REPORT

Ozone Impacts on Carbon Sequestration in Northern and Central European Forests

Per Erik Karlsson

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John Munthe
Vice President, Research

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Address P.O. Box 53021 SE-400 14 Göteborg	**Project sponsor** The Swedish Environmental Protection Agency
Telephone +46 (0)31-725 62 00	

Author

Per Erik Karlsson

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Summary

The ozone impacts on forest carbon sequestration were assessed for some northern and central European countries. The analysis was based on UN-ECE statistics regarding forested areas, forest growth and harvest rates for the 2000-2005 period. This was combined with ozone exposure – growth response relationships for different forest types and age-classes in combination with nation-wide values for AOT40 April – September.

The following conclusions were made:

1. The by far most important countries for carbon sequestration in the forest living biomass carbon stocks were Sweden, Finland, Poland and Germany.

2. The estimated annual increase in the living biomass carbon stocks under current ozone conditions for the ten countries was 171 M t CO_2e yr^{-1}, while it was estimated to have been 190 M t CO_2e yr^{-1} under pre-industrial ozone levels.

3. The difference caused by current ozone conditions on the annual living biomass carbon stock change was thus 19 M t CO_2e yr^{-1}, i.e. the carbon sequestration in these countries would have been 10 % higher in the absence of the ozone pollution problem.

4. The magnitude of the predicted relative ozone effect for the different countries strongly depended on the gap between forest growth and harvest rates

5. The knowledge regarding ozone impacts on mature trees under field condition is to a large extent incomplete and further research is strongly needed.

The abatement of the ozone pollution problem clearly has the co-benefit to increase the carbon sequestration in northern and central European forests for at least some decades into the future.

Keyword

Ozone, carbon sequestration, northern Europe, forest, living biomass

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Forword

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Summary

The ozone impacts on forest carbon sequestration were assessed for some northern and central European countries, i.e. Sweden, Finland, Norway, Denmark, Estonia, Latvia, Lithuania, Poland, Czech Republic and Germany. Since the most important increase in forest carbon stocks today is to the living biomass, the analysis focused on ozone impacts on the living biomass carbon stock changes. The analysis was based on UN-ECE statistics regarding forested areas, forest growth and harvest rates for the 2000-2005 period. This was combined with ozone exposure – growth response relationships for different forest types and age-classes in combination with nation-wide values for the AOT40 April – September.

The following conclusions were made:

1. The by far most important countries for carbon sequestration in the living biomass carbon stocks were Sweden, Finland, Poland and Germany.

2. The estimated annual increase in the living biomass carbon stocks under current ozone conditions for the ten countries was 171 M t CO_2e yr^{-1}, while it was estimated to have been 190 M t CO_2e yr^{-1} under pre-industrial, lower ozone levels.

3. The difference caused by current ozone exposure on the annual living biomass carbon stock change was 19 M t CO_2e yr^{-1}, i.e. the carbon sequestration to the forests in these countries was estimated to have been 10 % higher in the absence of the ozone pollution problem.

4. The magnitude of the predicted ozone effect for the different countries strongly depended on the gap between forest growth and harvest rates.

5. The knowledge regarding ozone impacts on mature trees under field condition is to a large extent incomplete and further research is strongly needed.

The abatement of the ozone pollution problem clearly has the co-benefit to increase the carbon sequestration in northern and central European forests for at least some decades into the future.

Contents

1. Introduction

1.1 The significance of terrestrial ecosystem carbon sequestration

The world's annual fossil CO_2 emissions (including emissions from cement production) correspond to approximately 25000 Mt CO_2e (CO_2 equivalents), with emissions from land-use change (mainly tropical deforestation) contributing an additional 5000 Mt CO_2e (IPCC, 2007). The vegetation in temperate and boreal ecosystems sequesters in the order of 5000 Mt CO_2e annually and most of this goes into the forests (Hyvönen et al., 2007, Royal Society, 2001). Intact tropical forests are estimated to sequester an additional 5000 Mt CO_2e annually (Trumper et al., 2009). A recent estimate of carbon sequestration by total global forests was ca. 14000 Mt CO_2e (excluding carbon storage in harvested wood products, Pan et al., 2011), of which living biomass carbon constituted close to 80%. European forests contributed around 10% of the global carbon sequestration in forests (Figure 1).

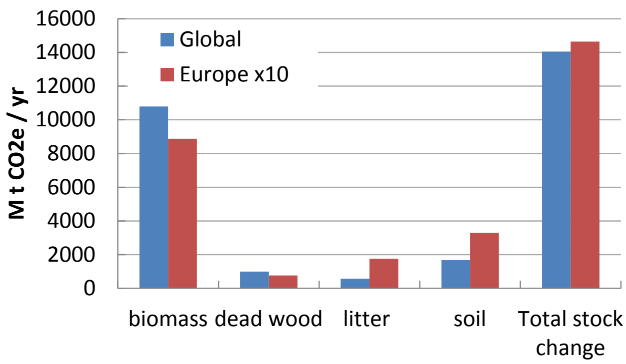

Figure 1. Annual changes in global and European forest carbon stocks, according to Pan et al. (2011.) Values for Europe are multiplied by a factor 10. Estimates do not include storage in harvested wood products. European estimates include the European parts of Russia. Global estimates include both intact and re-growth tropical forests but not deforestation.

The carbon sequestration by vegetation represents a considerable amount as compared to the fossil emissions and emissions from deforestation. As a result, the annual increment in atmospheric CO_2 concentration is substantially smaller than the increment expected from anthropogenic emissions alone (Canadell et al., 2007). This is described by the so called "Airborne Fraction" (AF), which is the ratio between the annual increase in atmospheric CO_2 concentration and the total anthropogenic emissions of CO_2 (fossil + deforestation) for the same year. This ratio varies considerable between years and range between 0 and 0.8. The AF has increased since 1960, implying that the carbon sequestration to terrestrial ecosystems and oceans has not been able to keep up with increasing anthropogenic CO_2 emissions (Canadell et al., 2007). This highlights the importance of the capacity for carbon sequestration to the terrestrial vegetation. Actions to expand the area of boreal forests in order to mitigate climate change has been criticized, since this can change the local albedo, increase the absorbance of heat radiation and thus cause local warming (Bala et al., 2006). However, this should apply mainly to land-use change (afforestation, reforestation) and not to the same extent for maintaining or increasing growth rates for already existing forested land.

The geographical distribution of the rates of forest carbon sequestration across Europe is illustrated in Figure 2. Regarding the ten northern and central European countries included in the present analysis, the highest rates of carbon sequestration occurs in southern Sweden, Germany and Poland. Note that the Baltic countries were not included in this study.

