, Nov 1994 (A). The height of the OTC construction is approximately 2.5 m. B shows the course of the stem volume increments, for all saplings present in the lowest ozone treatment (charcoal filtered air, blue symbols and line) and in the highest ozone treatment (the elevated ozone above ambient, red symbols and line). The ozone impact was calculated at the reduction in the stem volume increments rates between the experimental years 2 (1993) and 3 (1994). Ozone exposure is calculated at the yearly mean exposure.

The results from the GOSP experiment suggested that the stem volume increment growth rates of Norway spruce were reduced by ozone according to:

Reductions in relative stem growth rate (%) = -0.2 * AOT40 (AOT40 in ppmh)

Based on the values of AOT40 across Sweden (Table 2), the average reduction of the stem increment growth rates would be 2% (Figure 5).

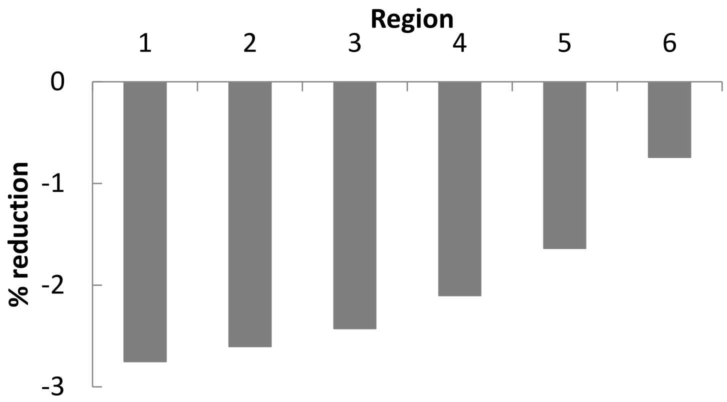


Figure 5. Growth reductions (% reduction in stem increment growth rates) of Norway spruce under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from GOSP, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

4.5.1.2 The maximum photosynthetic capacity of the tree canopy

Ozone impacts on the maximum photosynthetic capacity were incorporated in the 3-PG-model. However, the parameter used in the 3-PG-model was photosynthetic quantum yield while the experimental results used were photosynthesis under maximum photosynthetic radiation (PPFD).
The empirical information on ozone impacts on photosynthesis of Norway spruce originated from the experiment at Rörvik 1985-1989 (Wallin et al., 1990, Skärby et al., 1995, Table 3). The ozone impacts on maximum photosynthesis followed a complicated pattern. Results from measurements on shoots of different ages made during different years are shown in Figure 6.

It was clear from the photosynthetic measurements on the Norway spruce at Rörvik that the influence of the ozone exposure on the maximum photosynthesis was different depending on the age of the shoots. Regarding photosynthesis in the shoots that were one-year-old and older, the lowest rates of photosynthesis was found for the trees exposed to the highest ozone treatment, NF+, and the highest photosynthesis in the trees that were grown in charcoal filtered air. However, in the current-year shoots, the highest photosynthetic rates were found in the shoots from the trees grown in ambient ozone concentrations.

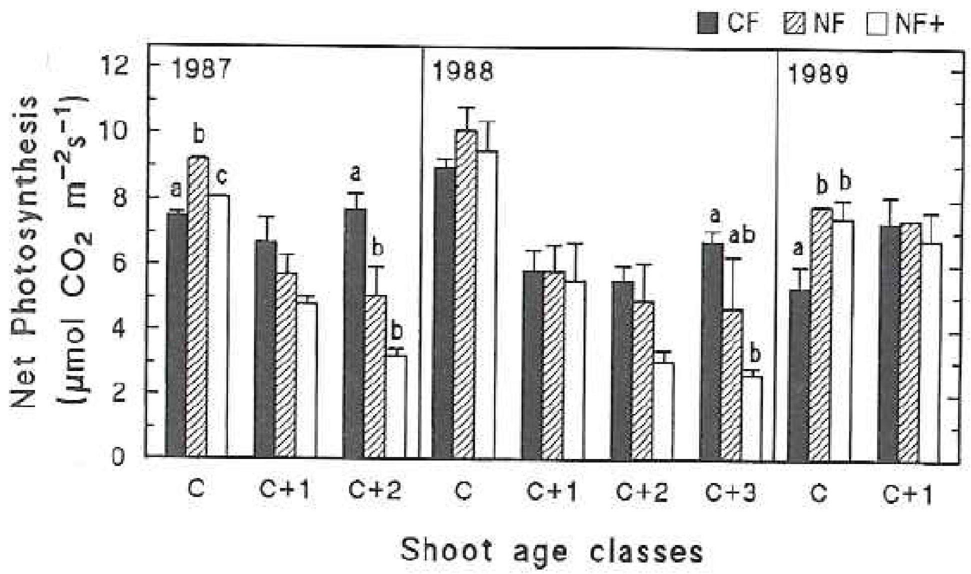


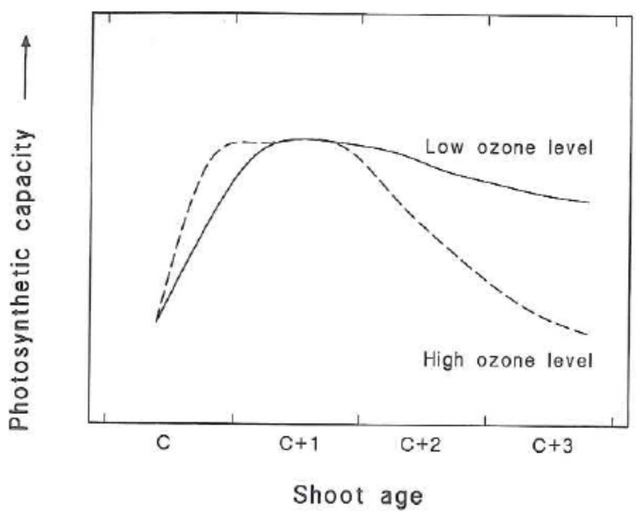
Figure 6. The results from measurements of maximum photosynthetic rates (i.e. under saturating light conditions) of Norway spruce shoots of different ages and during different years at Rörvik, ca 30 km south of Gothenburg, over the time period 1987-1989. On the x-axis is shown the age of the shoots that were measured. C, current-year shoots; C+1, one-year-old shoots; C+2, two-year-old shoots. CF, charcoal filtered air, low ozone concentrations; NF, non-filtered air, ambient ozone concentrations; NF+, non-filtered air with extra ozone added, concentrations elevated above ambient. The data originates from Wallin et al. (1990) and Skärby et al., (1995).

The results shown in Figure 6 were interpreted with a hypothesis that is illustrated in Figure 7. The hypothesis was that ozone accelerated the entire lifecycle of the needles, both the maturation and the senescence phase, as expressed by the maximum photosynthetic capacity (Skärby et al., 1995).

Figure 7. An illustration of an hypothesis about the impacts of ozone on the photosynthetic capacity of Norway spruce shoots, depending on shoot age. The hypothesis was that ozone accelerated the entire lifecycle of the needles, both the maturation and the senescence phase. The solid line represents Norway spruce grown under low ozone conditions, the broken line spruce grown under high ozone conditions.

C, current-year shoots; C+1, one-year old shoots; C+2, two-year-old shoots, etc.

From Skärby et al., 1995.



Based on the results shown in Figure 6 and the hypothesis shown in Figure 7, the impacts on ozone on the canopy photosynthesis of a young and old Norway spruce canopy was simulated (Skärby et al., 1995). The distribution of shoot between different ages for an old Norway spruce canopy was taken from Schulze et al. (1977).

The results from simulations suggested that the canopy photosynthesis of Norway spruce forests was reduced by ozone according to:
Reductions in maximum canopy photosynthesis rate (%) = -1.0 * AOT40 (AOT40 in ppmh)

Based on the modelled values of AOT40 across Sweden, the average reduction of the maximum canopy photosynthesis rates would be 10% (Figure 8).

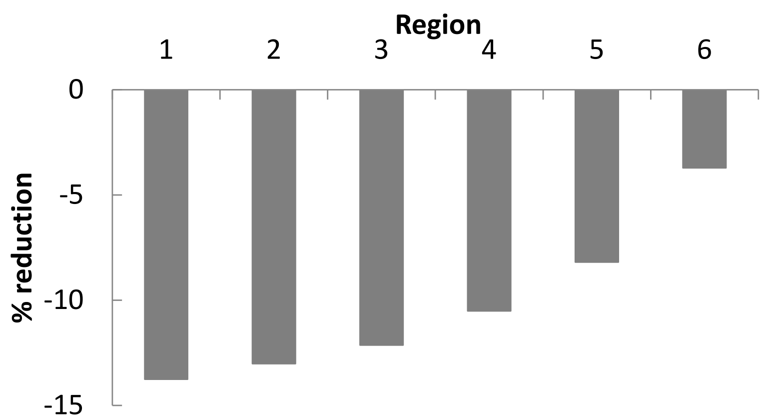


Figure 8. Reductions in the maximum photosynthesis rate (%) of Norway spruce under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from Rörvik, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

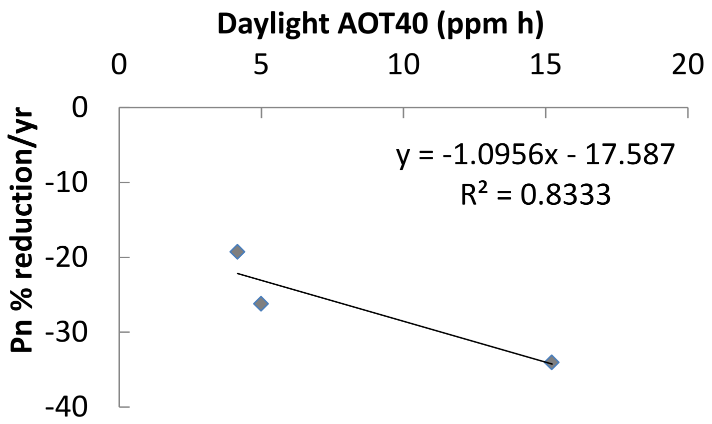
4.5.1.3 Accelerated senescence

There is a general hypothesis that ozone accelerates the life cycle and promotes the senescence of living tissue. This applies also for Norway spruce. The most evident result of accelerated senescence is the decline in the chlorophyll content of older needles of Norway spruce caused by ozone (Skärby et al., 1995, Wallin et al., 2002). The accelerated senescence is also evident as a reduced maximum photosynthesis capacity of older shoots (Wallin et al., 1990). These effects are shown in Figure 6.

