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Uncertainty of forest carbon stock changes – implications to the total uncertainty of GHG inventory of Finland

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Abstract Uncertainty analysis facilitates identification of the most important categories affecting greenhouse gas (GHG) inventory uncertainty and helps in prioritisation of the efforts needed for development of the inventory. This paper presents an uncertainty analysis of GHG emissions of all Kyoto sectors and gases for Finland consolidated with estimates of emissions/removals from LULUCF categories. In Finland, net GHG emissions in 2003 were around 69 Tg (±15 Tg) CO_2 equivalents. The uncertainties in forest carbon sink estimates in 2003 were larger than in most other emission categories, but of the same order of magnitude as in carbon stock change estimates in other land use, land-use change and forestry (LULUCF) categories, and in N_2O emissions from agricultural soils. Uncertainties in sink estimates of 1990 were lower, due to better availability of data. Results of this study indicate that inclusion of the forest carbon sink to GHG inventories reported to the UNFCCC increases uncertainties in net emissions notably. However, the decrease in precision is accompanied by an increase in the accuracy of the overall net GHG emissions due to improved completeness of the inventory. The results of this study can be utilised when planning future GHG mitigation protocols and emission trading schemes and when analysing environmental benefits of climate conventions.

1 Introduction

As the changing climate is seen as a serious environmental threat to nature and mankind, the world's nations agreed in 1992 in Rio de Janeiro on the United Nations Framework Convention on Climate Change (UNFCCC 1992). The ultimate objective of the Convention is

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to stabilise the greenhouse gas (GHG) concentrations in the atmosphere at a non-dangerous level. In 1997 in Kyoto the Parties to the Convention agreed on a protocol giving specified emission reduction commitments to developed countries (UNFCCC 1997). Requirements concerning reporting of emissions have been defined both in the Convention and the Kyoto Protocol, and further reporting rules have been set in the Conferences of Parties to the Convention (e.g. UNFCCC 2002). At the request of the Convention, the Intergovernmental Panel on Climate Change (IPCC) has developed practical guidelines for estimation and reporting of greenhouse gas emissions and removals (IPCC 1997, 2000, 2003). Industrial Parties of the Kyoto Protocol (Annex I Parties) have to report annual emissions from energy, transportation, agriculture, waste management, industrial processes and product use. In addition, emissions and removals of land use, land-use change and forestry (LULUCF) are to be reported (UNFCCC 2004a). Even though reporting of the LULUCF categories is required, in achieving the Kyoto target, only a small share of the sink can be credited according to the articles 3.3 and 3.4 of the Protocol and subsequent rules set by the Conference of the Parties. Article 3.3 covers afforestation, reforestation and deforestation, and article 3.4 covers revegetation, forest management, cropland management and grazing land management. (UNFCCC 2001, 2002; Pohjola et al. 2003).

In recent years, the reporting of the LULUCF sector under the UNFCCC has focused on the changes in the carbon stock of trees on forested land; according to the Kyoto Protocol and the Marrakech Accords, signatory countries have a commitment to report emissions or removals of different carbon pools including above- and belowground biomass, litter, soil organic carbon and dead wood (UNFCCC 2001). In addition to the forested land, reporting should cover other land-use categories as well as land-use changes between categories and related changes in the carbon pools (IPCC 2003).

The IPCC (2003) guidance provides users with three methodological tiers that progress from low to higher levels of certainty in estimates of emissions and removals. Tier 1 applies simple equations with default values given by the IPCC (2003), whereas Tier 3 requires country specific data and may apply complex national systems with sophisticated methods and country-specific parameters. In Finland, reported carbon sink of trees on forested land contribute notably to the national GHG budget (Statistics Finland 2005a), and forests are expected to continue to be one of the key categories. According to the decision tree given for methodological choice in IPCC Good Practice Guidance for LULUCF (IPCC 2003), Tier 3 method should be used if: (1) a category is a key category; (2) the subcategory in question (biomass, soil, dead organic matter) is significant in magnitude; and (3) country-specific data and methods are available. Because all the three conditions are fulfilled in Finland for carbon stock change in living biomass in the category ‘forest land remaining forest land’, Finland will very likely apply and develop methods that represent Tier 3. Estimation of soil carbon, which has not yet been reported to the UNFCCC but will be included in forthcoming reports, may be based on a dynamic soil carbon model that uses forest inventory data and climatic parameters as input (Statistics Finland 2005b).

From 2005 onwards, national inventory reports should provide uncertainty estimation of the GHG inventory including sinks and following methodological guidance given by the IPCC (2000, 2003). Uncertainty estimates are needed to prioritise efforts to improve the accuracy and precision of inventories in the future. The IPCC guidance (2003) proposed two methodological tiers for uncertainty analysis: (1) error propagation equations; and (2) Monte Carlo simulations.

Simulation-based uncertainty estimates of GHG emission inventories have thus far only been made in some industrial countries – Australia (Australian Greenhouse Office 2004), Austria (Winiwarter and Rypdal 2001), Finland (Monni et al. 2004a), Norway (Rypdal and Zhang 2000), the UK (Charles et al. 1998), and the USA (EIA 2004). These estimates cover most anthropogenic sources of GHGs reported to the UNFCCC, but only the estimates for Austria and the UK include also removals (or emissions) from land-use change and forestry. Uncertainties in forest carbon budget projections have been addressed in various studies separately from GHG inventories (e.g. Peltoniemi et al. in press; Paul et al. 2003a, b; Smith and Heath 2001; Heath and Smith 2000; Zhang and Xu 2003; Nilsson et al. 2000). In general, it is expected that the reported uncertainties in sinks will be notable, and the inclusion of sinks will increase the uncertainty estimate of the total GHG inventory (Rypdal and Winiwarter 2001; Winiwarter and Rypdal 2001; Nilsson et al. 2000). However, accuracy of total GHG budget increases with increasing coverage of the inventory, even though the precision of estimates of net emissions may decrease.

Collecting information about the uncertainty of the estimates is crucial in order to provide a complete picture of the extent to which carbon accumulation into forests may offset the effect of emissions from fossil fuel combustion and other anthropogenic sources. This information is of use in decision making, if one wants to be certain that GHG mitigation commitments have real environmental benefits. Information on uncertainties concerning emissions and sinks can also be used to give priorities for further improvements of emission and sink estimation.

This paper presents uncertainty analysis of the forest carbon sink that was calculated on the basis of forest inventory data with biomass models and a dynamic soil carbon model. These models were consolidated with the KASPER model that calculates uncertainties of other GHG emission sources (Monni et al. 2004a) and LULUCF categories (agricultural cropland and grassland, biomass burning on forest land, agricultural lime application, N fertilisation of forests) (Statistics Finland 2005a). The aim of the study is to give a picture of the effect of the forest carbon pool on the overall uncertainty of national GHG inventory. Uncertainty analysis and identification of key categories were carried out using the Tier 2 method of the IPCC Good Practice Guidance for LULUCF (IPCC 2003). Consequently, key category analysis utilised uncertainty assessment carried out using Monte Carlo simulation to combine uncertainties. The uncertainty estimate and key category analysis presented in this paper cover all anthropogenic GHG emissions and removals which Finland reported to the UNFCCC in 2005 (Statistics Finland 2005a). In this study, the model and uncertainty estimate of carbon sink of forest biomass was more detailed than the one used in the National Inventory Report (Statistics Finland 2005a). In addition, uncertainty of carbon stock change in forest soils (not yet included in the official reporting to the UNFCCC – Statistics Finland 2005a) was estimated by a dynamic model. This estimate excludes the changes in land use as well as carbon stock of peat soils in forest land.