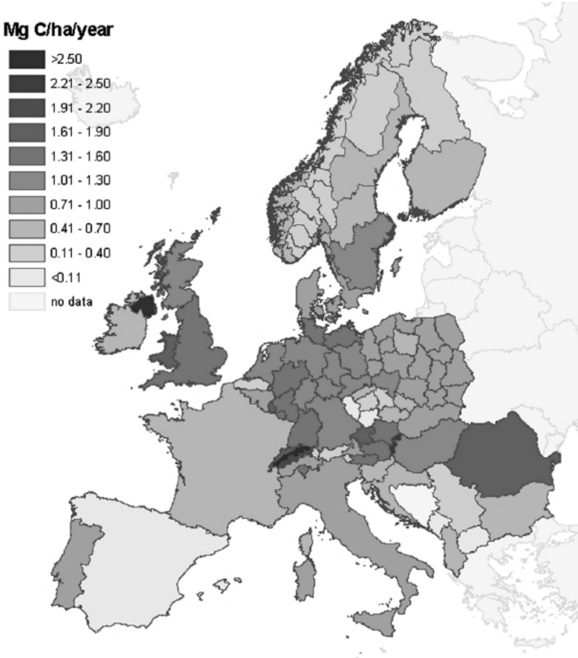

Figure 2. The geographical distribution of the rates of forest carbon sequestration across Europe over the period 1990-1995, not including harwested wood products. 1 Mg C ha-1 yr-1 corresponds to approximately 3.7 t CO2e ha-1 yr-1. From Karjalainen et al. (2003).

1.2. A description of northern European forests

Some FAO statistics on forests in ten northern European countries are provided in Table 1. The forested areas are largest in Germany, Finland, Norway and Sweden. This applies also for the growing stocks, although also Poland adds to the list. Regarding to total amount of carbon stored in the forests, the highest values applies for Poland, Germany, Sweden and Finland.

Table 1. Forested areas, growing stocks and carbon stocks for ten major, northern and central European countries for the year 2005 and annual changes 2000-2005. The four highest values for each parameter are highlighted with a grey background. Source: FAO statistics, State of the World Forests, 2009. n.a.: data not available.

Country	Extent of forest		Growing stock			Carbon in biomass	
	Forest area 1000 ha	Annual change %	Per area, m^3/ha	Total, $M\ m^3$	Com-mercial, %	Per area, t C/ha	Total, Mt C
Czech Rep	2 648	0.1	278	736	97	123	326
Estonia	2 284	0,4	196	447	94	73	167
Latvia	2 941	0.4	204	599	85	79	231
Lithuania	2 099	0.8	190	400	86	61	128
Poland	9 192	0.3	203	1864	94	97	896
Germany	11 076	n.a.	n.a	n.a.	n.a.	118	1303
Denmark	500	0.6	153	77	76	52	26
Finland	22 500	0.0	96	2158	84	36	816
Norway	9 387	0.2	92	863	78	37	344
Sweden	27 528	0.0	115	3155	77	43	1170
All	90155						

The distribution of the forest area between different types and age-classes is shown in Table 2. It was assumed that the age-class <10 years represented young stands, the age-class 11-60 years represented highly productive stands while the age-class > 60 years represented aging forests with lower production. The fraction of highly productive coniferous forests was particularly high for Denmark and Sweden and it was low for Estonia. Instead Estonia had a relatively high fraction of productive broadleaved forests, together with Lithuania. Sweden and Finland had low fractions of productive broadleaved forests. The fraction of young forests was relatively similar between the countries. This applies also for the fraction of old coniferous forests except that Denmark had a low fraction. The fraction of forests characterized as mixed was generally low.

Table 2. Description of the distribution of forest areas in regard to age-classes and forest types for ten major, northern European forested countries. Distributions are shown as percent of total forest area in each country. Absolute values for total forest area are also shown for each country. Source: UN-ECE statistics, Age Structure of Even-aged Forest and Other Wooded Land by Availability for Wood Supply and Forest Type, Age Class, Country and Year. n.a.; data not available. Data for Germany was obtained from http://www.bundeswaldinventur.de/enid/4d7ce5a78ed8275860f9cf240b3ac7e3,0/76.html.

	%								
age (years)	<=10			11-60			> 60		
	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed
Czech Rep.	6	1	2	26	6	6	39	8	6
Denmark	8	5	0	49	16	0	6	15	0
Estonia	1	4	1	16	28	14	20	6	10
Finland	8	1	1	31	4	7	40	2	5
Germany*	6	4	1	27	11	1	30	22	1
Latvia	4	4	2	18	21	6	28	11	7
Lithuania	4	3	2	20	27	9	20	8	7
Norway	1	3	3	19	10	12	33	11	7
Poland	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Sweden	14	1	1	40	4	10	27	1	3

* The age classes available for German forests were <20, 20-60 and >60 years.

1.3. The mechanisms for carbon stock changes in managed forests

In general, forests that are actively managed sequester carbon at much higher rates than non-managed forests (Eriksson et al., 2007, Hyvönen et al., 2007, Nabuurs et al., 2008., Pingoud et al., 2001). Any measures that increase the productivity of temperate or boreal forest, such as e.g. fertilization or a more favourable climate, are likely to increase the forest carbon sequestration (Hyvönen et al., 2007, Eggers et al., 2008). Furthermore, forest carbon sequestration rates change with stand age (Pregitzer and Euskirchen, 2004, Eriksson et al., 2007, Lindroth et al., 2009), with stands acting as a carbon source at young age, as a strong sink at medium age and as a weak sink or being carbon neutral at high age.

Annual national values for changes in carbon stocks in total forest land in Finland, Germany, Poland, France and Sweden reported to the Climate Convention (UNFCCC) are shown in Figure 3. Values are from the National Inventory Reports (NIR), are expressed as CO_2-equivalents (CO_2e) and are in most cases based on data from National Forest Inventories (NFI). Positive values indicate emission to, negative values uptake from the atmosphere. The patterns for the rates of changes in the forest carbon stocks over time vary for the different countries depending on the methods applied in the NFIs. Sweden probably has the world´s most extensive NFI, with ca. 30000 observation plots that are revisited every 5th year, i.e. 6000 each year (Sweden, NIR 2011). Since the changes in carbon stocks are interpolated for the years between the assessment occasions, the result is a gradual change in carbon stock change rates between years. In Germany, on the other hand, all forests are assessed in an inventory during a certain year, e.g. 1987, 2002 and 2008, and the carbon stock changes are interpolated between these years. As a result, there will be a sudden change in the estimated rates of carbon stock changes between the different assessment periods. Data for 2009 and 2010 were extrapolated from the 2003-2008 period. German forests have all the time been a sink for carbon. The reduced rates of carbon sequestration during recent years are explained by a doubling rate of harvests (Germany, NIR 2011).

The annual carbon sequestration to the forest ecosystems in these selected countries is substantial. For all countries that report differentiated carbon stock changes in the forest ecosystems, it can be seen that the major part of the carbon that is sequestered goes into the living biomass carbon stock. Dead biomass (including humus) and soil carbon also contribute, but these rates are slower, for soil carbon depending on that organic soils are sources for carbon to the atmosphere.