Based on the results shown in Figure 6, the rate of decline in the photosynthetic capacity from current-year shoots to one-year-old shoots, and from one-year-old shoots to two-year-old shoots, respectively, was calculated (Figure 9) according to the formula

$(Pn_{yr2} – Pn_{yr1})/Pn_{yr1}*100$
Unit: % decline in max P/yr

Figure 9. The increased rate of senescence of Norway spruce shoots was calculated as the rate of decline in the maximum photosynthetic capacity of shoots between years. The calculation was based on the results from Wallin et al., 1990 and Skärby et al., 1995). Ozone exposure is calculated at the yearly mean exposure.



From the results described above, it was estimated that the rate of senescence (the rate expressed as % reduction of Pn per year) of Norway spruce shoots were increased by ozone according to:

Accelerated rate of senescence (%) = +5.0 * AOT40 (AOT40 in ppmh)

Based on the modelled values of AOT40 across Sweden, the average increase of the rates of senescence of Norway spruce would be 36% (Figure 10).

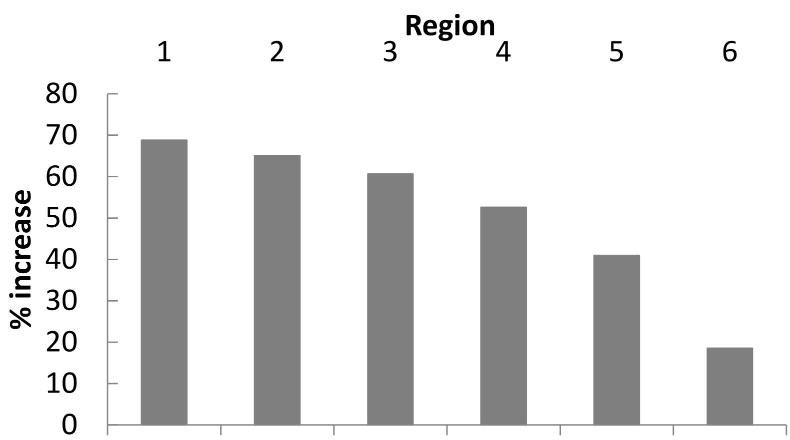


Figure 10. Accelerated rate (% increase of the rate) of Norway spruce under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the

experimental results from the Östad/ GOSP experiment, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

4.5.2 Impacts on Silver birch

4.5.2.1 Relative growth

As stated above, direct ozone impacts on growth could not be incorporated in the 3-PG-model, but could be used for comparisons of the NPP output from the 3-PG model.

The Östad-birch experiment was performed using the same experimental facility as Östad/GOSP (Table 3). However, only the main experiment was performed.

The Östad/birch experiment used three ozone levels (non-filtered air (NF) was the control treatment). No combined treatments were used. The replication for each ozone treatment was 4 OTC´s. There were twelve birch saplings per OTC from the beginning of the experiment. Six saplings per OTC were harvested each time. The birch saplings were harvested three times during the experiment; before the start of the experiment, 7 November 1997 and 13 November 1998. Results were analysed with a three-way ANOVA, with ozone, plot and year of harvest as independent variables.

In Figure 11 is shown the % reduction in total (perennial) biomass increment rates for each year and treatment, correlated with the mean yearly daylight AOT40. There was a strong correlation between the reduction in the rates of the yearly total biomass increments and the mean yearly AOT40 during the exposure period.

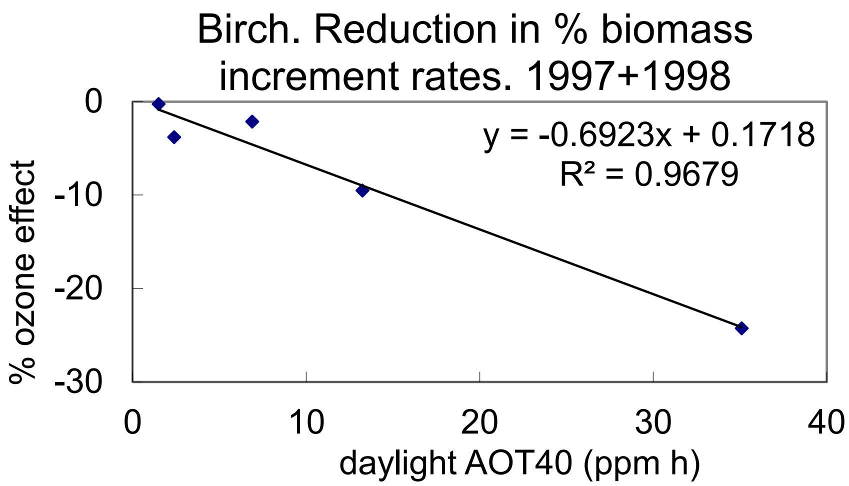


Figure 11. Growth reductions (% reduction in total biomass increment) of Silver birch under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from the Östad /birch experiment, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is the southwest of Sweden and region 6 the northernmost region. Ozone exposure is calculated at the yearly mean exposure.

The results from the Östad/birch experiment suggested that the total increment of Silver birch were reduced by ozone according to:

Reductions in relative total biomass growth (%) = -0.7 * AOT40 (AOT40 in ppmh)

The negative impact on biomass increment growth of birch was thus three times higher as compared to the negative ozone impacts on the stem increment growth of Norway spruce. Based on the modelled values of AOT40, the average reduction of the biomass increment growth rates of birch of the entire area of Sweden would be 4 % (Figure 12).

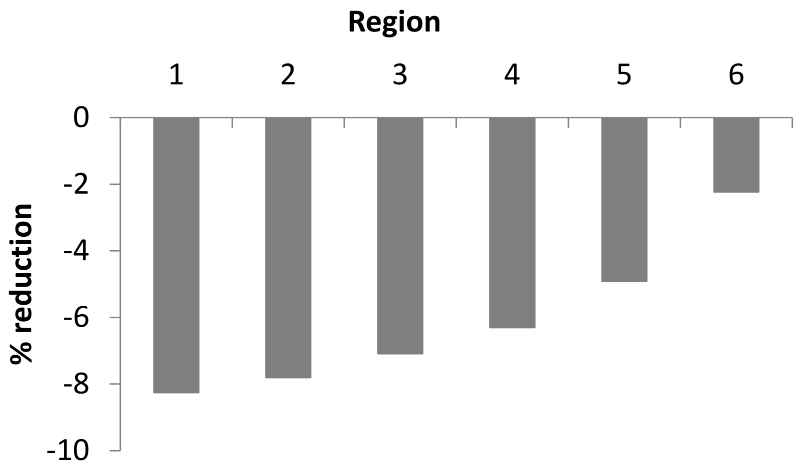
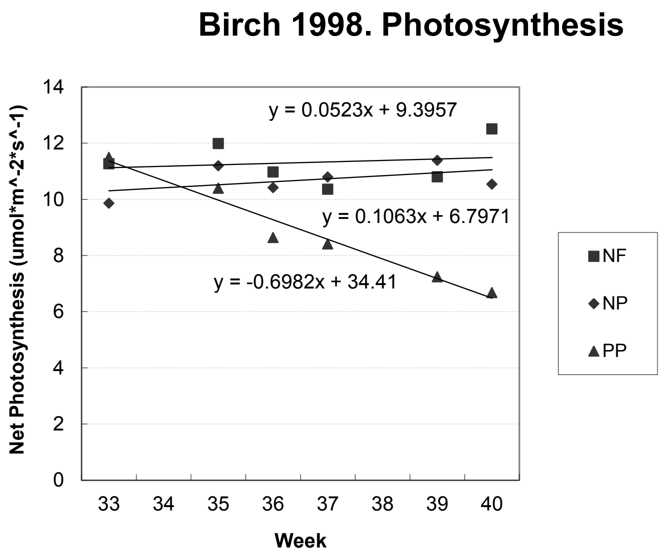


Figure 12. Growth reductions (% reduction in total biomass increment growth rates) of Silver birch under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from Östad/ birch, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

4.5.2.2 The maximum photosynthetic capacity of the tree canopy

Ozone impacts on the maximum photosynthetic capacity were incorporated in the 3-PG-model. The empirical information on ozone impacts on photosynthesis of Silver birch originated from the experiment Östad/birch (Karlsson et al., 2003, Uddling et al., 2006). Results from photosynthesis measurements on leaves that emerged in mid-July 1998 are shown in Figure 13. It can be seen that the photosynthetic capacity of the leaves in the highest ozone treatment, NF++, declined steadily over a time period of 8 weeks, while photosynthesis in the lower ozone treatments remained high.

Figure 13. The rates of photosynthesis measured under saturating light intensities on leaves that emerged in mid-July 1998 in the different ozone treatments NF, non-filtered air; NF+ (NP), non-filtered air with some extra ozone added; NF++ (PP), non-filtered air with more extra ozone added. The results are from Uddling et al., 2006.