2 Material and methods

2.1 Calculation of emissions and removals

In Finland GHG emission inventory reported to the UNFCCC covers energy, transportation, industry, solvent and other product use, agriculture, waste, and land-use change and forestry. The emission inventory is compiled as a joint effort of various institutions – namely Finnish Environment Institute (SYKE), VTT Technical Research Centre of Finland, Finnish Forest Research Institute (Metla), MTT Agrifood Research Finland, and Statistics Finland. Statistics Finland is the responsible unit for the GHG inventory in Finland.

2.1.1 Estimation of emissions from energy, industry, agriculture and waste sectors

In the Finnish GHG emission inventory, emissions from stationary combustion are estimated based on import and export statistics, fuel consumption and emission factors. Data are partly plant- or boiler-specific, taking into account different combustion processes and different fuel mixes, and partly based on a top-down approach, i.e. on fuel statistics. Emission factors used are mainly national (Statistics Finland 2005a). Emissions from transportation are estimated based on vehicle mileages driven using emission factors suitable for various subcategories. Fugitive emissions from fuels arise from peat production and oil and gas operations. Emission factors for fugitive emissions from peat production are country-specific, because other suitable data are not available. In agriculture, activity data is based on agricultural statistics on animal numbers, area of agricultural land, etc. Emission factors used are both national and IPCC emission factors. The emissions from landfills are calculated using a dynamic waste degradation model, the parameters of which are partly national and partly IPCC default parameters (Statistics Finland 2005a).

2.1.2 Estimation of carbon sink/source of living biomass

The estimates of the forest carbon sinks/sources used in this study were based on national forest inventory data. The volumes of the growing stock estimated by national forest inventory (NFI) were used as a basis for forest biomass estimation.

National forest inventory has measured growing stock of forests for decades. Latest inventories had about 70 000 inventory plots from where trees were measured. The cycle of a single inventory is about 10 years. In addition to growing stock, information on increment, growth index, natural mortality, etc. is collected in these inventories. A more detailed description of the 8th NFI is available in Tomppo et al. (2001).

In this study, the estimates of the carbon stock and sink of forest vegetation were specific to forested land according to NFI classification (i.e. forests excluding other wooded land where the stem volume growth is less than 1 $m^3 yr^{-1}$).

The estimates of emissions or removals were calculated as the difference between stocks in two consecutive years (1989–1990 and 2002–2003). The volume and the area measured by the NFI for the forests in Southern and Northern Finland were assigned to the volume weighted mean years of the inventory periods (a period of about 5 years in Southern Finland, and 3 years in Northern Finland). Stock estimates were available for 1983, 1993 and 2002 for Northern Finland, and for 1988 and 1998 for Southern Finland. Stocks for years after the last inventory mean years were extrapolated. Stocks between the inventory mean years were interpolated and adjusted with annually reported drain (timber removed from the forests) and with growth indexes that describe the annual volume growth of a tree species compared to the average of that time series. Growth indexes were estimated for Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) and separately for Southern and Northern Finland based on increment cores that were collected during the field surveys of NFIs (Henttonen 1998). Reported growth indexes were available for 1989 and 1990, but for 2002 and 2003 long-term averages were used. For Birches (Betula pubescens and Betula pendula), an average of Scots pine and Norway spruce was used.

The volume estimates were converted to biomass by tree species and age-class specific biomass expansion factors (BEFs) (Lehtonen et al. 2004a). These component-specific BEFs can be used to convert stem volumes to biomass components, like foliage, branches, stem and roots. BEFs are a product of volume of biomass component and its density value, compared to stem volume. Each of these biomass components has an average life span that is used to estimate annual litter production. Litter production is thereafter used as an input to the soil model that estimates decomposition of this input based on climatic data and litter quality. Biomass estimates for understorey vegetation were based on a model that relates stand age to average vegetation biomass per unit area. Regression models for understorey biomass were based on measured vegetation cover to aboveground biomass relation on ten experimental sites with 100 sample plots, and also on measured vegetation cover data to stand age relation on 1830 sample plots. Parameter values for these regression models were published by Peltoniemi et al. (2004). Finally, all the biomass was converted to carbon using a carbon content of 50%.

2.1.3 Assessment of soil carbon of upland forest soils

In this study, estimation of the soil carbon stock changes was made using the dynamic soil carbon model Yasso (Liski et al. 2005). The model requires data on annual litter production and climate, which is described with effective temperature sum as input. The model describes decomposition and dynamics of soil carbon in well-drained upland soils (soils in which poor drainage does not slow down decomposition). This analysis covers the upland forest soils (16.1 million ha), which is about 77% of the Finnish forest area. The Yasso soil model was linked with empirical models that estimate annual litter fall as described in Section 2.1.2. The total litter input includes litter from living trees, understorey, natural mortality and harvesting residues; the input was provided for each main species, and separately for Southern and Northern Finland. The linkage between the two models (Yasso and model for carbon in living biomass) is described in more detail by Liski et al. (accepted).

Soil carbon stocks were calculated annually from 1988 to 2003. The initial soil carbon stocks at the beginning of the calculation were set by assuming the soil to be in steady state in 1988 and using litter input and climate data from that year. Thus, the trend in soil carbon, which may exist due to increasing litter production because of increasing growing stock size prior to the year 1988, was eliminated.

2.1.4 Estimation of other LULUCF categories

Carbon stock change in agricultural grassland and cropland was estimated in the Finnish 2005 inventory using mainly methodologies of the IPCC (2003). In the case of mineral soils, emissions/removals were estimated based on carbon stock changes, and in the case of organic agricultural soils, national and IPCC emission factors were used (Statistics Finland 2005a). Emissions from agricultural lime application, nitrogen fertilisation of forests and biomass burning were estimated using IPCC emission factors and national activity data values (Statistics Finland 2005a).

2.2 Uncertainty estimates

In general, estimation of GHG inventory uncertainty can be based on measurement data, domestic and international literature, IPCC default uncertainties or expert judgement. In this study, measurement data and literature were used in all cases where suitable data were available. In many cases, available data had to be complemented with expert judgement, and in some cases, estimates had to rely entirely on expert judgement. Expert judgements were obtained from Finnish national experts involved in inventory compilation or in specification of input parameters for the models used (see Appendix 1 and Monni et al. 2004a). Input parameter uncertainties were given mainly by uniform, normal and lognormal distributions

(Appendix 1) as suggested also by the IPCC (2000). A normal distribution was used most frequently because it is usually suitable for the estimation of symmetrical uncertainties where the specified mean value can be assumed more probable than the other values in the range. In cases where the possible range of values was known, but there was no good basis to assume which is the most likely value, a uniform distribution was used. If the parameter could only assume positive values and uncertainty was estimated to be asymmetric, a lognormal distribution was used.

In this study, uncertainty estimates of different parameters were combined using Monte Carlo simulation, as recommended by the IPCC Good Practice Guidance for LULUCF (IPCC 2003). In the Monte Carlo method, random numbers are generated from input distributions (e.g. thousands of times), and the output distribution is calculated based on each set of random numbers.

2.2.1 Uncertainty of the energy, industry, agriculture and waste sectors

In the energy sector, uncertainty in aggregated fuel consumption was estimated using differences between bottom-up and top-down methods (i.e. import vs. export statistics were compared with consumption figures). This reflects systematic error in fuel statistics (IPCC 2000), and random error is likely to be small in energy statistics (EIA 1997). This is a reliable method for uncertainty estimation in Finland, where all fossil fuels (coal, oil, natural gas) are imported. For domestic fuels (peat, biomass), uncertainty was estimated based on expert judgement. Uncertainty estimates of emission factors were based on available measurement data combined with expert judgement. Some specific features of Finnish energy production (e.g. wide use of peat and fluidised bed combustion) also resulted in specific needs for the estimation of emission factor uncertainties (Monni et al. 2004a).