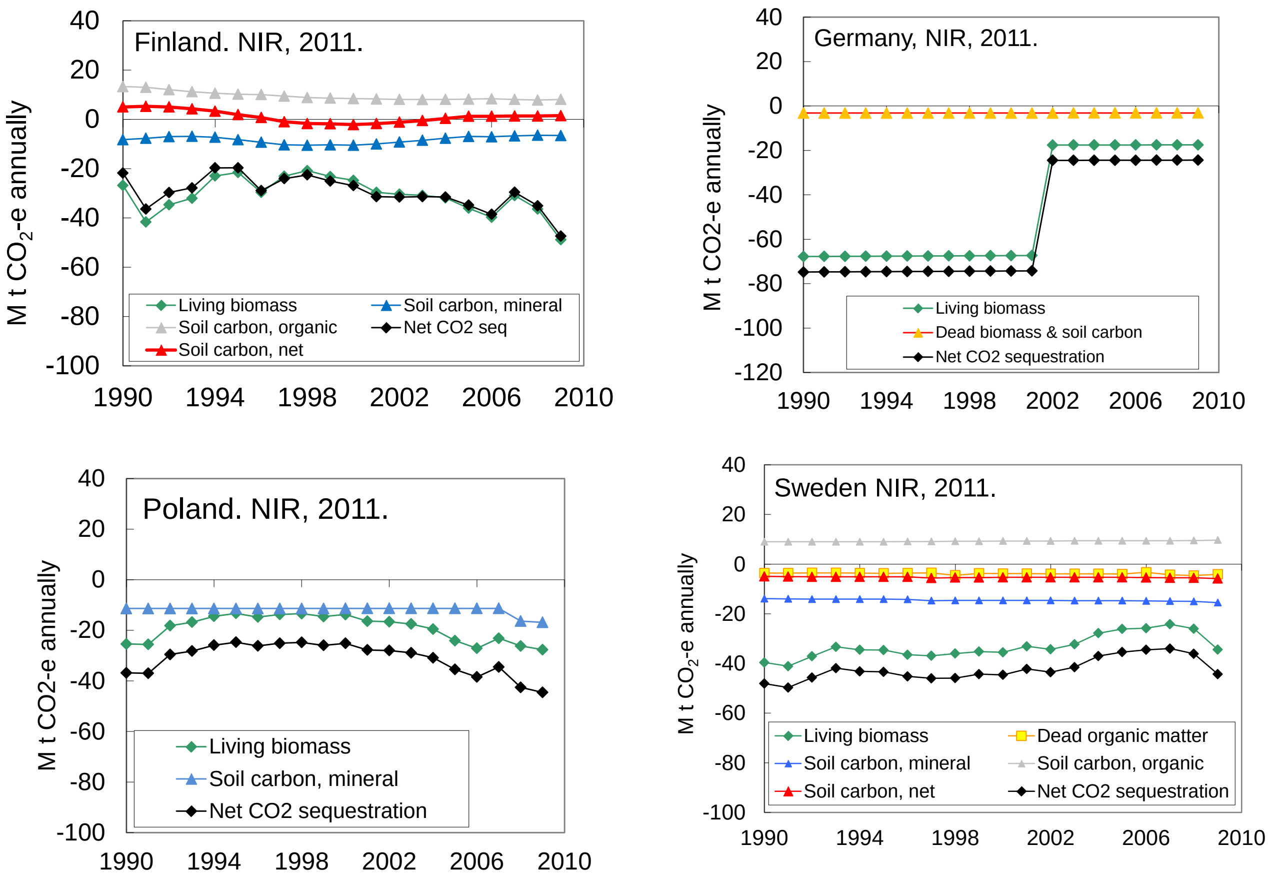

Figure 3. Annual national values for changes in carbon stock in total forested land in Finland, Germany, Poland and Sweden. Values are from the National Inventory Reports 2011, and expressed as CO2-equivalents (CO2e). Positive values indicate emission to, negative values uptake from the atmosphere. When reported, the carbon sequestration rates are shown for different compartments of the forest ecosystems.

The most important aspect of forest management for carbon sequestration is the rate of harvests in relation to the forest growth rates (Figure 4), i.e. the higher the rates of harvests compared to growth, the lower carbon sequestration. This aspect has to be analyzed on the landscape level and/or over long time periods, since individual stands are regularly harvested.

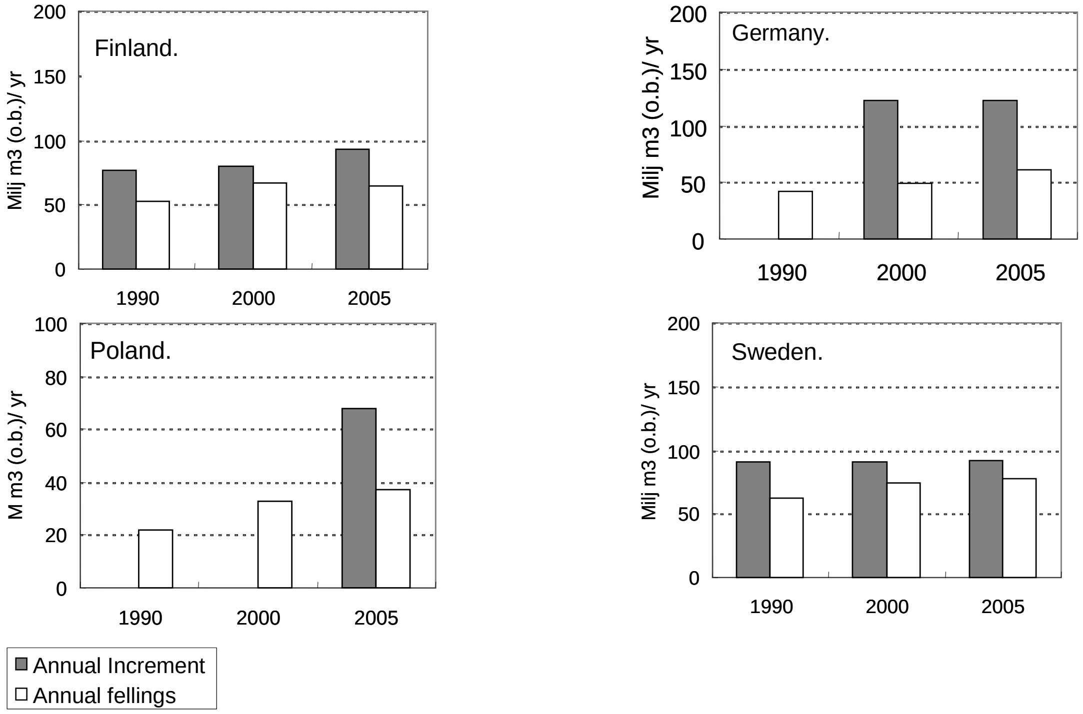

Figure 4. Annual national values for stem volume increment growth and annual fellings in Finland, Germany, Poland and Sweden. Values are from United Nations Economic Commission for Europe (UNECE, http://www.unece.org/forests/welcome.html), which in turn is based on FAO statistics.

2. The scope of this report

In this report, the impacts of ground-level ozone on European tree species and the possible implications for the carbon sequestration in northern and central European forest ecosystem are assessed. The analysis includes temperate and boreal forest ecosystems in some major forest producing countries. There are large uncertainties regarding ozone impacts on mature forest ecosystems. Hence, the aim of this analysis was to make a first estimate of how ozone might negatively affect carbon sequestration and to be transparent about the input values used for the analysis.