We do not have information about the ozone impacts on the entire canopy photosynthesis of the birch saplings in the experiment. Instead, we have to make an assumption. New leaves emerge during the entire growing season. Hence, it seems reasonable to assume that the mean photosynthetic capacity of the leaves of the birch saplings in the highest ozone treatment during the two months period of measurements shown in Figure 13 represent the canopy photosynthesis of these birch saplings. The assumption is that if the photosynthesis would be reduced further, then the leaves would be shed. Thus the canopy photosynthesis will be reduced 20% at an ozone exposure of 84 ppm h AOT40, which was the annual ozone exposure in the highest ozone treatment during 1998.

The results from the measurements in Figure 13 in combination with the analysis above suggested that the canopy photosynthesis of Norway spruce forests were reduced by ozone according to:

Reductions in maximum canopy photosynthesis rate (%) = -0.24 * AOT40 (AOT40 in ppmh)

Based on the modeled values of AOT40, the average reduction of the maximum canopy photosynthesis rates of Silver birch across the entire area of Sweden would be 2% (Figure 14).

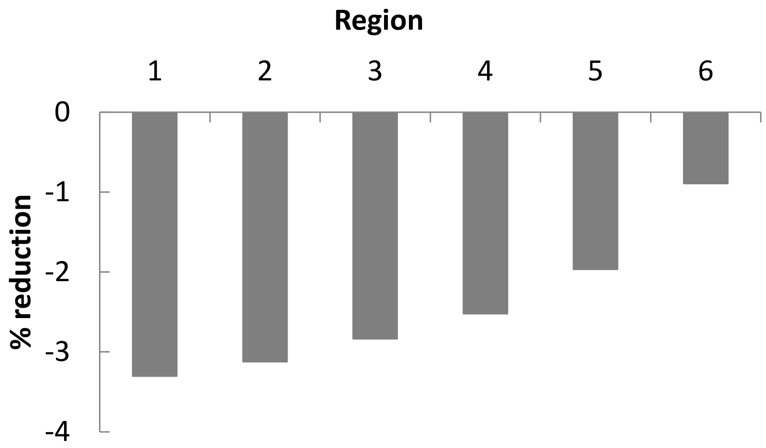


Figure 14. Reductions in the maximum photosynthesis rate (% reduction) of Silver birch under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from the Östad/birch experiment, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

4.5.2.3 Accelerated senescence

The most evident result of ozone induced accelerated senescence in Silver birch was the accelerated rates of leaf shedding (Figure 15, Uddling et al., 2006). This was particularly important since the pre-mature leaf shedding occurred before the trees had resorbed the nitrogen from the leaves.

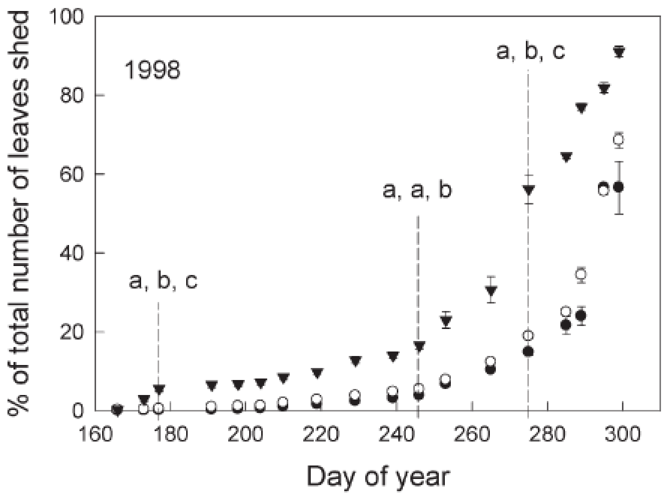


Figure 15. The leaf shedding of saplings of Silver birch exposed to different levels of ozone exposure in the Östad/birch experiment. The black circles represent the treatment with non-filtered air (NF); the open circles represent the treatment with non-filtered air with some extra ozone added (NF+); the black triangles represent the treatment with non-filtered air with more extra ozone added (NF++). The letters a,b,c, illustrate statistically significant differences between the ozone treatments at each sampling occasion.

The results are from Uddling et al., 2006.

It is not straightforward to estimate the ozone impacts on the rates of leaf shedding from the results shown in Figure 15. We chose to estimate the time it took in each ozone treatment to reach a level of 30% of available leaves shed and calculated a rate of leaf shedding, %/day. These were converted to relative rates of leaf shedding between the different ozone treatments and plotted against the ozone exposure. As a results, it was estimated that the increase in the rate of leaf shedding was 0.2% per AOT40 (ppm h) ozone exposure. In this case the increased rates of leaf shedding were related to the ozone exposure the same year.

The results suggested that the rate of senescence of Silver birch was increased by ozone according to:

Accelerated rate of senescence (%) = +0.2 * AOT40 (AOT40 in ppmh)

Based on the modeled values of AOT40 across Sweden, the average increase of the senescence rates of Silver birch would be 2% (Figure 16).

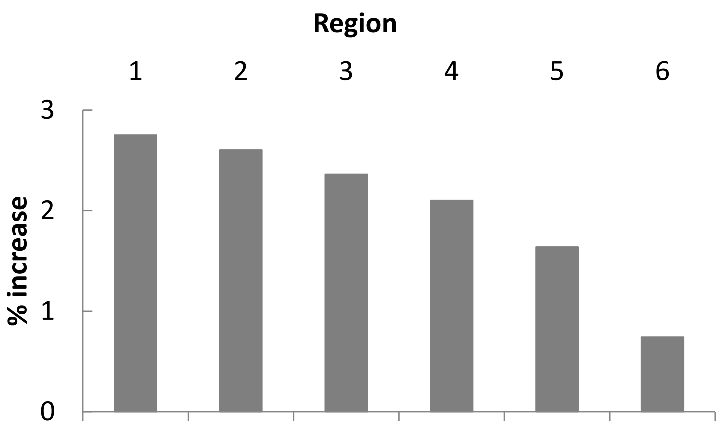


Figure 16. Accelerated rate (% increase) of Silver birch under current ozone exposure in different geographical regions (Figure 2) across Sweden, suggested from the experimental results from the Östad/birch experiment, in combination with the mean values for AOT40 in the different regions (Table 2). Region 1 is in the southwest of Sweden and region 6 is the northernmost region.

4.6 An overview over the application of factors for ozone impacts in the 3-PG model

For each of the two processes used in the 3-PG model as well as for growth, an ozone impact factor was estimated separately for coniferous and broadleaf tree species and separately for each county based on the ozone levels (AOT40) in each county. The ozone impact factors were calculated from a dose – response relationship, Δ * AOT40 (AOT40 in ppmh), where estimated AOT40 values were used for each county.

The different values used for Δ for the application in the formula Δ * AOT40 for the different tree species and for different processes used in the 3-PG model and used as a basis for the analysis of empirical data are shown in Table 4.

For Norway spruce, the relative ozone impacts on growth are smaller compared to the relative impacts on photosynthesis, while the opposite was the case for Silver birch.

Table 4. An overview of the different values used for Δ for the application in the formula Δ * AOT40 for the different tree species and for different processes used in the 3-PG model and used as a basis for the analysis of empirical data.

Parameter	Parameter in the 3-PG-model	Parameter for empirical data	Value for Δ *
Norway spruce			
Photosynthesis	Quantum yield efficiency	Net photosynthesis rate at saturating PPFD	-1
Senescence	Rate of litter fall	Rate of decline in max photosynthesis	+5
Growth	-	Stem increment growth rate (% increase/yr)	-0.2
Silver birch			
Photosynthesis	Quantum yield efficiency	Net photosynthesis rate at saturating PPFD	-0.24
Senescence	Rate of litter fall	Rate of leaf shedding during autumn	+0.2
Growth	-	Total biomass increment (% increase/yr)	-0.7

*values used for Δ for the application in the formula Δ * AOT40

4.7 Modelling

4.7.1 The 3-PG Model

The model 3-PG (Physiological Principles in Predicting Growth) was developed by Landsberg and Waring (1997). It is a simple process based stand level model which requires few parameter values and some stand data as inputs for simulation. The model can be applied to several sites. The model needs to be parameterized for individual species. 3-PG is a transition model between conventional mensuration based growth models and process based carbon balance models (Sands, 2004; Landsberg et al., 2003).

4.7.2 Basic Concept of 3-PG model

The 3-PG model consist of five sub models: biomass production, allocation of biomass between foliage, roots and stems (including branches and bark); stem mortality; soil water balance and a module to convert stem biomass to variables of interest to forest managers (Figure 17). The sub models of 3-PG models are briefly explained here.

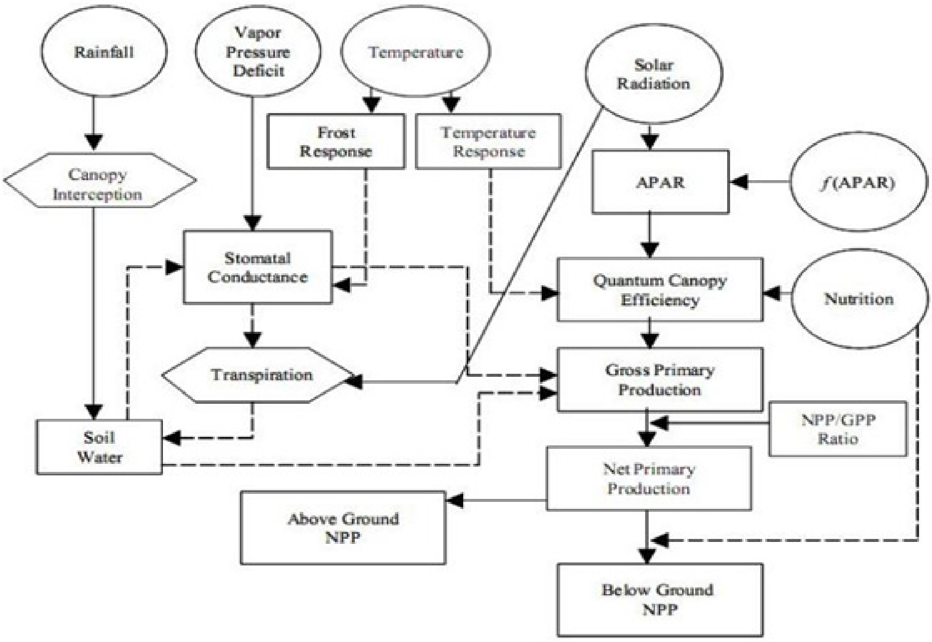


Figure 17. Conceptual diagram of 3-PG model.