Fugitive emissions from peat fuel production are very uncertain, and the emission source is also very specific for Finland. Uncertainty estimates of this source were based on area estimates, scarce measurement data of emissions, literature and expert judgement (Monni et al. 2004a). This emission source is very closely linked to the LULUCF category.

In non-combustion industrial processes, both plant-specific measurement data and expert judgement were used for the estimation of uncertainty in CO_2, CH_4 and N_2O emissions. The uncertainty in F-gas (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6)) emissions was assessed at the Finnish Environment Institute and reported in the National Inventory Report (Statistics Finland 2005a).

Uncertainty estimates of the agriculture sector are presented in detail by Monni et al. (2006). In this sector, some specific features occur: (1) suitability of the IPCC default emission factors to Finnish climate and agricultural practices is an important issue when estimating uncertainty (Monni et al. 2006); and (2) annual variation in emission factors is treated as uncertainty in the analysis – this is the case also in other sectors, but in agriculture this variation is especially significant, e.g. in the case of N_2O emissions from agricultural soils (Monni et al. 2004a).

In the waste sector, uncertainty analysis of emissions from landfills was carried out using the dynamic waste degradation model. The uncertainties in input parameters were estimated using the IPCC default values, measurement data from landfills and expert judgement (Monni et al. 2004a). The uncertainty ranges of input parameters were also estimated to cover a possible model error. This approach is very similar to that used in the dynamic soil carbon model.

In the uncertainty model of energy, industry, waste and agriculture sectors, it was assumed that emission factors correlate across years (correlation coefficient = 1). This is due to use of same emission factors or same assumptions for emission factors during the entire time series 1990–2003. Activity data, instead, was assumed to be independent (Monni et al. 2004a).

2.2.2 Uncertainty of the biomass carbon estimates

The stem volume and forest area data provided by national forest inventory was appended with uncertainty estimates (Tomppo et al. 2001). These estimates were provided by tree species, and for Southern and Northern Finland separately. In this study, the variance of age-classes that represented a share of volume or area was approximated based on relative shares of areas and volumes in a way that the sum of age-class volumes (or areas) had the same error distribution as that reported for the total volume.

The reported growth indexes did not cover the year 2003, and therefore, the annual value of growth indexes and the uncertainties related to them were replaced with long-term averages and inter-annual variation based on the reported series from 1920 to 1993 (Mikola 1950; Tiihonen 1979; Henttonen 1998). The same data series were used to determine the correlation of growth indexes between two consecutive years.

BEFs for the stand biomass by species and stand age were assumed to be applicable for the entire timber volume in Finland, as the BEFs were developed for this area. The relative standard error (RSE) of BEFs takes into account the sampling error and residual component of the model error. When BEFs were applied to Southern and Northern Finland, the uncertainty was estimated based on relative shares, similarly as in the case of stem volume estimates by age-classes.

Uncertainty estimates of input parameters are presented in Appendix 1. The sink/source distribution was obtained by simulating the difference between two consecutive vegetation carbon stocks (2002–2003).

2.2.3 Uncertainty of soil carbon sink/source

The soil model Yasso used in this study should only be applied to the well-drained upland mineral soils. Therefore, the proportions of area and growing stock of forest land located on peat soils were excluded from the input to soil (but were included in the calculation of vegetation carbon stock). There is information available about total loggings in Finland only, and therefore, loggings on peat lands were assumed to cover a constant proportion of total loggings during the time series, but simulated with some annual variability (see Appendix 1). The values of volume, area and the share of loggings on peat lands were assigned uncertainty in the simulations when they were subtracted from the corresponding totals.

The uncertainty related to litter production is affected by the uncertainty in component-specific (foliage, branches, etc.) biomass estimates and the turnover rates. Both model and parameter uncertainties were reported for component-specific BEF models, while RSE including sampling and model error were reported only for total BEF by Lehtonen et al. (2004a). Instead of using reported model uncertainties, the RSE for the total stand BEFs was divided up into biomass components according to Equation 1. The RSE for the component BEF is:

$$r_i = \sqrt{\frac{s_i}{\sum_i s_i} \frac{B}{B_i} r} \quad (1)$$

where s_i is the uncertainty simulated for the model, r is the reported RSE for the total stand biomass BEF, B is the total BEF, and B_i is the component BEF. The component-specific BEFs were multiplied with the volume distribution and distributions for turnover rates to get the estimate for the component litter production. The uncertainty estimates for the turnover rates were based on collected data complemented with expert estimates (Appendix 1).

The uncertainty of the soil carbon stock change was estimated by combining the uncertainty of litter input and soil carbon model parameters, e.g. decomposition rates, fractionation rates, humification parameters and initial soil carbon stock values, with Monte Carlo simulation. The uncertainties of the soil carbon model parameters were partly estimated based on the calibration method and data (Appendix 1), and partly on expert knowledge. The uncertainty of initial soil carbon stocks was based on the varying litter production estimates and model parameters. The assumption of the equilibrium of the initial soil carbon stocks was not considered in this uncertainty analysis.

2.2.4 Uncertainty of other LULUCF categories

Uncertainty estimates of biomass burning on forest land and agricultural lime application were based on IPCC (2003) default uncertainties and expert judgements (Statistics Finland 2005a). Uncertainty in emissions from N fertilisation of forests was estimated to contain the same relative uncertainties as emissions from N fertilisation of agricultural soils (Monni et al. 2006; Statistics Finland 2005a). Emissions and removals from carbon stock changes in agricultural grasslands and croplands were carried out rather roughly based on IPCC (2003) estimates and expert judgement.

3 Results

Table 1 presents emissions and removals by sector in 1990 and 2003 with corresponding uncertainties. Uncertainty in GHG emission from energy, industry, agriculture and waste sectors from Finland in 2003 was estimated at −4 to +8% (expressed as bounds of 95% confidence interval relative to the mean value). When the carbon sink of forest biomass was included in the estimates, uncertainty increased to ±19%. Inclusion of the sink of upland forest soils increased the uncertainty estimate to around ±24%. Finally, inclusion of all the LULUCF categories Finland reported to the UNFCCC in 2005 in addition to the categories of this study resulted in an uncertainty of some ±23% in total net emissions. However, even though precision decreases when LULUCF categories are included in the estimates, the accuracy of the inventory increases due to better coverage.

The carbon sink of forests varies considerably from year to year (Fig. 1). The carbon sink of vegetation was larger than that of soil during the entire time series (1990 to 2003). The difference between the magnitude of sink (both vegetation and soil) in 1990 (46 Tg CO_2) and 2003 (20 Tg CO_2) is mainly due to more intense harvests and removed timber from forests in 2003. Differences in relative uncertainties (±30% in 1990, ±70% in 2003) are due to differences in availability of data. For 1990, measured data of volume and growth indexes were available, whereas for 2003, averaged values were needed, which were appended with larger error estimates.

In 2003, forests carbon sink absorbed more than 20% of the emissions. In 1990, forest sinks offset over 60% of emissions according to the results (Fig. 2).