3. Methods

3.1 Basic approaches

For the assessment of today´s ozone impacts on forest ecosystem carbon sequestration it is necessary to specify a number of definitions. The first definition is the choice of baseline scenario, i.e. to what should the today´s ozone impacts be compared. The issue of background ozone levels has been a matter of controversy. However, in this study the baseline ozone scenario is defined as pre-industrial ozone levels, with concentration ranging from 10-15 ppb and no occurrence of ozone episodes, i.e. with AOT40[1] = 0.

The second definition that has to be considered is what time horizon over which carbon sequestration should be considered. Here we apply the general principle that is often applied in Life Cycle Analysis, i.e. that the assessment regards the current situation, as an average over a few years, and it does not involve predictions for the future. However, in northern European countries, it has been estimated that forest production might increase substantially in a future climate (e.g. Poudel et al., 2011).

The results shown above in Figures 1 and 3 clearly indicates that the main changes in the forest carbon stocks today occur in the living biomass compartment of the ecosystem. Hence, this study focus on the living biomass and impacts of ozone on other carbon stocks will be assessed only in a qualitative manner.

3.2 Estimates of forest ozone exposure

Forest exposure for ozone can be expressed either based as the accumulated exposure on concentrations in the atmosphere close to the canopy (e.g. AOT40, Fuhrer et al., 1997) or as the phytotoxic ozone dose (POD, Mills et al., 2011), i.e. accumulated ozone uptake through the stomatal pores on the surface of leaves. The latter approach is most relevant from a physiological point of view. However, exposure – response relationships based on AOT40 are more commonly reported in the literature and therefore applied in the current study. The nationwide values for AOT40 used for different countries in this study are shown in Table 3.

[1] The sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each our when the concentration exceeds 40 ppb, accumulated during daylight hours and a defined period (i.e. April – September for northern and central European forests).

Table 3. Estimated nationwide mean values for annual, daylight AOT40 accumulated during the growing season the values are annual means for the time period 2000-2005. Source: EMEP model (David Simpson 2011-09-27, generic deciduous tree parameterization).

	AOT40 ppm h		AOT40 ppm h
Czech Rep.	28	Latvia	10
Denmark	13	Lithuania	12
Estonia	7	Norway	4
Finland	3	Poland	21
Germany	24	Sweden	5

3.3 Derivation of ozone dose – growth response relationships

3.3.1 Criteria for dose –response relationships

Results from ozone impact studies on perennial plants, in contrast to annual plant species, 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 m^3 yr^{-1}, i.e. a growth rates over a long 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, so that 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. Assume for example an exposure experiment were trees have the same biomass at the start of the experiment and when the trees in the low ozone treatment double their biomass, e.g. from 1 to 2, and the trees in the high ozone treatment has a biomass at the end of the experiment that is 90% as compared to the biomass of the trees in the high ozone treatment, i.e. they increase their biomass from 1 to 1.8. The ozone effect as calculated in the percent biomass reduction at the end of the experiment will, of course, be -10 % while the ozone effect as calculated based on the growth rates will be -20 %, i.e. 0.8 as compared to 1.0. If similar conditions are applied but the biomass in the low ozone treatment instead increases four times during the experiment, e.g. from 1 to 4 in the low ozone and from 1 to 3.6 in the high ozone, then the reduction in growth rates in the high ozone will be -13 % (2.6 as compared to 3.0), while the biomass reduction at the end of the experiment will again of course be -10 %. Moreover, a growth rate expressed as m^3 yr^{-1} will have a different implication for a young, small tree as compared to an adult, large tree. Hence, it is more relevant to use the relative growth rates, i. e. the percent change in e.g. stem volume over time. The discussion above applies also for the relative growth rates.

The response variable used for calculating the ozone effects in this study was the relative increment of either stem volume or total biomass, i.e. the increment during a period relative to the value at the start of the period. This period was usually the last year of the experiments. The impacts on the relative stem volume or biomass increments were related to the mean, annual daylight AOT40 during the entire experimental period.

3.3.2 Previously reported assessments

Wittig et al. (2009) have 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%. Furthermore, they concluded that above- and below ground biomass was equally affected. The gymnosperm genera *Picea* and *Pinus* were found equally sensitive to ozone and the angiosperm genera *Betula* and *Populus* were equally sensitive. Gymnosperms were reported to be less sensitive to ozone than angiosperms but this depends to some extent on the time horizon applied.

There are some problems with the applicability of the Wittig study for the purposes needed in the current study: 1. From the Wittig study it could not be established how many of the studies included in the analysis used tree species that are relevant for European forests. 2. Ozone exposure was calculated as the mean hourly ozone concentration for the exposure period, which cannot be converted to AOT40 values. 3. Effects of the ozone treatments were calculated as the % reduction in biomass over time periods that were not specified. Hence, it is not possible to convert these effects to impacts on growth rates. In the current study, impacts on growth rates are required, as discussed above. Consequently, the results provided by the Wittig study could not be used for the current assessment of negative impacts of ozone on annual forest ecosystem carbon stock changes.

3.3.3 Assessments for northern European forests

Ideally ozone impacts should be specified separately for coniferous and broadleaved tree species as well as separately for trees of different age classes. The information available to achieve this is limited, but in this study ozone impacts were assessed differently for young trees before canopy closure (age <10 years), for productive age classes (age 10-60 years) and for old forests (age >60 years).

The response variable used for calculating the ozone effects was the relative increment rate of either stem volume or total biomass and this was related to the mean, annual daylight AOT40 during the entire experimental period.

3.3.3.1 Impacts on coniferous tree species

Ozone exposure – growth response relationships for young coniferous trees were derived from Karlsson et al. (2005) (Table 4). The main reason to choose the results from the Swedish Gothenburg Ozone Spruce Project (GOSP) with Norway spruce (*Picea abies*) was that ozone impacts on relative growth rates could be determined. Furthermore, Skärby et al (2004) showed that the results from GOSP were comparable to the results from several other experiments with young Norway spruce from a large number of European studies.

3.3.3.2 Impacts on broadleaved tree species

The ozone exposure – growth response relationship for young broadleaved trees was also taken from Karlsson et al. (2005) (Table 4). This in turn was based on information on ozone impacts on total plant biomass of European silver birch (*Betula pendula*) saplings obtained from a two-year, open-top chamber experiment in Sweden (Karlsson et al., 2003). It was shown that the results from this experiment were comparable with the results obtained from a number of open-air release experiments in Finland as well as with another open-top chamber experiment in Switzerland (Uddling et al., 2004).

It was assumed that the ozone impacts in the >60 year age-classes were 50% of the 10-60 year age-class, both for coniferous and broadleaved tree species (Table 4).

Table 4. Ozone impacts on the annual stem volume increment growth rates of coniferous and broadleaved tree species separated into three different age classes, as related to the annual mean daylight AOT40, accumulated from 1 April to 30 September and expressed as ppm h. Ozone impact on the relative stem volume increment rates is expressed as % change. For the derivation of different impact values, see the text.