4.7.2.1 Biomass Production sub-model

The net solar radiation intercepted and utilized by the leaves is calculated using total incoming solar radiation and LAI of the tree species through Beer's Law (Sands, 2004). Absorbed Photosynthetically Active Radiation utilized (APARu) is a function of Absorbed Photosynthetically Active Radiation (APAR), which is reduced by constraint modifiers imposed by a) stomatal closure caused by high day time VPD (Landsberg and Waring, 1997), b) soil water balance which is the difference between total monthly rainfall and moisture stored in soil from previous month rainfall and transpiration calculated using Penman-Monteith equation (see equation 1) (Coops et al., 1998), c) the negative effect of subfreezing temperature which is calculated using frost modifier calculated based on number of frost days per month. The value of frost modifier is between 0 (system shutdown) and 1 (no constraints) (Coops et al., 1998). Gross primary productivity (GPP) is calculated from APARu and canopy quantum efficiency. Net primary productivity is considered to be a constant fraction of GPP (Coops et al., 1998).

4.7.2.2 Carbon allocation sub-model

The NPP produced through photosynthesis is allocated to other parts of the trees like roots, stem (including branches and bark) and foliage. Allocation of NPP to various parts depends on various environmental factors which act as constraints to photosynthesis (Coops et al., 1998). The environmental factors are determined by available soil water, VPD and site fertility (Sands, 2004). The NPP allocated to roots increases during adverse environment like less soil fertility or less available soil water. The allocation of NPP to foliage and stem depends on the diameter at breast height (dBH) of the tree. As the dBH of the trees increases the allocation to foliage decreases and that to the stem increases (Sands, 2004).

4.7.2.3 Soil water balance sub-model

Soil water sub-model is based on the total monthly rainfall received which is balanced against evapo-transpiration (ET) (Sands, 2004). The proportion of the rainfall which is intercepted by the tree canopy is called the canopy rainfall interception. Canopy rainfall interception is directly proportional to LAI (Sands, 2004). Canopy conductance is a function of LAI and stomatal conductance. As LAI increases the canopy conductance increases. At maximum canopy conductance it is also affected by VPD, available soil water and stand age (Sands, 2004).

$$\text{Soil water balance} = Ppt_{total} - (M_{soil} + T) \qquad (1)$$

Where

Ppt_{total} = total monthly precipitation; M_{soil} = Moisture stored in soil from the previous rainfall; T = Transpiration from trees.

4.7.2.4 Stem mortality sub-model

The mortality sub-model is based on the concept of age dependent probability of tree death. It also considers the mortality caused by the long-term stress factors such as water stress, pest and diseases (Sands, 2004). In this sub-model the changes in stocking is calculated based on the self-thinning relationship which is based on the -3/2 power law (Drew and Flewelling, 1977). An upper limit is estimated to mean single tree stem mass for the current stocking (Sands, 2004). When the current mean stem mass of the tree exceeds this limit, the population is reduced to a level corresponding to the limit.

4.7.2.5 Data inputs

The data inputs required for simulation in 3-PG are classified into three types:
a) Climate data such as monthly average of daily solar radiation (Q, $MJ/m^2/day$), mean air temperature (Ta, ^oC), day time atmospheric Vapour Pressure Deficit (VPD, mbar), total monthly rainfall(R, mm/month) and number of frost days (dF, number of days per month).
b) Site specific data such as site latitude, site fertility rating, maximum available soil water and soil texture (Sands, 2004).
c) time series data for the initial conditions of stand such as foliage (WF), stem biomass including branches and bark (WS) and root (WR) dry biomass (tonDM/ha), density (number of trees/ha), available soil water (mm). The basic unit of time used in 3-PG is day but the most commonly basic unit of time is considered to be month.

4.7.2.6 Basic equations used in 3-PG model

The carbon balance equations used in 3-PG are adapted from McMurtie and Wolf (1983). If x is the change in value of X over a time of t days then

$$W_F=n_FPn-r_FW_Ft-m_F(W_F/N)n) \quad (2)$$
$$W_S=n_SPn-m_S(W_S/N)n) \quad (3)$$
$$W_R=n_RPn-r_RW_R-m_R(W_R/N)n) \quad (4)$$

Where Pn= NPP in ton/ha/day, ni= fraction of NPP allocated to the ith pool, r_F= litter fall rate per day, mi = fraction of biomass per tree lost in the ith pool when a tree dies, r_R = root turnover rate per day, N= stem number (trees per ha) (Sands, 2004).

4.7.2.7 Data outputs

The outputs obtained from 3-PG are variables such as stand evapotranspiration, NPP, specific leaf area and canopy leaf area index (Sands, 2004). Other stand level outputs which are familiar for forest managers are main stem volume, mean annual increment (MAI) and the mean dBH (Sands, 2004).

4.7.2.8 Assigning species specific values to 3-PG parameters

3-PG has to be assigned with species specific parameters. Usually the parameter values are assigned by direct measurement. The parameters of Norway spruce were obtained through literature review and also by trial and error method where the output data from 3-PG simulations were compared with observed stand data.

4.7.2.9 Climate data

The climate data were obtained from the SMHI website. The maximum number of observation points was included for each county and their average were taken in order to get near to real climate data. Climate data like T_{max} , T_{min} and the number of frost days were directly available from the SMHI website. The number of rainy days was obtained indirectly from a calculation of the number of dry days found at the SMHI website.

4.7.2.10 Parameterisation of 3-PG model for Pine and Birch

Tree specific parameters were taken from previous studies of Norway spruce (Ågren et al., 2008; Bergh et al., 2003; Cao et al., 2008; Eliasson et al., 2004; Subramanian, 2010), Scots pine (Landsberg et al., 2005; Vanninen, 2003; Vanninen and Mäkelä, 2005) and birch (Landsberg et al., 2003; Nakai et al., 2003; Nasahara et al., 2008; Ohtsuka et al., 2005; Potithep and Yasuoka, 2011; Saigusa et al., 2002).

4.7.2.11 Climate scenarios

The climate scenarios considered were the A2 and B2 scenario where the mean global warming according to the Hadley centre model has been estimated to be 3.2°C for the A2 scenario and 2.3°C for the B2 scenario (Houghton et al., 2001; Nakicenovic et al., 2000). The CO_2 concentration for the A2 scenario was 850 ppm and for the B2 scenario 600 ppm during the year 2100 (Houghton et al., 2001; Nakicenovic et al., 2000).

Table 5. Climate scenarios

Features	A2-scenario	B2-scenario
Emission level of GHG	Higher emission level	Lower emission level
Development of world	Heterogenous world with development concentrated in certain regions	Homogenous world
Economic growth	Slow	Intermediate
Technological development	Slow	Better development than A2
Population growth	Fast	Moderate

Source: Bergh et al., 2010.

4.7.2.12 Simulation

The 3-PG model was used to simulate the potential NPP in Norway spruce, Scots pine and birch. Three ozone level scenarios were considered for the study, 1. Prehistoric ozone level, 2. Ambient ozone level and 3. Increased ozone level. Each ozone concentration run was combined with two climate scenario runs, A2 and B2.

Further details of the modelling are described in Appendix 1.

5 Results

5.1 Potential NPP under various ozone scenarios

The simulated NPP for ambient and increased ozone scenarios were compared with simulations of NPP for pre-historic ozone scenario (Figures 18, 19 and 20) for Norway spruce, Scots pine and birch, respectively. The highest NPP was estimated in pre-historic ozone level and the lowest NPP in the increased ozone level for all the tree species.

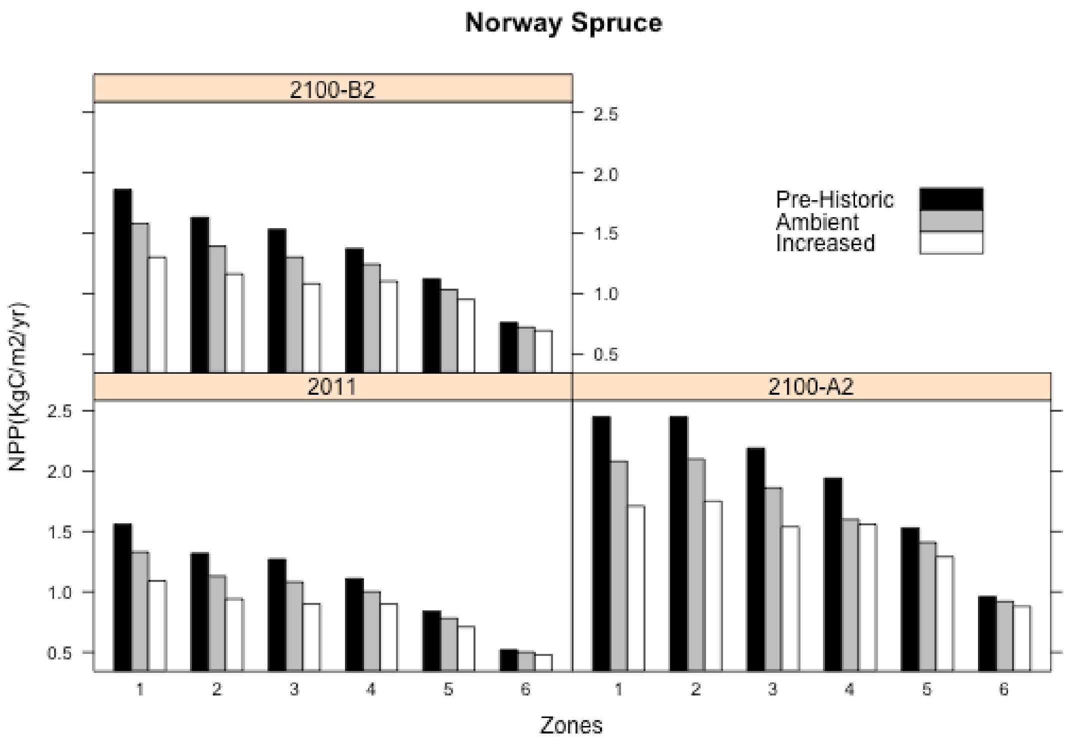


Figure 18. Simulated NPP (Kg C/m²/yr) of Norway spruce under different ozone and climate scenarios. Simulations were made for six geographical zones in Sweden. Zone 1 represents the south-western part of Sweden, zone 8 the northernmost part.