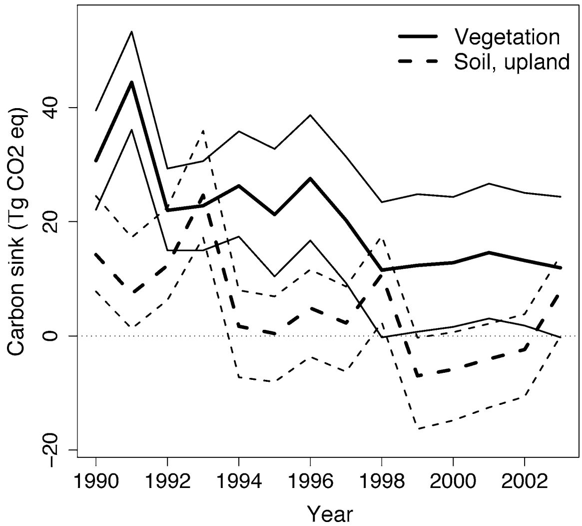
Relative uncertainties of the emission estimates of the other GHGs were larger than those of CO_2 (Table 2) when LULUCF was excluded from the estimates. The uncertainty of CO_2

Table 1 Emissions and removals in Finland by sector in 1990 and 2003. Other emissions than forest carbon stock changes are based on National Inventory Report (Statistics Finland 2005a). Columns "lower bound" and "upper bound" refer to 95% confidence interval

Sector	1990 Emissions Tg CO_2 eq[a]	1990 Lower bound Tg CO_2 eq	1990 Upper bound Tg CO_2 eq	2003 Emissions Tg CO_2 eq[a]	2003 Lower bound Tg CO_2 eq	2003 Upper bound Tg CO_2 eq
Fuel combustion	55	54	56	72	71	74
Fugitive emissions from fuels	0.6	0.2	1.7	0.7	0.2	1.8
Industry (other than combustion)	3.0	2.1	4.6	3.5	2.6	4.8
Solvent and other product use	0.06	0.04	0.09	0.04	0.03	0.06
Agriculture	6.9	3.9	15	5.4	3.1	11.9
Forest biomass	−31	−39	−22	−12	−24	0.6
Upland forest soils	−15	−25	−8	−7.7	−14.8	−0.7
Other LULUCF categories	1.0	−1.0	3.4	3.6	0.2	6.9
Waste	4.0	2.4	5.6	2.7	1.6	3.8
Non-energy use of fuels	0.6	0.3	1.0	0.8	0.4	1.2
Total (excluding LULUCF)	70	66	79	85	82	93
Total	26	11	40	69	54	86

[a] Positive values indicate emissions and negative values indicate removals.

Fig. 1 Time series of forest vegetation and soil sink from 1990 to 2003 in Tg CO_2. Thin lines denote the calculated 95% confidence interval.



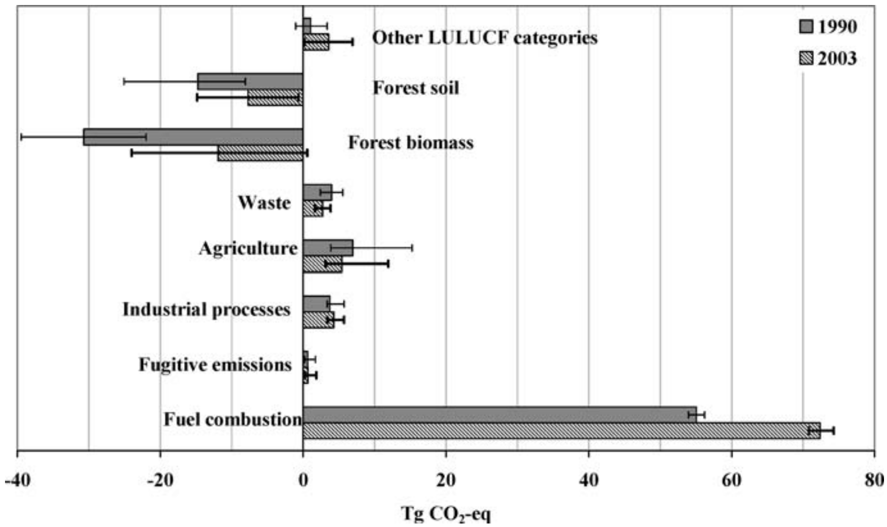


Fig. 2 Greenhouse gas emissions and removals in 1990 and 2003 according to National Inventory Report (Statistics Finland 2005a) and results of this study (forest vegetation and forest soils). Industrial processes include also non-energy use of fuels and product use. Error bars denote 95% confidence interval of emissions/removals according to the results of this study.

emissions from fuel combustion and other energy/industry related sources was as low as ±2%. Inclusion of the LULUCF categories in GHG inventory increased uncertainty of the CO_2 estimate to ±25% which is higher than the uncertainty estimate of HFCs, PFCs and SF_6 and close to that of CH_4.

According to the results, trend in Finnish GHG emissions according to IPCC definition of trend (change between net emissions in 1990 and 2003 relative to net emissions in 1990) was 170% (meaning that net emissions in 2003 were around 2.7 times net emissions in 1990). The 95% confidence interval of this figure (170%) lies between 70 and 500%.

Table 2 Net greenhouse gas emissions from Finland in 2003 by gas with corresponding absolute and relative uncertainties according to the results of this study. Upper and lower bound refer to the 95% confidence interval. Relative uncertainty is the difference between mean value and upper/lower bound of the confidence interval divided by the mean value as recommended by the IPCC (2000, 2003)

Gas	Net emissions Tg CO_2 eq	Lower bound Tg CO_2 eq	Upper bound Tg CO_2 eq	Relative uncertainty %
CO_2 (excluding LULUCF)	73	72	75	±2
CO_2 (including LULUCF)	57	43	72	±25
CH_4	5.0	3.8	6.2	±24
N_2O	6.7	3.9	13.7	−40 to +100
HFCs, PFCs and SF_6	0.7	0.6	0.9	−11 to +22

The key category assessment that was carried out according to the Tier 2 method of the IPCC Good Practice Guidance for LULUCF (IPCC 2003) indicated that carbon sink of forest vegetation and that of forest soil were the most important key categories of the inventory in 2003 (Table 3). The next three key categories were related to emissions from agricultural soils.

4 Discussion and conclusions

This integrated uncertainty estimate covering forest carbon sink estimated using detailed models and GHG emissions/removals from other sectors revealed that inclusion of LULUCF categories increases the overall uncertainty estimate of the GHG inventory in 2003 notably – the uncertainty excluding the LULUCF sector is −4% to +8% (95% confidence interval relative to mean value), and the uncertainty including the LULUCF sector is ±23%. On the other hand, completeness of the inventory increases when LULUCF categories are included, and therefore accuracy of total inventory increases even though precision decreases.

According to the results, sink of forest vegetation was 12 ± 12 Tg CO_2 and that forest soil 8 ± 7 Tg CO_2 in 2003. In 1990, both sinks were larger, due to differences in input (removals/logging residues, growth indices, temperature sum, and forest area change) and previous year's soil carbon stock.

In 1990, relative uncertainty in sink estimate (including both biomass and soil) was much smaller than in 2003 due to better availability of data. Therefore, timely data collection would allow assurance of the quality of sink estimates reported to the UNFCCC.

The carbon sink of forest vegetation calculated in this study (12 Tg CO_2) for 2003 is different from the figure reported to the UNFCCC (21 Tg CO_2, Statistics Finland 2005a). We applied more representative biomass expansion factors, considered annual variation in the growth rate of trees, and applied it on the average growth calculated using a stock change approach (i.e. growth = stock X − stock Y + removals from forests between years X and Y).