Forest type	Age class <10 years	Age class 11-60 years	Age class >60 years
Conifers	-0.26 * AOT40	-0.26 * AOT40	-0.13 * AOT40
Broeadleaved	-0.49 * AOT40	-0.49 * AOT40	-0.25 * AOT40

The forest stem increment growth for the baseline scenario, i.e. the low ozone exposure, was calculated as:

$$y = h/(100+(i*j)/100)$$

where y= annual increment growth (m^3 yr^{-1}), h=annual increment growth under current ozone exposure levels (m^3 yr^{-1}), i=AOT40 (ppm h), j=the slope for the correlation between AOT40 and the per cent growth reduction (% (ppm h)$^{-1}$, negative values implies growth reductions).

3.3.4 Ozone impacts on mature trees

There are few experimental ozone exposure studies with large, mature trees under stand conditions. One example is the Kranzberg Forest experiment in southern Germany, where mature Norway spruce and European beech trees were exposed to twice ambient ozone concentrations for 8 years in an open-air release system. The disadvantage with this experiment was that the replication was low. However, this problem was partly eliminated by making use of the ozone gradient from the center of the experimental area (Pretzsch et al., 2010) and 11 tree individuals of Norway spruce and 6 beeches were fully exposed to the ozone treatment. Furthermore, the possibilities to detect impacts of the ozone treatment were enhanced by applying a method where initial differences between the two groups were eliminated. An additional problem with this type of experiment was that impacts of below-ambient ozone concentrations could not be assessed. On the other hand, this long-term experiment is unique in its application for mature trees in Europe.

Fumigation of mature trees of Norway spruce and European beech to twice ambient ozone concentrations induced a shift in the resource allocation into height growth at the expense of diameter growth (Pretzsch et al., 2010). Annual diameter growth was reduced on average 11% across both species, but significantly reduced only during some years of the total 8-year experimental period. Both Norway spruce and European beech shifted their resource allocation under ozone fumigation to height growth at the expense of diameter growth. For Norway spruce, the increased height growth compensated for the reductions in growth at the stem basis, so that the whole stem production showed no losses. For beech, the increase in height growth was not enough to compensate for the reduced diameter growth, so there was a significant reduction in stem volume increment in beech due to elevated ozone. The results from the Kranzberg Forest experiment demonstrated that the growth patterns of both Norway spruce and beech were indeed affected by the twice ambient ozone fumigation, and this could be detected despite the low number of replication. However reductions in stem volume growth were significant only for beech. Similar results were found for European birch saplings after two years of exposure to elevated ozone concentrations in open-top chambers, where the ozone treatment increased both the shoot/ root ratio as well as the stem height/ diameter ratio (Karlsson et al., 2003).

A statistically significant negative impact of ozone on stem growth of mature Norway spruce trees under stand conditions in southern Sweden was demonstrated by Karlsson et al. (2006a). However, the problem of co-linearity between ozone levels and certain meteorological conditions prevented the quantitative assessment between ozone exposure dose and response in this study. Other field studies have also shown significant relations between ozone exposure and impacts on different growth parameters and foliar symptoms for beech (Stribley & Ashmore, 2002; Dittmar et al., 2004; Braun et al., 1999, 2007), Norway spruce (Braun et al., 2004, Kivimaenpää et al., 2004), Scots pine (Augustatis & Bytnerowitz, 2008), and Pinus cembra (Dahlstein et al., 2002).

To summarize, there is so far no indication that mature trees are less affected by elevated ozone concentrations compared to juvenile trees. On the contrary, Wittig et al. (2009) suggest that chamber studies on young trees might even underestimate ozone impacts compared to open-air field studies over longer periods. Therefore, it was assumed in this study that the same dose-response relationships apply for young trees and trees in the productive age. It is assumed however, that old trees (>60 years) have a lower ozone sensitivity due to overall reduced growth rates (Table 4).

4. Results

The current annual, gross stem volume increment growth was estimated for the ten countries based on statistical information from UN-ECE, valid for the year 2005. This information is provided as total growth and felling values for each country. Hence, these values had to be distributed among different forest types and age classes, which was made based in the information shown in Table 2 above, in combination with the assumption of different relative area-based growth rates for different forest types and age classes. These assumed relative growth rates per area were derived based on information from the Swedish NFI for southern Sweden and were: Conifers <10 years, 0.2; Conifers 11-60 years, 1.5, Conifers >60 year, 0.8; Broadleaf <10 years, 0.4; Broadleaf 10-60 years, 1.3; Broadleaf > 60 years, 0.8. These adjustments were made so that the overall stem increment growth rates matched the values reported in the UN-ECE statistics. The estimated annual, stem volume increment growth rates under current ozone levels are shown in Table 5 as the values before the slash. The estimated annual, stem volume increment growth under pre-industrial ozone levels are also shown in Table 5, as the values after the slash.

Table 5. Estimated annual, stem volume increment growth per country in current- and pre-industrial ozone exposure levels, 2000-2005, for different forest types and age-classes as well as for total forests. Values for the current ozone exposure is shown before the slash, values for the pre-industrial ozone exposure is shown after the slash. o.b., over bark.

	M m³ o.b. / yr									
age (years)	<=10			11-60			> 60			
	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Total forest
Czech Rep.	0.233/0.252	0.086/0.100	0.103/0.115	7.95/8.57	1.60/1.85	1.86/2.08	5.66/5.87	1.20/1.28	0.896/0.946	19.6/21.1
Denmark	0.086/0.089	0.109/0.117	0.000/0.000	3.80/3.93	1.10/1.17	0.000/0.000	0.210/0.210	0.595/0.614	0.000/0.000	5.90/6.13
Estonia	0.011/0.012	0.183/0.189	0.036/0.037	2.66/2.71	4.04/4.18	2.19/2.25	1.56/1.57	0.463/0.471	0.790/0.800	11.9/12.2
Finland	1.54/1.55	0.198/0.201	0.326/0.329	43.1/43.4	4.93/5.00	9.47/9.57	26.0/26.1	1.49/1.50	3.68/3.70	90.8/91.4
Germany	1.43/1.53	2.11/2.40	0.242/0.266	50.3/53.5	17.3/19.7	1.38/1.51	25.6/26.5	19.9/21.2	1.09/1.14	119/128
Latvia	0.126/0.129	0.250/0.262	0.075/0.078	4.33/4.44	4.50/4.72	1.29/1.34	3.29/3.33	1.40/1.43	0.843/0.859	16.1/16.6
Lithuania	0.084/0.087	0.108/0.115	0.049/0.051	2.90/3.00	3.52/3.75	1.22/1.28	1.42/1.44	0.593/0.611	0.509/0.521	10.4/10.9
Norway	0.071/0.071	0.310/0.316	0.196/0.198	6.90/6.99	3.13/3.19	3.89/3.94	5.61/5.63	2.04/2.06	1.18/1.19	23.4/23.6
Poland	0.673/0.712	0.511/0.569	0.336/0.365	23.0/24.3	14.7/16.3	7.25/7.87	14.2/14.6	4.00/4.21	3.22/3.35	67.9/72.3
Sweden	2.52/2.55	0.200/0.205	0.322/0.329	54.5/55.3	4.28/4.39	12.3/12.6	17.4/17.5	0.800/0.809	2.03/2.05	94.4/95.7
All										**460/478**

The total harvest rates obtained from the UN-ECE statistics for 2005 for each country was distributed across forest types and age-classes using identical relative factors as used to distribute current growth. The results are shown in Table 6.