The simulations showed that biomass production was reduced between 4-15% for Norway spruce in the ambient ozone scenario as compared to the pre-industrial ozone scenario (Table 6). Biomass reductions were shown for all the zones, with the highest biomass reductions for the southernmost zones. In the A2- and B2- scenarios the biomass reductions were of similar magnitudes as compared to that in reference climate. In the increased ozone scenario the biomass production was reduced by 8-30% compared to the pre-industrial ozone scenario. The highest reduction of biomass was in zone 1 and the lowest reduction in zone 6. Similar trends were observed in the B2 scenario.

The simulated NPP of Norway spruce at the increased ozone level was compared with simulations at ambient ozone level (Table 7). In the reference climate scenario, the NPP was reduced by around 4-18%. The highest reduction in NPP during the reference climate scenario was found in zone 1 (18%) and the lowest reduction in zone 6 (4%). In both theA2 and B2 scenarios the reduction in NPP had a similar trend to that of the reference climate.

Table 6. The change in NPP (Kg C/m^2/yr) of Norway spruce for different ozone scenarios (ambient level and increased level ozone) compared with the pre-historic level of ozone. These comparisons were performed for two different climate scenarios (A2 and B2).

	Ambient ozone			Increased ozone		
Zone	2011	2100		2011	2100	
		A2	B2		A2	B2
1	0.85	0.85	0.85	0.70	0.70	0.70
2	0.86	0.85	0.86	0.72	0.71	0.72
3	0.85	0.85	0.85	0.71	0.70	0.70
4	0.90	0.82	0.90	0.81	0.80	0.81
5	0.92	0.92	0.92	0.85	0.84	0.84
6	0.96	0.96	0.96	0.92	0.91	0.91

Table 7. The change in NPP (Kg C/m^2/yr) of Norway spruce for the increased ozone scenario when compared to the ambient ozone scenario. This comparison was performed for two different climate scenarios (A2 and B2)

Zone	2011	2100	
		A2	B2
1	0.82	0.82	0.82
2	0.84	0.83	0.84
3	0.83	0.83	0.83
4	0.89	0.98	0.89
5	0.91	0.91	0.91
6	0.96	0.96	0.96

The NPP of Scots pine was reduced by 4-16% at ambient ozone levels when compared to the pre-historic ozone level (Figure 19 and Table 8). The ambient ozone reductions of NPP in the A2 and B2 scenarios were similar to the current climate. A further reduction of NPP was found in the increased ozone level scenario (Table 9). The results were similar to that of Norway spruce with higher reduction of NPP in the southernmost zones compared to the northernmost zones. With increased ozone levels the reduction of NPP was around 4-21% when compared to ambient ozone levels regardless of climate scenario chosen. The NPP was highly reduced in zone 1 and least affected in zone 6.

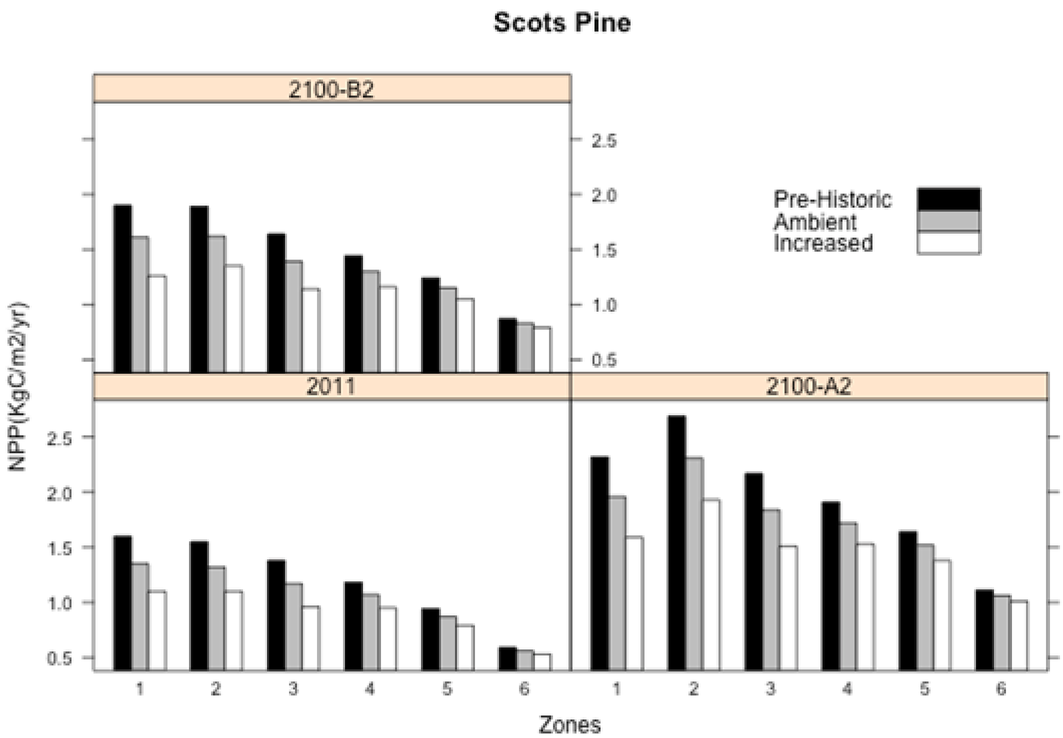


Figure 19. Simulated NPP (Kg C/m²/yr) of Scots pine under different ozone and climate scenarios. Simulations were made for six geographical zones in Sweden. Zone 1 represents the south-west part of Sweden, zone 6 the northernmost part of the country.

Table 8. The change in NPP (Kg C/m²/yr) of Scots pine for different ozone scenarios (ambient level and increased level ozone) compared with the pre-historic level of ozone. The comparisons were performed for two different climate scenarios (A2 and B2).

	Ambient ozone			**Increased ozone**		
Zone	2011	2100		2011	2100	
		A2	B2		A2	B2
1	0.84	0.85	0.85	0.69	0.69	0.67
2	0.86	0.86	0.86	0.71	0.72	0.72
3	0.85	0.85	0.85	0.70	0.70	0.70
4	0.90	0.90	0.90	0.80	0.80	0.80
5	0.93	0.92	0.93	0.84	0.84	0.84
6	0.96	0.95	0.95	0.91	0.91	0.91

Table 9. The change in NPP (KgC/m^2/yr) of Scots pine in the increased ozone scenario when compared to the ambient ozone scenario. The comparison was performed for two different climate scenarios (A2 and B2).

Zone	2011	2100	
		A2	B2
1	0.81	0.81	0.79
2	0.83	0.84	0.83
3	0.82	0.82	0.82
4	0.89	0.89	0.89
5	0.91	0.91	0.91
6	0.96	0.95	0.95

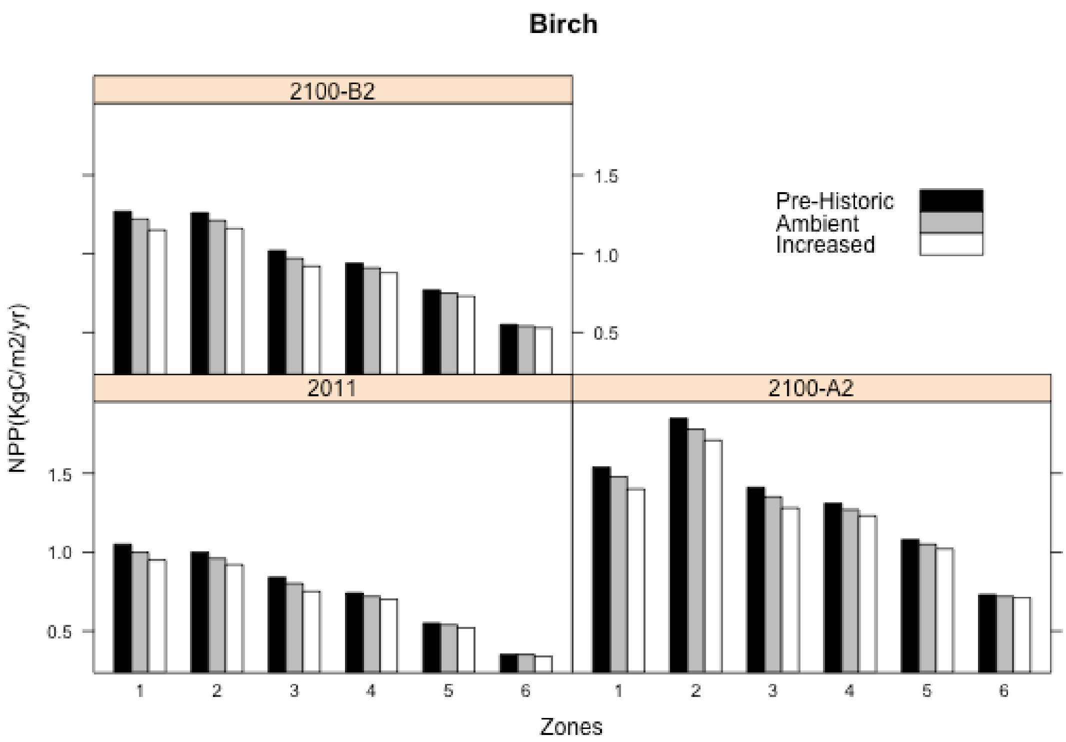


Figure 20. Simulated NPP (Kg C/m2/yr) of birch under different ozone and climate scenarios. The simulations were made for six geographical zones in Sweden. Zone 1 represents the south-western part of Sweden while zone 6 is the northernmost part of the country.