The IPCC (2003) defines the trend of net emissions as the change in net emissions between the base year (1990) and the latest inventory year (in our study, 2003) relative to net emissions in the base year. Thus, in Finland, the trend of net emissions between 1990 and 2003 was 170% (meaning that net emissions were 2.7 times higher in 2003 than in 1990). The 95% confidence interval of this figure lies between 70 and 500% which represents a remarkable uncertainty. This is largely due to weak correlation of uncertain sink estimates between the two years. However, the definition of trend proposed by the IPCC (2003) is problematic, because forest sink estimates, which are highly variable between the years, are themselves

Table 3 Key categories in Finland in 2003 by Tier 2 level assessment of IPCC Good Practice Guidance for LULUCF (IPCC 2003)

IPCC category	Greenhouse gas	Emissions/ removals in 2003 (Tg CO_2 eq)	Level assessment[a]	Cumulative level assessment
5.A.1. Forest Land remaining Forest Land: carbon stock change in living biomass	CO_2	−11.9	0.28	0.28
5.A.1. Forest Land remaining Forest Land: net carbon stock change in soils	CO_2	−7.7	0.16	0.44
4.D. Agricultural soils: direct emissions, animal production and sludge spreading	N_2O	2.6	0.14	0.57
5.C.1. Grassland Remaining Grassland: net carbon stock change in mineral soils	CO_2	2.9	0.06	0.64
4.D. Agricultural soils: indirect emissions	N_2O	0.6	0.04	0.68
1.A.3b Road Transportation: Cars with Catalytic Converters	N_2O	0.4	0.04	0.72
2.B.2 Nitric Acid Production	N_2O	1.4	0.03	0.75
5.B.1. Cropland Remaining Cropland: net carbon stock change in organic soils	CO_2	1.3	0.03	0.78
1.B.1 Fugitive emissions from solid fuels: Peat production areas	CO_2	0.5	0.03	0.80
5.B.1. Cropland Remaining Cropland: net carbon stock change in mineral soils	CO_2	−1.1	0.03	0.83
6.A. Solid Waste Disposal on Land	CH_4	2.5	0.02	0.85
1.A. Fuel Combustion: Liquid fuels	CO_2	27.6	0.02	0.87
1.A. Fuel Combustion: Solid fuels	CO_2	22.8	0.02	0.89
1.A. Fuel Combustion: Other fuels	CO_2	10.7	0.02	0.91

[a] According to equation 5.4.4 in (IPCC 2003).

differences between stocks in two consecutive years. Another option would be to directly estimate change of stock of the latest inventory year and the stock of the base year.

The forest inventory data used in this study were spatially comprehensive covering forested area of entire country. However, the data cannot be considered comprehensive with regard to time, because the inventory results for Southern and Northern Finland are averages of 3–5 years measured every 10 years. The growth figures used for the calculation of annual sinks/sources are, therefore, derived partly on averaged data, which were later adjusted with drain and annual variation of growth (growth indexes). A new round of the Finnish forest inventory that began in 2004 is to be based on the measurements taken throughout the country every year. Thus, in the future, some of the uncertainties related to construction of inventory time series may be avoided, since NFI can provide annual growth estimates with known precision for the entire country.

In LULUCF categories, uncertainty in the average of several years may be better known than a single year estimate due to inter-annual variation. This is because uncertainty in a certain parameter as a long-term average may be small, but its applicability to a specific year may be more uncertain. Compliance of the Kyoto Protocol is measured as an average of a five-year period (2008–2012), but the reference of the Protocol (base year 1990) is a single year estimate only.

When the key category assessment was carried out according to the IPCC Good Practice Guidance for LULUCF (IPCC 2003), carbon sink of vegetation and that of soil were identified as the most important contributors to the overall GHG inventory uncertainty. The following three key categories of the inventory were also linked with land use: direct and indirect N_2O from agricultural soils, and carbon stock change in agricultural mineral grassland. In these categories of emissions and removals, reduction of uncertainty is often difficult and costly. The processes that generate emissions and removals in these categories are poorly understood, and therefore reduction of uncertainties by using models is difficult. In addition, emissions or removals occur over large geographical areas, and therefore their direct monitoring is estimated to be expensive. It is also difficult to separate natural and human-induced changes in carbon sinks (Gupta et al. 2003). To be able to improve estimates of forest carbon sinks further, it would be necessary to identify the most important parameters and input data.

This uncertainty analysis was based on propagation of uncertainties of input parameters in the models used. Therefore, possible bias due to model structure cannot be assessed. Estimates of the possible model error could be done based on expert estimates or by comparing the results with other models made for the same purpose. In Austria (Winiwater and Rypdal 2001), simple uncertainty estimate of the vegetation carbon sink was combined with uncertainty estimate of GHG sources, and in the UK (Charles et al. 1998) the soil carbon sink was also taken into account in inventory uncertainty estimates. However, uncertainties of the inventories of different countries should not be directly compared due to different methods used and possible subjectivity of uncertainty estimates due to a large number of expert estimates needed. Comparison based on relative uncertainties is also problematic when sinks or sources are close to zero.

Compliance with the emission reduction targets of the Kyoto Protocol deal with 'best estimate' values of emissions and removals. No specifications on acceptable levels of uncertainties are included in these requirements (UNFCCC 2002). According to the basic principles of the reporting to the UNFCCC, emission inventories should be transparent, accurate, comparable, complete and consistent. Use of higher Tier methods aims at increasing accuracy of inventories. However, comparability between parties as well as transparency may decrease when models are more complex.

In developed countries, the majority of CO_2 emissions come from fuel combustion. CO_2 emissions from combustion are usually known as accurately as $\pm$1–5%, and therefore CO_2 is often the GHG containing smallest uncertainties when LULUCF is not included in the estimates (Monni et al. 2004a; Rypdal and Winiwarter 2001). According to this study, inclusion of forest sinks to the inventory raised the uncertainty of CO_2 close to the uncertainties for other GHGs in Finland. In the European Union and in many other industrial countries, the proportion of forest sink of net emissions is lower (Liski et al. 2000; Pohjola et al. 2003; UNFCCC 2004b), and therefore the effect of sink on the total inventory uncertainty is assumed to be lower than in Finland. This difference is emphasised when uncertainties are expressed relative to the net emissions.

The emissions trading of the European Union began in the beginning of 2005. This trading system covers only CO_2 emissions from combustion of fossil fuels and selected industrial processes. These emissions are known with quite a good accuracy and the extension of the trading system to other gases and categories would increase the uncertainty both in the scales of Finland and the EU (Monni et al. 2004b). In the emissions trading under the Kyoto Protocol, all emissions/removals can be traded, including removal units (RMUs), if set

Appendix 1 Parameters and uncertainty estimates in calculation of forest carbon sink. See bottom of the table for column headings.