Table 6. Estimated annual harvest rates for different forest types and age-classes as well as for total forests. o.b., over bark.

	M m3 o.b./ yr									
age (years)	<=10			11-60			> 60			
	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Total forest
Czech Rep.	0.196	0.072	0.086	6.66	1.34	1.56	4.75	1.003	0.751	17.2
Denmark	0.031	0.039	0.000	1.35	0.390	0.000	0.07	0.211	0.000	1.84
Estonia	0.006	0.095	0.019	1.39	2.103	1.142	0.81	0.241	0.411	5.7
Finland	1.072	0.138	0.227	30.0	3.43	6.58	18.1	1.03	2.56	64.5
Germany	0.712	1.052	0.120	25.0	8.64	0.69	12.8	9.92	0.54	61
Latvia	0.086	0.171	0.051	2.96	3.078	0.88	2.25	0.956	0.577	11.3
Lithuania	0.062	0.079	0.036	2.12	2.579	0.896	1.04	0.434	0.373	7.24
Norway	0.033	0.144	0.091	3.2	1.45	1.81	2.60	0.948	0.549	11.1
Poland	0.370	0.281	0.185	12.7	8.07	3.99	7.8	2.20	1.77	37.2
Sweden	2.153	0.171	0.276	46.6	3.66	10.55	14.9	0.68	1.74	78.1
All										295

The net stem increment growth was calculated for each country, forest type and age-class based on the values provided in Tables 5 and 6. These yearly increment values were then converted to carbon stock changes as described in IPCC's "Good Practice Guidance for Land Use, Land-Use Change and Forestry" (Penman et al., 2003), somewhat modified as described by von Arnold et al. (2005).

$$\Delta C = Iv * BEF * D * CF$$

ΔC, Carbon sequestration to tree living biomass (tonnes C ha^{-1} yr^{-1}); Iv; yearly increment of timber volume (m^3 ha^{-1} yr^{-1}; D, density stem (tonnes dry weight m^{-3}); CF, "carbon fraction", of dry matter (tonnes $tonnes^{-1}$); BEF, biomass expansion factor, converts between stem biomass and total living biomass including branches, leaves and roots. The value of ΔC was then converted to CO_2-eqvivalents (CO_2e) by multiplying with 3.67.

The differences between the changes for the living biomass carbon stocks in the current ozone exposure and the pre-industrial ozone exposure scenario are shown in Table 7, in absolute values for the different forests types and age-classes as well as the total forests in each country and as percent change for the total forests. The estimated change of the living biomass carbon stock across total forests in all ten countries was a reduction of 10 %. For different countries these values ranged between 2 - 32 %. The differences depended on the size of the gap between growth- and harvest rates, as discussed below.

Table 7. Estimated reductions in annual carbon sequestration due to current ozone exposure as compared to pre-industrial ozone levels for different forest types and age-classes as well as for total forests. Also presented is the percent reduction due to ozone exposure, for the total forest in each country.

	M tonnes CO_2e yr^{-1}										%
age (years)	<=10			11-60			> 60				
	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Coni-ferous	Broad-leaved	Mixed	Total forest	% reduction
Czech Rep.	0.02	0.01	0.01	0.65	0.26	0.23	0.22	0.09	0.05	1.55	32.0
Denmark	0.00	0.01	0.00	0.13	0.07	0.00	0.00	0.02	0.00	0.24	5.8
Estonia	0.00	0.01	0.00	0.05	0.14	0.06	0.01	0.01	0.01	0.28	4.5
Finland	0.01	0.00	0.00	0.32	0.07	0.10	0.10	0.01	0.02	0.64	2.2
Germany	0.10	0.29	0.03	3.49	2.42	0.14	0.86	1.30	0.05	8.69	12.3
Latvia	0.00	0.01	0.00	0.11	0.23	0.05	0.04	0.03	0.02	0.51	8.8
Lithuania	0.00	0.01	0.00	0.10	0.23	0.06	0.02	0.02	0.01	0.46	13.8
Norway	0.00	0.01	0.00	0.07	0.06	0.05	0.03	0.02	0.01	0.24	1.8
Poland	0.04	0.06	0.03	1.37	1.73	0.64	0.41	0.22	0.14	4.64	12.8
Sweden	0.04	0.01	0.01	0.77	0.12	0.25	0.12	0.01	0.02	1.34	8.6
All countries										**18.6**	**9.8**

5. Discussion

5.1 Comparison with previous assessments of the carbon sequestration of European forests

Pan et al. (2011) presented summed values for the current boreal forest carbon stock increase for the three countries Sweden, Norway and Finland, for which they estimated 77 M t CO_2e yr^{-1} for the biomass carbon stock change. The calculations presented here for living biomass in the same three countries resulted in a value in the same range but somewhat lower, 56 M t CO_2e yr^{-1} (data not shown). The value calculated from this study also included temperate forests, but temperate forests cover a relatively small part of these countries. Hence, the assumptions made in this study were reasonable regarding forest types and age-class distributions, as well as the conversions between stem volume increments and carbon stock changes, at least for these three Nordic countries.

5.2 Previous assessments of ozone impacts on forest growth and carbon sequestration

Clearly, the most well-documented case on large-scale impacts of ozone on forest ecosystems is the Montane Forests in southern California (McBride and Miller, 1999). In the San Bernardino Mountains, reduction in the volume growth due to chronic ozone exposure of up to 60% has been documented for Ponderosa pine. The ozone levels in the San Bernardino Mountains were far higher as compared to northern Europe today, with hourly ozone concentrations at the most exposed sites exceeding 120 ppb more than 20% of the monitoring days (Watson et al., 1999). However, the case of Ponderosa pine in the San Bernardino Mountains is very useful to demonstrate the potential of high ozone levels to severely affect entire forest ecosystems.

Sitch et al. (2007) suggested that the indirect radiative forcing by ozone effects on plants could contribute more to global warming than the direct radiative forcing due to tropospheric ozone increases. They predicted that increasing ozone concentrations between 1901 and 2000 might reduce vegetation carbon stocks between 7 and 19 %, depending on the assumed plant ozone sensitivity and assuming constant CO_2 concentrations over the period. It was not possible to judge from the article what changes in the AOT40 that was predicted by the model over the period 1901-2100.

Although percent changes in tree biomass at the end of an experiment due to ozone cannot directly be translated into changes in carbon stocks (section 3.2.2), the meta-analysis conducted by Wittig et al. (2009) indicated a similar reduction in biomass (7%) as found in this study for carbon stocks (10%) when comparing current ambient levels with pre-industrial levels of ozone.