The NPP of birch was least reduced (1-4%) in the ambient ozone scenario when compared to pre-industrial ozone levels among the three tree species and regardless of climate scenario (Figure 20 and Table 10). In the increased ozone scenario, NPP was reduced 3-10% as compared to pre-industrial ozone levels.

The biomass production was reduced by 1-6% in increased ozone levels while compared to ambient ozone level (Table 11).

Table 10. The change in NPP (Kg C/m^2/yr) of birch for different ozone scenarios (ambient level and increased level ozone) compared with the pre-historic level of ozone. The comparisons were performed for two different climate scenarios (A2 and B2).

	Ambient			Increased		
Zone	2011	2100		2011	2100	
		A2	B2		A2	B2
1	0.96	0.96	0.96	0.90	0.91	0.91
2	0.96	0.96	0.96	0.91	0.92	0.92
3	0.96	0.96	0.96	0.90	0.91	0.90
4	0.97	0.97	0.97	0.94	0.94	0.94
5	0.97	0.97	0.97	0.94	0.94	0.94
6	0.99	0.98	0.98	0.97	0.97	0.97

Table 11. The change in NPP (KgC/m^2/yr) of birch in the increased ozone scenario when compared to the ambient ozone scenario. The comparisons were performed for two different climate scenarios (A2 and B2)

Zone	2011	2100	
		A2	B2
1	0.94	0.95	0.94
2	0.96	0.96	0.96
3	0.94	0.95	0.94
4	0.97	0.97	0.97
5	0.97	0.97	0.97
6	0.99	0.98	0.98

5.2 Potential NPP under various climate scenarios

The NPP was generally higher in the future A2 and B2 climate scenarios than in the current climate, for all tree species and in all geographical zones across Sweden. The NPP was higher for the A2-scenario than for the B2-scenario and this difference was similar for all three tree species. For birch the increase in the A2 climate scenario was very large.

5.3 The impacts of the ozone and climate scenarios on forest growth and carbon sequestration in the living biomass carbon stocks

A managed forest contributes to the reduction of carbon dioxide (CO_2) emissions to the atmosphere in several ways: through the carbon sink into the forest biomass and soil, the increasing storage of carbon in harvested wood products, and the use of wood as a substitute for fossil fuel and other energy-intensive materials. Wood biomass from sustainably managed forests has generally been considered to be “carbon neutral” in that its use for bioenergy has zero net carbon emissions since the emissions released in its utilization for energy are subsequently captured in forest re-growth (Nabuurs et al., 2007). Poudel et al. (2012) showed both short- and long-term carbon balance benefits due to silvicultural practices increasing forest growth on the landscape level.

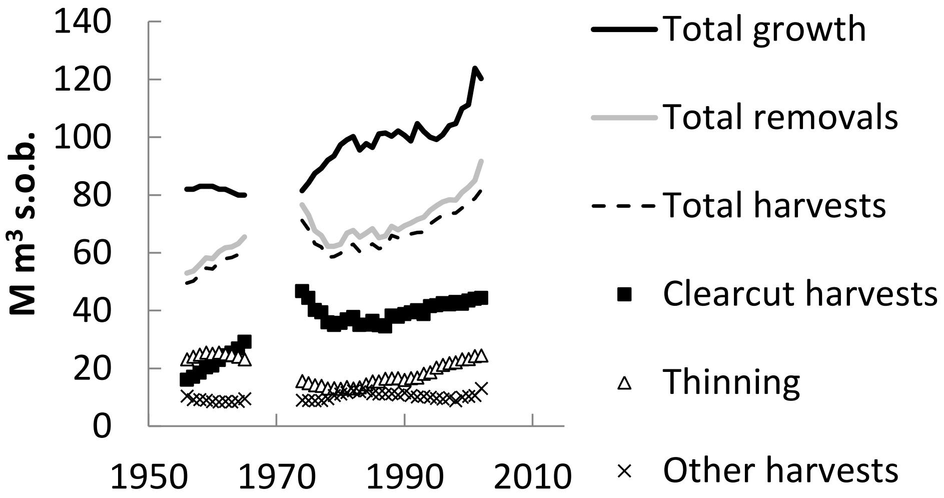
During 2011 the total carbon sequestrated by Swedish forests was approximately 37.6 million tons of CO2 equivalents (Lundblad et al., 2013). The annual change of sink was small when compared to the size of the pools, which includes living biomass, dead organic matter and soil carbon. Therefore this national level carbon sequestration estimates are associated with significant uncertainties (Lundblad et al., 2013). A reduced production as an effect of ozone, shown in this study, would result in a substantial decrease in the potential for carbon sequestration.

The annual increase in the carbon stock of Swedish forests is mainly due to the increase in the living biomass carbon stocks (Lundblad et al., 2013). The increase in the living biomass carbon stocks depends in turn on the gap between the yearly growth and harvests rates. Thus, assumptions have to be made about how the forest harvest rates will change as a result of changed growth rates. On the timber market, there will in principle be a balance between supply and demand. In a previous study (Karlsson, 2012) it was assumed that the relatively small increase in the forest growth rates, in the absence of ozone exposure, will not be large enough to affect the harvest rates.

Some information between the change in growth rates and the gap between growth and harvest rates can be gained from the statistics in the Swedish National Forest Inventory. In Figure 21 yearly values are shown for growth (gross growth before fellings) and harvest rates for the period 1956-2006. There were two major storm events in Sweden in 1969 and 2005 where data three years before and three years after these events were not included (since the observation plots within the NFI are re-visited every 5th years, and the growth between these years is interpolated, the storm will have an impact on the values also for the years before the storm).

There was a relation between the gap between the growth and harvest rates (Figure 21B). Of course, this relation could have been affected by other changes over this relatively long time period. However, based on this relationship it was assumed that there is a direct correlation between changes in the growth rates and the gap between growth and harvest rates. As a consequence, it was assumed that a change in growth rates, if not too large, will result in a proportional change in the gap between growth and harvest rates and thus in a proportional change in the living biomass carbon stock change and in the carbon sequestration in the forest ecosystems.

A



B

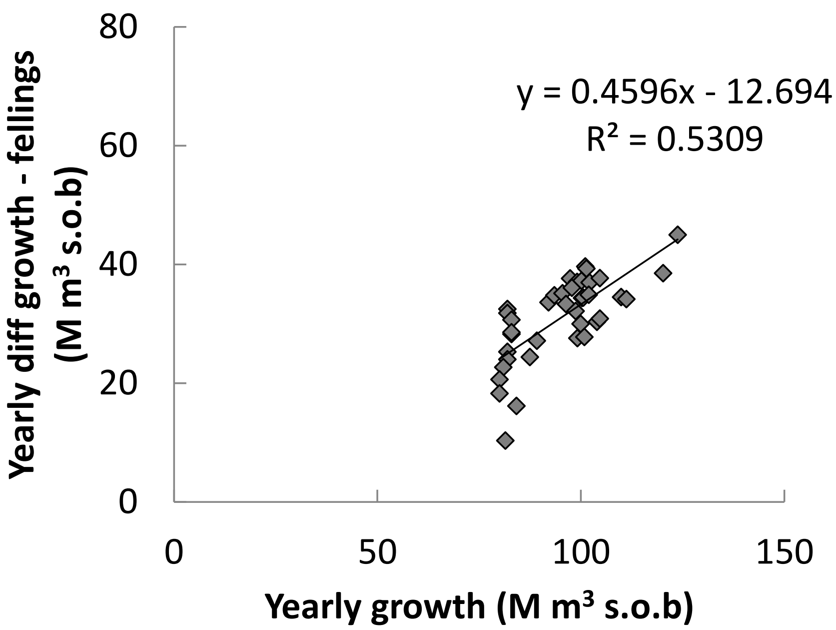


Figure 21. A, Yearly values for different growth and removal parameters for the Swedish forests, obtained from the Swedish National Forest Inventory. Yearly data three years before and after two big storms in 1969 and 2005 were excluded. B, The calculated yearly difference between total growth and total harvest rates were plotted against the yearly total growth rates.

Hence, it was estimated that on a national level the total carbon sequestrated might have been 39.1-42.5 million tons of CO_2 equivalents if tropospheric ozone concentrations over Sweden would have been at low, pre-historic levels during the year 2011, as compared to the current value for 2011 of 37.6 million tons of CO_2 equivalents (Lundblad et al., 2013). The uncertainty range reflects the differences in the percent NPP reduction estimated for the different geographical zones (Tables 6-11). There is not enough statistical information available to be able to estimate separate values for the ozone impacts on the forest carbon sequestration in the different zones. If the tropospheric ozone concentrations would have increased to twice the ambient levels (based on AOT40), the total carbon sequestrated by the Swedish forest would have been reduced to 32.7-36.1 million tons of CO_2 during the year 2011.