A	B	C	D	E	F	G	H	I	J	K
Input data										
Forest area	10^6 ha	N	2	6	ts	0.60%			Variability in time by interpolating between the reported stocks	Tomppo et al. 2001; Kuusela and Salminen 1991; Inventory results for northern Finland 2002, to be published
Growing stock	10^6 m^3	N	2	6	ts	S 0.7%; N 1.3%			Variability in time by interpolating between the reported stocks	Tomppo et al. 2001; Kuusela and Salminen 1991; Inventory results for northern Finland 2002, to be published
Natural mortality	m^3 ha^{-1}	N	0	2	0–0.4	30%			Zero for treeless, increases with increasing age	Unpubl. data from NFI permanent sample plots
Drain (timber removed from the forests)	10^6 m^3	N	2	4	ts	2%			Consecutive estimates are independent between the years	Metla 2003. Uncertainty estimate: Expert opinion/Yrjö Sevola, Finnish Forest Research Institute 10.4.2004
Growth Index		N	0	4	ts	2.50%			Growth indices of consecutive years correlate by 47–63%	Henttonen 1998; Uncertainty estimate: Expert opinion/Helena Henttonen, Finnish Forest Research Institute, 10.9.2004
Growth Index extrapolation		N	0	4	average from 1990s	13.2%–16.4%			CV% represents the interannual variability in long term data series. Growth indices of consecutive years correlate by 47–63%	Mikola 1950; Tiihonen 1979; Henttonen 1998
Temperature sum (0°C threshold)		N	0	1	ts	1%			N and S Finland values correlate in the same year by 90%; values in different years vary independently	Mitchell et al. 2004

Appendix 1 (continued)

Share of area on peatlands	%	N	0–1	1	ts	S 1%; N 1.4%			Subtracted from total area. Variability in time by interpolating between the reported stocks	Tomppo et al. 2001; Kuusela and Salminen 1991; Inventory results for northern Finland 2002, to be published
Share of growing stock on peatlands	%	N	0–1	1	ts	S 1.6%; N 3%			Subtracted from total volume. Variability in time by interpolating between the reported stocks	Hökkä et al. 2002
Share of loggings on peatlands	%	U	0–1	0	ts, average 0.14	16.00%			Subtracted from total drain. A part (50%) of the uncertainty estimate is on base value and rest of the variance is dedicated to inter-annual variability	Nuutinen et al. 2000 (Error is based on three scenarios; interannual variability assumed)
Stem cutting residues		N	0	0	0.0873	5%				
Vegetation model parameters										
Nutrient intake		U	1	3	0.79		0.77	0.81	Shed leaf mass/dried living leaf mass	Viro 1955
Density of stem residues	g m^{-3}	N	1	3	368–470	10%				Hakkila 1966
Harvesting yield, first thinning	%	N	2	4	0.085–0.14	19%			Percentages of total drain	Metla 2003; Tapio 2005
Harvesting age, first	yr	N	2	4	37–55	19–25%				Unpubl. data from NFI permanent sample plots
Harvesting age, second	yr	N	2	4	64–93	12%				Unpubl. data from NFI permanent sample plots
Harvesting age, final	yr	N	2	4	87–116	7%				Unpubl. data from NFI permanent sample plots
BEF: total	kg m^{-3}	N	2	5	0.69–0.87	2.7–21.3%	0		For tree species/age-class distribution of RSE, see Lehtonen et al. 2004a	Lehtonen et al. 2004a

Appendix 1 (continued)

A	B	C	D	E	F	G	H	I	J	K
BEF: foliage	kg m^{-3}	N/L	1	5	0.01–0.12	18–99%	0		Error derived using Eq 1	Lehtonen et al. 2004a
BEF: branches	kg m^{-3}	N/L	1	5	0.08–0.18	8–75%	0		Error derived using Eq 1	Lehtonen et al. 2004a
BEF stem	kg m^{-3}	N	1	5	0.34–0.4	2–24%	0		Error derived using Eq 1	Lehtonen et al. 2004a
BEF: stump	kg m^{-3}	N	1	5	0.04–0.1	2–20%	0		Error derived using Eq 1	Lehtonen et al. 2004a
BEF: roots	kg m^{-3}	N/L	1	5	0.03–0.06	13–78%	0		Error derived using Eq 1	Lehtonen et al. 2004a
Biomass ratio: Fine root – foliage	kg m^{-3}	L	0	4	0.3–0.5	20–30%	0		Linked to biomass of foliage with factor 0.5 for deciduous and pines, 0.3 for spruces	Vanninen and Mäkelä 1999; Cronan 2003; Helmisaari and Hallbäcken 1998
Biomass ratio: underground – stem		T	0	4	0.46		0.2	1	For deciduous	Laitakari 1935
Share of foliage biomass to branch biomass Wf= *a**AGE^ (b)*Wbr		N	0	4	a=6.45; b= −0.91	10%			For deciduous, for both parameter a and b	Unpubl. data from NFI permanent sample plots
Stump/(stump+roots) ratio deciduous		U	0	4	0.5		0.25	0.75	For deciduous	
Turnover: foliage	yr^{-1}	N	1	4	0.05–0.21	4–13%			Larger estimates for pines/S Finland than for spruces/N Finland; Estimate is 1 for deciduous species	Muukkonen 2005; Muukkonen and Lehtonen 2004
Turnover: branches pine	yr^{-1}	L	1	5	0.007–0.06	65%				Lehtonen et al. 2004b
Turnover branches (Spruces, deciduous)	yr^{-1}	T	0	3	0.0125–0.0135		0.004	0.0246	Upper limit for pines, lower limit for spruces	Muukkonen and Lehtonen 2004

Appendix 1 (continued)

Turnover (bark, epiphytes, cones; of stem and stump biomass)	yr^{-1}	T	0	3	0.0027–0.0052	0.0013	0.0078	Upper limit for spruces, lower limit for deciduous	Viro 1955; Mälkönen 1974
Turnover: roots	yr^{-1}	T	0	3	0.0125–0.018	0.0063	0.0276	Upper limit for pines, lower limit for spruces and deciduous	Assumed to equal the one of branches
Turnover: fine roots pine	yr^{-1}	T	0	3	0.868	0.434	1.3		Kurz et al. 1996
Turnover: fine roots, spruces	yr^{-1}	T	0	3	0.811	0.405	1.22		Majdi 2001
Turnover: fine roots, deciduous	yr^{-1}	T	0	3	1	0.5	1.5		Assumed to equal the one of pine stands
Understorey biomass lichens	kg ha^{-1}	U	0	4	0.3–0.5	50%	150%	Exact estimate depends on tree species and stand age	Peltoniemi et al. 2004
Understorey biomass bryophytes	kg ha^{-1}	U	0	4	0.7–1.6	50%	150%	Exact estimate depends on tree species and stand age	Peltoniemi et al. 2004
Understorey aboveground biomass herbs	kg ha^{-1}	U	0	4	0.03–0.23	50%	150%	Exact estimate depends on tree species and stand age	Peltoniemi et al. 2004
Understorey aboveground biomass shrubs	kg ha^{-1}	U	0	4	0.3–1.2	50%	150%	Exact estimate depends on tree species and stand age	Peltoniemi et al. 2004
Understorey aboveground biomass total	kg ha^{-1}	U	0	4	2.1–5.4	50%	150%	Exact estimate depends on tree species and stand age	Peltoniemi et al. 2004
Turnover: Lichens aboveground	yr^{-1}	U	0	0		0.05	0.15		Longton 1992; Kumpula et al. 2000
Turnover: Bryophytes aboveground	yr^{-1}	U	0	0		0.1667	0.5		Kellomäki et al. 1977; Havas and Kubin 1983; Nakatsupo et al. 1997

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Appendix 1 (continued)

A	B	C	D	E	F	G	H	I	J	K
Turnover: Dwarf shrubs aboveground	yr^{-1}	U	0	0			0.125	0.375		Mork 1946; Mälkönen 1974; Havas and Kubin 1983
Turnover: Herbs+Grasses belowground	yr^{-1}	U	0	0			0.1667	0.5		Head 1970
Turnover: Dwarf shrubs belowground	yr^{-1}	U	0	0			0.1667	0.5		Head 1970
Aboveground – belowground biomass ratio		U	0	0			1	3	For herbs, grasses and dwarf shrubs, belowground biomass was estimated to be twice the aboveground biomass estimates	Mälkönen 1974; Perina and Kvet 1975; Kubícek and Simonovic 1982; Kubícek et al. 1994
Carbon		N	1	0	0.5	2%				
Turnover: Herbs+Grasses aboveground	yr^{-1}	U	0	0			1	1		Aboveground parts of herbs and grasses assumed to grow and die yearly