5.3. Key assumptions and uncertainties

- Ozone impacts on forest ecosystem carbon stock changes were assessed only as direct impacts on growth rates, no indirect impacts were included such as reduced vitality etc.
- Forest harvest rates were assumed not to be affected by the different ozone scenarios and total harvest rates were distributed among forest types and age-classed as related to growth rates in the same classes.
- It was assumed that AOT40 could be used as a relevant ozone exposure index across all countries independent of differences in climate.
- Ozone impacts on growth were assessed on the nation-wide scale, no distinctions were made for sub-national differences.
- Estimates of ozone impacts on growth rates were derived mainly from experimental studies on young trees. It must be emphasized that **knowledge about ozone impacts on mature trees under stand condition is to a large extent incomplete and further research is strongly needed**.

The most important assumption that was made in the study was that the forests harvest rates were assumed to be the same in the high and low ozone scenarios, not taking into account the differences in the forest growth rates between the two scenarios. The underlying assumption was that harvest rates are more strongly depending on the demand for roundwood rather than on the supply, that is within the relatively small differences in growth rates between the two ozone scenarios.

Karjalainen et al. (2003) estimated the current and future European forest carbon cycles, based on different scenarios. When constructing these scenarios they listed a number of factors that may influence the current and future rates of fellings:

1. Increased demand for wood products.

2. Higher demand of wood because of large scale application for bioenergy.

3. A reduced interest of forest owners in wood production since they in many cases do not depend on the forest for their income.

4. A higher interest of forest owners in nature values of the forests

5. Large imports of roundwood from outside Europe

None of these factors relates directly to changed growth rates. Hence, it was concluded that the assumption with identical forests harvest rates in the high and low ozone scenarios was reasonable.

6. Evaluations and conclusions

Despite the uncertainties associated with this study, it can be concluded that today´s levels of ozone exposure in northern and central Europe has the potential to reduce the rate of increase in the forest living biomass carbon stocks in the order of 10%, as compared to pre-industrial ozone exposure levels. This value is of a similar order of magnitude as implicated by modeling studies.

Higher growth rates in combination with constant harvest rates will eventually result in higher stand densities at the landscape level. This can not go on forever. It has been estimated that future climate change will increase the growth rates of European forests quite considerably (Karjalainen et al., 2003) and abatement of the ozone pollution problem would add on to this increase. However, modeling by Karjalainen et al. (2003) shows that this can only go on for a few decades and that this increase in forest growth rates will level off and maybe even reverse, due to high stand densities at the large geographical scale.

It is important to realize that the most important factor that determines the increase in the forest living biomass carbon stock is the gap between growth and harvest rates. If this gap is small, then a certain growth reduction caused by ozone will have a relatively large impact on the carbon stock change, while if the gap is large, then the ozone impact will be smaller on a percent basis. This explains why the relative ozone impact is similar in Sweden and Germany, despite ozone exposure being much higher in Germany. The gap between growth and harvests has been much larger in Germany compared to Sweden, at least until 2005.

The assessment made in this study did not include carbon stock changes in other parts of the forest ecosystems, besides the living biomass of trees. Dead biomass and soil carbon also contributes to the carbon stock increases, although at lower rates (Figure 3). It might be assumed that also these processes are affected by reduced growth rates so that the negative ozone impacts on forest carbon stock changes might be even larger compared to what was calculated in this study.

In absolute values, the estimated impact of ozone on carbon sequestration in the selected ten northern European countries was 19 M t CO_2e yr^{-1}. In addition, the ozone induced growth reductions will also result in an economic loss for the forest owners, since they can sell less roundwood to the forest industry (Karlsson et al., 2005). The annual, total economic loss for the Swedish forests owners has been estimated to approximately 40 M Euro (Karlsson et al., 2006).

Main conclusions regarding ozone impacts on the living biomass carbon stock changes in ten countries (Sweden, Finland, Norway, Denmark, Estonia, Latvia, Lithuania, Poland, Czech Republic, and Germany):

1. The by far most important countries for carbon sequestration to the living biomass carbon stocks are Sweden, Finland, Poland and Germany.

2. The estimated annual increase in the living biomass carbon stocks under current ozone levels for the ten countries was 171 M t CO_2e yr^{-1}, while it was estimated to have been 190 M t CO_2e yr^{-1} under pre-industrial ozone levels

3. The difference caused by ozone on the annual living biomass carbon stock change was 19 M t CO_2e yr^{-1}, i.e. the carbon sequestration to the forests in these countries would have been 10 % higher in the absence of the ozone problem. Reductions were country-specific, ranging from ca. 2% (Norway, Finland) to 32% (Czech Republic).

4. The magnitude of the predicted ozone effect for the different countries strongly depended on the gap between forest growth and harvest rates.

The abatement of the ozone pollution problem clearly has the co-benefit to increase the carbon sequestration in northern and central European forests at least for some decades into the future.

7. References

Augustatis, A., Bytnerowitz, A. 2008. Contribution of ambient ozone to Scots pine defoliation and reduced growth in the Central European forests: A Lithuanian case study. Environmental Pollution 155, 436-445.

Bala, G., Caldeira, K., Mirin, A., Wickett, M., Delire, C. and Philips, T.J. (2006), Biogeophysical effects of CO2 fertilization on global climate. Tellus B, Volume 58, pp. 620–627.

Braun, S., Rihm, B., Schindler, C., Flűckiger,W., 1999. Growth of mature beech in relation to ozone and nitrogen deposition: an epidemiological approach. Water Air Soil Pollut. 116, 357–364.

Braun, S., Zugmaier, U., Thomas, V., Fluckiger, W. 2004. Carbohydrate concentrations in roots of young beech and spruce along an ozone pollution gradient. Atmospheric Environment 38, 2399–2407

Braun, S., Schindler, C., Rihm, B., Fluckiger, W. 2007. Shoot growth of mature Fagus sylvatica and Picea abies in relation to ozone. Environmental Pollution 146, 624-628.

Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P, Houghton, R.A., Marland, G. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. PNAS 104, 18866–18870.

Dalstein, L., Torti, X., Le Thiec, D., Dizengremel, P. 2002. Physiological study of declining Pinus cembra (L.) trees in southern France. Trees 16:299–305.

Dittmar, C., Elling, W., Gunthardt-Goerg, M., Mayer, F.-J., Gilge, S., Winkler, P. and Fricke, W. 2004. Ozonbelastung and Schadsymptime in Extremsommer 2003. AFZ Der Wald B 1089, 683-685. (In German)

Eggers, J., Lindner, M. , Zudin, S. , Zaehle, S., Liski, J. 2008. Impact of changing wood demand, climate and land use on European forest resources and carbon stocks during the 21st century. Global Change Biology 14, 2288 – 2303.

Eriksson, E., Gillespie, A.R., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R., Stendahl, J. 2007. Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research 37, 671-681.

Fuhrer, J., Skärby, L., Ashmore, M.R., 1997. Critical levels for ozone effects on vegetation in Europe. Environmental Pollution 97, 91– 106.