Hence, the reduced NPP caused by current, ambient ozone levels was estimated to reduce the carbon sequestration for the living biomass in Swedish forests by the range of 1.5 – 4.5 million tons of CO_2 equivalents per year. If the ozone concentrations are even further increased, the carbon sequestration for the living biomass in Swedish forests might be reduced by 2.6-9.8 million tons of CO_2 equivalents per year (i.e. a reduction of 7-26%).

6 Discussion and implications

The results show that the NPP was reduced between 4-15% for Norway spruce in ambient ozone as compared to the pre-industrial ozone scenario. The values for reduction in NPP for Scots pine and birch were 4-16% and 1-4%.

Reductions in NPP were shown for all parts of Sweden, with the largest biomass reductions for the southern parts depending on the higher ozone exposure values. In the future A2 and B2 climate scenarios, the biomass reductions were of similar magnitudes as compared to the reference current climate. The NPP was reduced between 8-30%, 9-31% and 3-10% in Norway spruce, Scots pine and birch, respectively, in the increased ozone scenario when compared to pre-industrial ozone scenario. The NPP was generally higher in the future A2 and B2 climate scenarios than for the current climate, for all tree species and in all geographical zones across Sweden.

The negative influence of current, ambient ozone levels on NPP are generally larger than the negative influence of ozone estimated for the growth of young trees under experimental conditions. These estimates have for ambient ozone levels in southern Sweden been a 2% growth reduction for Norway spruce and an 8% growth reduction for birch (Karlsson et al., 2005). From this Karlsson (2012) estimated the negative impacts of current ozone levels on biomass carbon sequestration for 10 northern European countries. The mean reduction for these countries was estimated to -10 % and the value estimated for Swedish forests was 9%.

To some extent, the results from this simulation study confirm the results from growth reductions of young trees under experimental conditions. The measurements of the impacts of ozone on photosynthesis and the estimated rates of leaf senescence can to some extent be regarded as independent of the measurements of the ozone impacts of growth, especially for Norway spruce, where the measurements on photosynthesis /senescence and growth originates from different experiments (Rörvik and Östad). However, the experimental studies were conducted in open-top chamber with young potted seedlings and the response factors of the seedlings were scaled up to matured trees. Morphological, physiological and phenological characters of mature trees differ from that of seedlings (Kolb and Matyssek, 2001; Samuelson and Kelly, 2001) which might influence the outcome of the studies.

Conifer needles are characterized by low photosynthetic capacity and low stomatal conductance when compared to broadleaves such as birch (Körner et al., 1979). Therefore conifers are less prone to pollutant uptake and injury than broadleaves with high stomatal conductance (Reich, 1987). Thus, in theory biomass growth in mature birch trees should have been affected to a greater extent than predicted here.

The methodology of this study involves experiments with Open Top Chambers and modelling at different scales with Heureka-standwise model (see Appendix 1) and 3-PG model. There are uncertainties associated with each step in this exercise. The response factors to ozone pollution were derived from short time experimental studies using seedlings and it was extrapolated to mature trees all over Sweden. The initial stand factors for the 3-PG model were simulated using the empirical model Heureka-standwise which doesn't have climate change implemented, therefore the trees considered in this study grow in a similar climatic condition until they became mature trees in current and future climate which is an unlikely event. Moreover there is no ozone modifier implemented in the 3-PG model. Instead, the ozone parameterization is done using other input parameters such as maximum photosynthetic capacity and accelerated senescence. The results might have been different if the model was parameterized for a longer period of time. More research has to be done in this field in future.

7 Conclusions

Model simulations, based on empirical information about negative impacts of ozone on photosynthesis and leaf senescence, show that forest growth (NPP) is reduced by 4-12% under current, ambient ozone levels across Sweden, as compared to assumed, pre-industrial, low ozone levels. The forest growth would be further reduced under higher increased ozone levels across Sweden. In general, these ozone impacts are larger than growth reductions observed for young trees in experimental studies. The reduced NPP caused by current, ambient ozone levels was estimated to reduce the carbon sequestration for the living biomass in Swedish forests by the range of 1.5 – 4.5 million tons of CO2 equivalents per year. If the ozone concentrations are even further increased, the carbon sequestration for the living biomass in Swedish forests might be reduced by 2.6-9.8 million tons of CO2 equivalents per year (i.e. a reduction of 7-26%).

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Appendix 1. Further details of the modelling with 3-PG.

Initial stand data for 3-PG

The initial stand data for the 3-PG model was simulated using the empirical forest growth model Heureka. The Heureka Decision Support System (DSS) was used for stand, forest and regional analysis and planning (Wikström et al., 2011). The Heureka DSS could handle economic values, silvicultural treatments, timber production, forest fuels, biodiversity, recreation and carbon sequestration (Wikström et al., 2011). Heureka is based on a common core model base and it consists of three different models (Lämås et al., 2003). These models were developed to suit the needs of end user categories. The models included in Heureka are Heureka-regwise (national and regional analyses), Heureka-standwise (operational planning and planning for small scale forestry) and Heureka-planwise (for long-term planning in forest companies) (Lämås et al., 2006). The Heureka-standwise model was used for this study. Further information on the Heureka DSS could be found elsewhere (Elfving and Nyström, 2010; Lämås and Eriksson, 2003; Wikström; Wikström et al., 2011).

A representative Norway spruce stand was selected for each zone . The site index of Norway spruce for each zones were derived from Swedish statistical yearbook of forestry (Skogsstyrelsen, 2012). Slightly higher values were considered for site index than recommended by the Swedish statistical yearbook of forestry (Urban Nilsson, Personal communication, March 3rd, 2013). Using the "register tree data" function in Heureka-standwise, a plot of size one ha was simulated with 10 sample trees. The site variables such as mean age, mean age type, latitude, altitude, county, site index, site index species, slope, slope direction, soil depth, age diversity, vegetation type, bottom layer, soil moisture, soil texture, lateral water and maturity class; stand variables such as age (year planted), stem density, basal area and height were the input variables for the "register tree data" function in the Heureka-standwise model. The value of these input variables was considered based on knowledge of geographical location and climatic conditions of representative stands (table 3). Process based models such as 3-PG is more accurate to simulate NPP of middle-aged trees (Landsberg and Gower, 1996; Law et al., 2008; Law et al., 2001; Malhi et al., 2002). Therefore, care has been taken to consider middle-aged trees for this study and the entire representative stand considered was assumed to have a height of 9m and 2000 stems/ha during the initial period of the simulation. The age at which the stand attains 9m height at a stem density of 2000/ha was considered as the initial age of the representative stand. The basal area of the stand during that stage was considered as the initial basal area of the representative stand. The trees grow faster in fertile sites, therefore the representative stands in fertile sites attain 9m height at a lower age than those at less fertile sites. Then the model simulated 10 sample trees in each plot with different diameter and height. These sample trees were distributed randomly over the representative stand. Norway spruce stands were first simulated. Minor adjustments were then made on the site variables, in order to get exact site index value to the one pre-assumed. The Heureka-standwise model could calculate the site index for conifers given the site variables (Elfving and Nyström, 2010). This function was used to calculate the site index for Scots pine in all the representative stands. Since the Norway spruce and Scots pine representative stands were in the same geographical location, the site properties of the representative stand were assumed to be the same. In order to calculate the site index for Scots pine representative stands at a particular zone, the same site variables as for the Norway spruce representative stands, at that particular zone, were used (table 5). Scots pine representative stands were thus simulated in the Heureka-standwise sub-model using the calculated site index. It wasn't possible to calculate the site index for birch representative stands in a similar way using Heureka.

Calculation of site index of birch

The site index of birch was estimated from the site properties using the following model (Ekö et al., 2008).

$$SI = b0 + b1 * alt + b2 * Lat + D1 \dots Dn + \varepsilon$$

Where SI= site index for birch, i = plot index, alt1= altitude, $D1$ .... Dn = Indicator variables for site properties, b0....bn = coefficients estimated by ordinary least squares and εi = normally distributed random deviations with expectation zero (Table A1).

Table A1. Model input variables for calculating site index of birch (Ekö et al., 2008).

Site properties	Coefficient	SE
Southern Sweden		
$b0$	0.259	8.550
$b1$	-0.00729	0.00255
$b2$	0.287	0.0147
$b3$(Tall herbs)	2.173	0.563
$b4$(Herbs)	2.582(Ekö, P.M., Personal communication)	
$b5$(Swamp mosses type)	1.224	0.5333
$b6$(Mesic-soil mosses type)	2.213	0.465
$b7$(Frequent surface/subsurface water flow)	1.978	1.198
Northern Sweden		
$b0$	88.469	8.379
$b1$	-0.00869	0.00186
$b2$	-1.112	0.013
$b4$(Herbs)	1.397	0.595
$b7$(Frequent surface/ subsurface water flow)	2.216	0.662

Table A2. Site variables of zones 1-6.