Appendix 1 (continued)

Soil model parameters (See Liski et al. 2005 for parameter definitions)									
s	U	0	0	0.6	16.67%	0			Liski et al. 2005
k_ext	N	1	3	0.48	3.13%	0			Liski et al. 2005
k_cel	N	1	0	0.3	3.33%				Liski et al. 2005
k_lig	U	0	0			0.14	0.30		Liski et al. 2005
k_hum1	U	0	0			0.004	0.02		Liski et al. 2005
k_hum2	U	0	0			0.0004	0.002		Liski et al. 2005
a_fwl	U	1	0			0.077	1		Liski et al. 2005
a_cwl	N	1	0	0.077	5%				Liski et al. 2005
c_nwl_ext	N/L	1	3	0.06–0.38	26–37%	0	0.12–0.72	Values below zero omitted for normal distributions with cut distributions with limits at roughly ±CV*mean	Hakkila 1989
c_nwl_cel	N	0	3	0.36–0.54	18–28%				Hakkila 1989
c_fwl_ext	L	0	3	0.3	33%	0	0.6		Hakkila 1989
c_fwl_cel	N	0	3	0.61–0.66	15–16%				Hakkila 1989
c_cwl_ext	L	0	3	0.01–0.03	33–100%	0	0–0.06		Hakkila 1989
c_cwl_cel	N	0	3	0.63–0.77	13–16%				Hakkila 1989
c_lichens_ext	N	0	0	0.112	10%				Hakkila 1989
c_lichens_cel	N	0	0	0.836	10%				Hakkila 1989
c_mosses_ext	N	0	0	0.133	10%				Hakkila 1989
c_mosses_cel	N	0	0	0.736	10%				Hakkila 1989
c_herbs_ext	N	0	0	0.702	10%				Hakkila 1989
c_herbs_cel	N	0	0	0.273	10%				Hakkila 1989
c_shrubs_ext	N	0	0	0.312	10%				Hakkila 1989
c_shrubs_cel	N	0	0	0.557	10%				Hakkila 1989
p_ext	U	0	0			0.1	0.3		Liski et al. 2005
p_cel	U	0	0			0.1	0.3		Liski et al. 2005

Appendix 1 (continued)

A	B	C	D	E	F	G	H	I	J	K
p_lig		U	0	0			0.1	0.3		Liski et al. 2005
p_hum1		U	0	0			0.1	0.3		Liski et al. 2005
beta (for temperature)		N	1	0	0.000447	10%				Liski et al. 2003
Share of fine woody litter of all ground vegetation litter		U	0	0			0	0.1		
Other thinnings are estimated as 100 % – final cuts – first thinnings										

A – variable
B – unit
C – distribution: N = normal, L = lognormal, T = triangular, U = uniform
D – basis for uncertainty estimate: 0 = Expert opinion, 1 = Based on some data, 2 = Based on comprehensive data
E – level of detail: 7 = species/age class/region/time, 6 = species/age class/region, 5 = species / age class, 4 = species/region, 3 = species, 2 = age class/region, 1 = region, 0 = same for all regions, age-classes and species
F – mean of distribution/top value of triangular distribution, ts = time series (value is different for each year)
G – CV (percentages of mean value); S = Southern Finland, N = Northern Finland
H – Min (cut point for normal distributions, or minimum value for uniform or triangular distributions), % denotes % of the mean value
I – Max (cut point for normal distributions, or minimum value for uniform or triangular distributions), % denotes % of the mean value
J – notes
K – Reference for parameter estimate

reporting demands are qualified. However, removals to be credited under the Kyoto Protocol are limited to activities under Article 3.3 and 3.4, and it is also stated that use of mechanisms shall be supplemental to domestic action, and that domestic action shall constitute a significant element of the effort made by each Party (UNFCCC 2002). According to the results of this study, uncertainties in LULUCF categories are notable and problems with timely data collection may increase uncertainties. Therefore, it may not be practical to include them in the same trading scheme with better known emission sources.

Information on uncertainties of the GHG emissions and sinks is important when the contributions of the international policies and agreements to the mitigation of the climate change are assessed. Therefore, uncertainties of the different categories should be known when targets for the second and subsequent commitment periods from 2012 onwards are negotiated by the parties of the UNFCCC. For example, offset of well known emissions of fossil fuels with uncertain forest carbon sink may not necessarily give a desired result from the perspective of climate change mitigation if probability of net emission increase is notable. The results of this study indicate that more research is needed to more accurately and precisely assess carbon sinks so that they can be used in a more reliable and effective way in mitigation of climate change.

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References

Australian Greenhouse office (2004) National Greenhouse Gas inventory 2002. Australian Greenhouse Office, Canberra, 72 p

Charles D, Jones B, Salway A, Eggleston H, Milne R. (1998) Treatment of Uncertainties for National Estimates of Greenhouse Gas Emissions. Global Atmosphere Division, Department of the Environment, Transport and the Regions.

Cronan C (2003) Belowground biomass, production, and carbon cycling in mature Norway spruce, Maine, U.S.A. Can. J. of Fore. 33:339–350.

EIA (1997) Emissions of Greenhouse Gases in United States 1996, DOE/EIA-0573(96), Energy Information Administration, Washington DC.

EIA (2004) Documentation for Emissions of Greenhouse Gases in the United States 2002, DOE/EIA-0638(2002), Energy Information Administration, Washington DC.

Gupta J, Olsthoorn X, and Rotenberg E (2003) The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention. Envir. Sci. and Pol. 6:475–486.

Hakkila P (1966) Investigations on the basic density of Finnish pine, spruce and birch wood. Comm. Inst. For. Fenn. 61:1–98.

Hakkila P (1989) Utilization of Residual Forest Biomass, Springer-Verlag, Berlin, 568 p.

Havas P, Kubin E (1983) Structure, growth and organic matter content in the vegetation cover of an old spruce forest in Northern Finland. Ann. Bot. Fenn. 20:115–149.

Head G (1970) Methods for the study of production in root systems. In Phillipson J, Methods of study in soil ecology: proceedings of the Paris symposium, Eco. and Cons., UNESCO, Paris.

Heath L, and Smith J (2000) An assessment of uncertainty in forest carbon budget projections. Env. Sci. Pol. 3:73–82.

Helmisaari H-S, and Hallbäcken L (1998) Tree biomass belowground. In Andersson F, Braekke F, Hallbäcken L (eds) Nutrition and growth of Norway spruce forests in a Nordic climatic and deposition gradient, TemaNord 1998: 566, Nordic Council of Ministers, Copenhagen, p. 80–90.

Henttonen H (1998) Puiden kasvunvaihtelu. In Mälkönen E (ed), Ympäristömuutos ja metsien kunto, Metsien terveydentilan tutkimusohjelman loppuraportti, Metsäntutkimuslaitoksen tiedonantoja 691:pp. 24–32. Metla

Hökkä H, Kaunisto S, Korhonen K, Päivänen J, Reinikainen A, Tomppo, E (2002) Suomen suometsät 1951–1994. Metsätieteen aikakausikirja 2b/2002

IPCC (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 1. Reporting Instructions.

IPCC (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change (IPCC), Hayama.

IPCC (2003) Good practice guidance for land use, land-use change and forestry. Institute for Global Environmental Studies (IGES), Japan.

Kellomäki S, Hari P, Väisänen E (1977) Annual production of some forest mosses as a function of light available for photosynthesis. Sil. Fenn. 11:81–86.

Kumpula J, Colpaert A, and Nieminen M (2000) Condition, potential recovery rate, and productivity of lichen (Cladonia Spp.). Ranges in the Finnish Reindeer Management. Arctic **53**, 152–160.