Germany, NIR 2011. Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2011 National Inventory Report For the German Greenhouse Gas Inventory 1990 – 2009 Federal Environment Agency (Umweltbundesamt). Dessau, 15 April 2011.

Hyvönen, R; Ågren, G.I.; Linder, S.; Persson, T.; Cotrufo, F.M.; Ekblad, A.; Freeman, M.; Grelle, A.; Janssens, I.A.; Jarvis, P.G.; Kellomäki, S.; Lindroth, A.; Loustau, D.; Lundmark, T.; Norby, R.J.; Oren, R.; Pilegaard, K.; Ryan, M.G.; Sigurdsson, B.D.; Strömgren, M.; van Oijen, M.; Wallin, G. 2007, The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytologist 173, 463–480.

IPCC, 2007. Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, 2007: Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, g.J., Eggers, T., Lapvetelainen, T., Kaipainen, T. 2003. Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget, Forest Policy and Economics 5, 141-155.

Karlsson, P.E., J. Uddling, L. Skärby G. Wallin, G. Selldén. 2003. Impact of ozone on the growth of birch (Betula pendula) saplings. Environmental Pollution, 124, 485-495.

Karlsson, P.E., Pleijel, H., Belhaj, M., Danielsson, H., Dahlin, B., Andersson, M., Hansson, M., Munthe, J., Grennfelt, P. 2005. Economic assessment of the negative impacts of ozone on the crop yield and forest production. A case study of the Estate Östads Säteri in southwestern Sweden. Ambio, 34, 32-40.

Karlsson, P.E., Örlander, G., Langvall, O., Uddling, J., Hjorth, U., Wiklander, K., Areskoug, B., Grennfelt, P. 2006a. Negative impact of ozone on the stem basal area increment of mature Norway spruce in south Sweden. Forest Ecology and Management 232, 146-151.

Karlsson, P.E., Pleijel, H, Danielsson, H., Belhaj, M., Andersson, M., Hellsten, S. 2006b. An economic evaluation of the impacts of ozone on the vegetation in Sweden in relation to air quality standards IVL Report B 1678. (in Swedish)

Kivimäenpää, M., Jönsson, A. M., Stjernquist, I., Selldén, G., and Sutinen. S. 2004. The use of light and electron microscopy to assess the impact of ozone on Norway spruce needles. Environmental Pollution, 127, 441-453.

Lindroth, A., Lagergren, F., Grelle, A., Klemendtsson, L., Langvall, O., Weslien, P., Tuulik, J. 2009. Storms can cause Europe-wide reductions in forest carbon sink. Global Change Biology 15, 346-355.

McBride, J.R. and Miller, P. 1999. Implications of chronic air pollution in the San Bernardino Mountains for Forest Management and Future Research. In Oxidant Air Pollution Impacts in the Montane Forests of Southern California. Miller, P. and McBride, J.R. (eds). Ecological Studies 134. Pp. 405-417. Springer Verlag.

Mills, G., Håkan Pleijel, Sabine Braun, Patrick Büker, Victoria Bermejo, Esperanzo Calvo, Helena Danielsson, Lisa Emberson, Ludger Grünhage, Ignacio González Fernández, Harry Harmens, Felicity Hayes, Karlsson, P.E., David Simpson. 2011. New stomatal fluxbased critical levels for ozone effects on vegetation. Atmospheric Environment 45, 5064-5068.

Nabuurs, G.J., E. Thurig, N. Heidema, K. Armolaitis, P. Biber, E. Cienciala, E. Kaufmann, R. Mäkipää, P. Nilsen, R. Petritsch, T. Pristova, J. Rock, M.J. Schelhaas, R. Sievanen, Z. Somogyi, P. Vallet. 2008. Hotspots of the European forests carbon cycle. Forest Ecology and Management 256, 194–200.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S. Hayes, D. 2011. Science, 333, 988-993

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., et al. (Eds.) (2003). Good practice guidance for land use, land-use change and forestry. Kanagawa, Japan: Institute for Global Environmental Strategies.

Pingoud et al., 2001. Pingoud, K., Pohjola, J., Valsta, L. 2010. Asessing the integrated climatic impacts of forestry and wood products. Silva Fennica 44, 155-175.

Poudel, B. C., Sathre, R., Gustavsson, L. Bergh J., Lundström, A., Hyvönen, R. 2011. Effects of climate change on biomass production and substitution in north-central Sweden. Biomass and Bioenergy 35, 4340-4355.

Pregitzer, K., Euskirchen, E. 2004, Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology 10, 2052–2077.

Pretzsch, H., Dieler, J., Matyssek, R., Wipfler, P. 2010. Tree and stand growth of mature Norway spruce and European beech under long-term ozone fumigation. Environmental Pollution 158, 1061–1070.

Royal Society, 2001. Climate change: what we know and what we need to know. Policy document 22/02. ISBN 0 85403 581.

Sitch, S.,Cox,P.M.,Collins,W.J.,Huntingford, C.,2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature 448, 791–794.

Skärby, L., Ottosson, S., Karlsson, P.E., Wallin, G., Selldén, G., Medin, E.L. & Pleijel, H. 2004. Growth of Norway spruce (Picea abies) in relation to different ozone exposure indices. Atmospheric Environment 38, 2225-2236.

Stribley, G.H., Ashmore, M.R., 2002. Quantitative changes in twig growth pattern of young woodland beech (Fagus sylvatica L.) in relation to climate and ozone pollution over 10 years. For. Ecol. Manage. 157, 191–204.

Sweden NIR 2011. National Inventory Report 2011 Sweden. Swedish Environmental Protection Agency.

Trumper et al., 2009 Trumper, K., Bertzky, M., Dickson, B., van der Heijden, G., Jenkins, M., Manning, P. June 2009. The Natural Fix? The role of ecosystems in climate mitigation. A UNEP rapid response assessment. United Nations Environment Programme, UNEPWCMC, Cambridge, UK. ISBN: 978-82-7701-057-1

Uddling, J., Günthardt-Goerg, M.S., Matyssek, R., Oksanen, E., Pleijel, H., Selldén, G. and Karlsson, P.E. 2004. Biomass reduction of juvenile birch is more strongly related to stomatal uptake of ozone than to indices based on external exposure. Atmosheric Environment 38, 4709-4719.

von Arnold, K., Hånell, B., Stendahl, J., Klemedtsson, L. 2005, Greenhouse gas fluxes from drained organic forestland in Sweden, Scandinavian Journal of Forest Research, 20, 400 – 411.

Watson, J.G., chow, J.C., Frazier, C.A., Hinsvark, B., Green, M. 1999. Ambient air quality at Barton flats and other Californiaforests. In Oxidant Air Pollution Impacts in the Montane Forests of Southern California. Miller, P. and McBride, J.R. (eds). Ecological Studies 134. Pp. 81-105. Springer Verlag.

Wittig, V.E., Ainsworth, E.A., Naidu, S.L., Karnosky, D.F. & Long, S.P. (2009). Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis. Global Change Biology 15, 396-424.