Site variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Initial age (years)	Spruce 20 Pine 26 Birch 20	Spruce 33 Pine 35 Birch 20	Spruce 26 Pine 35 Birch 20	Spruce 29 Pine 30 Birch 20	Spruce 33 Pine 30 Birch 20	Spruce 42 Pine 32 Birch 20
Initial Basal area	Spruce 21.5 Pine 17.5 Birch 10.4	Spruce 15.9 Pine 15.8 Birch 10.4	Spruce 18.5 Pine 15.8 Birch 10.4	Spruce 17.2 Pine 16.7 Birch 10.4	Spruce 15.9 Pine 16.7 Birch 10.4	Spruce 14 Pine 15.8 Birch 10.4
Latitude	56	57	55.5	58.6	59.6	63.5
Altitude (m)	120	215	280	130	200	100
County	Skåne	Kalmar	Kronoberg	Uppsala	Dalarna	Västerbotten
Site index species	Spruce34 Pine 28 Birch 22	Spruce 26 Pine 22 Birch 20	Spruce 30 Pine 22 Birch 20	Spruce 28 Pine 26 Birch 22	Spruce 26 Pine 24 Birch 22	Spruce 22 Pine 22 Birch 20
Slope	0-10%	0-10%	10-20%	0-10%	10-20%	0-10%
Slope direction	Other	Other	Other	Other	Northeast	Other
Soil depth	Deep >70cm	Deep >70cm	Deep >70cm	Rather shallow 20-70cm	Deep >70cm	Deep >70cm
Plot type	Older stand	Older stand	Older stand	Older stand	Older stand	Older stand
Age diversity	Even aged	Even aged	Even aged	Even aged	Even aged	Even aged
Climate code	Other	Other	Other	Other	Other	Other
Vegetation type	High herb blueberry	Blueberry	High herbs lingonberry	Low herbs blueberry	Low herbs blue berry	Low herbs blueberry
Bottom layer	Mesic moist	Sphagnum type	Sphagnum type	Sphagnum type	Sphagnum type	Mesic moss type
Soil moisture	Mesic moist	Mesic moist	Moist	Mesic moist	Mesic moist	Mesic moist
Soil texture	Sandy medium	Sandy medium	Sandy medium	Sandy medium	Sandy medium	Sandy medium
Lateral water	Shorter period	Seldom	Shorter period	Longer periods	Longer periods	Longer periods
Maturity class	Middle aged unthinned	Middle aged, unthinned	Spruce-Middle aged thinned Pine-middle aged unthinned	Spruce-Middle aged thinned Pine-middle aged unthinned	Middle aged unthinned	Middle aged unthinned

Simulation of stands using Heureka-standwise

All the stands were simulated with an initial height of 9 m and initial stem density of 2000 stems/ha. A forest management programme was implemented in all the simulated stands, with two commercial thinnings apart from the final felling for all studied species. Thinnings were performed according to standard thinning guidelines for Norway spruce and Scots pine (Skogsstyrelsen, 1984). Thinning in birch stands was done according to the Finnish thinning programme for birch (Oikarinen, 1983). The biomass of foliage (Wf), stem (Ws) and root (Wr) (tonnes/ha) were output from Heureka-standwise (eqn 2, 3, 4) and were used as input parameter for 3-PG model.

$$Wf = Biomass\ needles \qquad (2)$$
$$Ws = Biomass\ (bark + branches + dead\ branches + stem) \qquad (3)$$
$$Wr = Biomass\ (roots > 5mm + \ roots\ 2 - 5mm\ ) \qquad (4)$$

Simulation of NPP using 3-PG model

The 3-PG model was used for simulating the NPP of Norway spruce, Scots pine and birch stands in each of the six zones. Single site simulation of 3-PG was used in order to simulate the NPP, where a representative site from each zone was identified for this purpose. Three simulations were done using the 3-PG model, one reference run for the year 2011 (reference) and two future scenario runs for the year 2100 for the A2 and B2 scenarios.

Climate data

The climate data used in this study was from Regional Climate Model simulations developed by the Rossby centre, Swedish Meteorological and Hydrological Institute (SMHI) (www.smhi.se). This climate data is based on ECHAM4 global climate model, RCA3 regional climate model (Bergstrom et al., 2001; Rummukainen et al., 2001). The climate data was downloaded for the year 2011 (reference) and for the year 2100 (A2 and B2scenarios). The various assumptions in the- scenarios is elaborately described elsewhere (Fischlin et al., 2009; McCarthy et al., 2001; Nakicenovic et al., 2000; Solomon et al., 2007).

The climate variables such as monthly maximum temperature, monthly miminum temperature, total monthly rainfall, average monthly incoming solar radiation, number of rainy days per month and number of frost days per month were obtained from climate data download application of SMHI for each county in Sweden (http://www.smhi.se/en/2.575/Climate-scenarios/climate-scenarios-1.6629). The big counties of north of Sweden such as Västerbotten, Norrbotten and Jämtland were divided in two separate (east and west) counties as the climate varies within these counties. The monthly average values of climate variables such as maximum temperature, minimum temperature, incoming solar radiation and total monthly rainfall were directly available from climate data download application. The number of frost days per month was obtained from climate scenario map of SMHI directly (http://www.smhi.se/klimatdata/klimatscenarier/scenariokartor). Number of rainy days value was not directly available from climate scenario map, but was calculated indirectly from data of dry days without precipitation.

The spatial resolution (pixels) of the regional climate model was 50 x 50 km and each county was represented by the maximum number of pixels (Rummukainen et al., 2004). There were maximum two observation points in small counties, four in average sized counties and 12 in big counties. The average of observation point data was pooled to get county level climate data. The combined average of county level data, for those counties belonging to a zone (table 3) was calculated to get zonal climate data. Conversions were made on the unit of climate data when necessary in order to suit to 3-PG requirements.

Site and stand initiation factors in 3-PG

The site and stand initiation factors used in 3-PG were the year the stand was planted, the month it was planted, initial age, end age, initial stem number, latitude, fertility rating, atmospheric CO_2 content, initial weight of foliage as well as root and stem (tonnes/ha). The CO_2 concentration for reference climate was assumed to be 390 ppm, for the A2 scenario it was 850 ppm and for the B2 scenario 600 ppm, respectively, during the year 2100 (Houghton et al., 2001). The fertility rating parameter for southern Sweden for conifers was 0.5 (reference climate) and 0.6 (A2 scenario), respectively (Subramanian, 2010). For the B2 scenario the fertility rating was supposed to be in between the reference and the A2scenario therefore it was assumed to be 0.55 for conifers in the southern regions. The critical factor for growth in northern Sweden is soil nutrients (Bergh et al., 2005), primarily nitrogen. This is primarily an effect of low soil temperature, which slows down the mineralization and decomposition rate (Kirschbaum, 2000; Vanhala et al., 2008). Therefore fertility rating for northern Sweden was lower, 0.4 (reference climate), 0.5 (A2 scenario) and 0.45 (B2 scenario), respectively.

The site quality ratio of birch/spruce was 0.71 and 0.57 respectively for southern Sweden and northern Sweden (Ekö et al., 2008). In the 3-PG model the site quality is determined by fertility rating. Therefore, in order to achieve a reduced NPP for birch species the fertility rating was reduced to a similar extent. The fertility ratings for birch were 0.4 (reference climate), 0.5 (A2 scenario) and 0.45 (B2 scenario) for southern Sweden. For Northern Sweden the fertility rating for birch were 0.3 (reference climate), 0.4 (A2 scenario) and 0.35 (B2 scenario). In order to analyse the impact of ozone on the tree species, ozone scenarios were also considered along with climate scenarios.

Ozone simulations in 3-PG model

The adverse impacts of ozone were not directly implemented in the 3-PG algorithm. The OTC empirical data for ozone impacts has been described above. The reduction in maximum photosynthetic rate in OTC measurement data was analogous to the canopy quantum efficiency parameter in 3-PG (Landsberg and Sands, 2010). The monthly litterfall parameter is empirically determined in the 3-PG model. The monthly litterfall rate is directly proportional to the maximum litterfall rate which in this context is the accelerated senescence (Landsberg and Waring, 1997; Sands and Landsberg, 2002). The decrease in maximum photosynthesis and increase in accelerated senescence under the ambient ozone and the increased ozone scenarios when compared to the pre-historic ozone scenario were summarized (Table 6). A normal simulation in 3-PG was ambient ozone scenario. In order to simulate the pre-historic ozone scenario, the correction factors of ambient ozone scenario were divided from ambient run. The NPP under increased ozone concentration was calculated by multiplying the ozone reduction factor under increased ozone concentration from pre-historic ozone concentration.

Table A3. Ozone correction factor for each zone, the reduction in the variables were when compared to pre-historic ozone scenario.

Ozone scenario	Zone	Deciduous trees		Coniferous trees	
		Maximum photosynthesis rate	Accelerated senescence	Maximum photosynthesis rate	Accelerated senescence
Ambient ozone	1	0.97	1.03	0.86	1.14
	2	0.97	1.03	0.87	1.13
	3	0.97	1.03	0.86	1.14
	4	0.98	1.02	0.91	1.09
	5	0.98	1.01	0.93	1.07
	6	0.99	1.01	0.96	1.04
Increased Ozone	1	0.96	1.03	0.83	1.12
	2	0.97	1.02	0.85	1.11
	3	0.96	1.02	0.84	1.12
	4	0.98	1.02	0.90	1.08
	5	0.98	1.02	0.92	1.07
	6	0.99	1.01	0.96	1.04

Comparing simulated NPP

Net primary production of the whole stand was an output in the 3-PG model and it was calculated in tonnes dry mass/ha/month (Sands and Landsberg, 2002). The annual NPP was calculated as the sum of all the monthly NPP during that particular year. NPP was converted to the standard unit of Kg C/m^2/year. The impact of climate effect and ozone effect on NPP was calculated by comparing the simulated NPP for the year 2011 (reference climate) for a particular zone and tree species, to NPP simulated during the year 2100 (A2 and B2 scenarios).

In order to analyse the impact of ozone molecules on NPP, the change in annual NPP in ambient and increased ozone scenarios were compared to the pre-historic scenario, which was calculated for all tree species (eqn 3). The change in annual NPP between the increased ozone scenario and the ambient ozone scenario was calculated to estimate the future impact of high ozone concentrations in NPP for each tree species (eqn 4).

$$Change\ in\ NPP = \frac{NPP(scenario)}{NPP(reference)} \quad (3)$$

$$Change\ in\ NPP = \frac{NPP(increased)}{NPP(ambient)} \quad (4)$$

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