Kubícek F, and Simonovic V (1982) Production analyses of the herbaceous layer in several fir communities. Ekológia (CSSR) 1:369–380.

Kubícek F, Simonovic V, and Somsák L (1994) Production-ecological parameters of the herb layer in coniferous forests. Ekológia (Bratislava) 13:145–153.

Kurz W, Beukema S, and Apps M (1996) Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector', Can. J. For. Res. 26:1973–1979.

Kuusela K, and Salminen S (1991) Finnish forest resources from 1977 to 1984 and their development from 1952 to 1980. Acta Fore. Fenn. 220.

Laitakari E (1935) The root system of birch (Koivun juuristo). Acta Fore. Fenn. 41:1–168

Lehtonen A, Mäkipää R, Heikkinen J, Sievänen R, and Liski J (2004a) Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For. Ecol. Managem. 188:211–22.

Lehtonen A, Sievänen R, Mäkelä A, Mäkipää R, Korhonen K, Hokkanen, T (2004b) Potential litterfall of Scots pine branches in southern Finland. Ecol. Model 180:305–315

Liski J, Karjalainen T, Pussinen A, Nabuurs G-J, and Kauppi P (2000) Trees as carbon sinks and sources in the European Union. Envir. Sci. Pol. 3:91–97.

Liski J, Nissinen A, Erhard M, Taskinen O (2003) Climatic effects on litter decomposition from arctic tundra to tropical rainforest. Glo. Chan. Bio. 9:1–10.

Liski J, Palosuo T, Peltoniemi M, Sievänen R (2005) Carbon and decomposition model Yasso for forest soils. Eco. Model. 189:168–182.

Longton R (1992) The role of bryophytes and lichens in terrestrial ecosystems. In Bates J, Farmer A (eds), Bryophytes and lichens in a changing environment, Clarendon Press, Oxford

Majdi H (2001) Changes in fine root production and longevity in relation to water and nutrient availability in a Norway spruce stand in northern Sweden. Tree Phy. 21:1057–1061.

Metla (2003) Finnish statistical yearbook of forestry 2003. Finnish Forest Research Institute, Helsinki, 388 p

Mikola P (1950) On variations in tree growth and their significance to growth studies. Comm. inst. fore. fenn. 38:131.

Mitchell T, Carter T, Jones T, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall Centre Working Paper 55.

Monni S, Syri S, Savolainen I (2004a) Uncertainties in the Finnish greenhouse gas emission inventory. Envir. Sci. Pol. 7(2):87–99.

Monni S, Syri S, Pipatti R, Savolainen I (2004b) Comparison of uncertainty in different emission trading schemes. In Proceedings of the International Workshop on Uncertainty in Greenhouse Gas Inventories: Verification, Compliance and Trading. Warsaw - Poland, September 24–25, 2004, Systems Research Institute, Warsaw, pp 106–115

Monni S, Perälä P, Regina K (2006) Uncertainty in agricultural CH_4 and N_2O emissions from Finland - possibilities to increase accuracy in emission estimates. Mitigation and Adaptation Strategies for Global Change.

Mork E (1946) Om skogbunnens lyngvegetasjon. Medd. fra det Nor. Skog. ksv. 33:274–356.

Muukkonen P (2005) Needle biomass turnover rates of Scots pine (Pinus sylvestris L.) derived from the needle-shed dynamics. Trees – Structure and Function 19(3):273–279.

Muukkonen P, Lehtonen A (2004) Needle and branch biomass turnover rates of Norway spruce (Picea abies). Can. Jour. For. Res. 34(12):2517–2527.

Mälkönen E (1974) Annual primary production and nutrient cycle in some Scots pine stands. Comm. inst. for. fenn. 84.5:1–87.

Nakatsubo T, Uchida M, Horikoshi T, Nakane K (1997) Comparative study of the biomass loss rate of moss litter in boreal and subalpine forests in relation to temperature. Eco. Res. 12:47–54

Nilsson S, Shvidenko A, Stolbovoi V, Gluck M, Jonas M Obersteiner M: (2000) Full carbon account for Russia, Interim Report IR-00-021, IIASA, Laxenbourg.
Nuutinen T, Hirvelä H, Hynynen J, Härkönen K, Hökkä H, Korhonen K, Salminen O (2000) The role of peatlands in Finnish wood production – an analysis based on large-scale forest scenario modelling. Silva Fennica 34:131–153.
Paul K, Polglase P, Richards G (2003a) Sensitivity analysis of predicted change in soil carbon following afforestation. Ecol. Model. 164:137–152.
Paul K, Polglase P, Richards G (2003b) Predicted change in soil carbon following afforestation or reforestation, and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). For. Ecol. Manag. 177:485–501.
Peltoniemi M, Palosu T, Monni S, Mäkipää R, (in press) Factors affecting uncertainty of sinks and stoks of carbon in Finnish forest soils and vegetation. For. Ecol. Managem.
Peltoniemi M, Mäkipää R, Liski J, Tamminen P (2004) Changes in soil carbon with stand age and evaluation of a modeling method with empirical data. Glo. Cha. Bio. 10:2078–2091.
Perina V, Kvet J (1975) Vliv prosvetlení horské smrciny na tvorbu biomasy prízemního patra [The effect of Montane spruce thinning on the biomass production of the ground vegetation]. (in Czech with English summary). Lesnictví 21:659–687.
Pohjola J, Kerkelä L, Mäkipää R (2003) Credited forest carbon sinks: how the cost reduction is allocated among countries and sectors. Clim. Pol. 3:445–461.
Rypdal K, Zhang L-C (2000) Uncertainties in the Norwegian Greenhouse Gas Emission Inventory, Statistics Norway, Oslo.
Rypdal K, Winiwarter W (2001) Uncertainties in greenhouse gas emission inventories - evaluation, comparability and implications. Envir. Sci. & Pol. 4:107–116.
Smith J, Heath L (2001) Identifying influences on model uncertainty: An application using a forest carbon budget model. Envir. Manag. 27(2):253–267.
Statistics Finland (2005a) Greenhouse Gas Emissions in Finland 1990–2003. National Inventory Report to the UNFCCC. Statistics Finland, Helsinki, 213 p.
Statistics Finland (2005b) National Greenhouse Gas Inventory System in Finland. Statistics Finland, Helsinki, 40 p
Tapio (2005) Loggins 2000, http://www.metsavastaa.net/index.cfm?docID=3674
Tiihonen P (1979) Variation in tree growth in Finland: results from the 6th National Forest Inventory. Folia Forestalia 407:Institutum Forestale Fenniae.
Tomppo E, Henttonen H, Tuomainen T (2001) Valtakunnan metsien 8. inventoinnin menetelmä ja tulokset metsäkeskuksittain Pohjois-Suomessa 1992–94 sekä tulokset Etelä-Suomessa 1986–92 ja koko maassa 1986–94. Metsätieteen aikakausikirja 1B/2001.
UNFCCC (1992) United Nations Framework Convention on Climate Change, UNFCCC Secretariat, Bonn
UNFCCC (1997) Kyoto Protocol, UNFCCC Secretariat, Bonn
UNFCCC (2001) Preparations for the first session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (decision 8/CP.4). Matters relating to land-use, land-use change and forestry, FCCC/CP/2001/L.11/Rev.1, UNFCCC Secretariat, Bonn
UNFCCC (2002) Report of the conference of the parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. Addendum. Part two: action taken by the conference of the parties, FCCC/CP/2001/13, UNFCCC Secretariat, Bonn.
UNFCCC (2004a) Guidelines for the preparation of national communications by Parties included in the Annex I to the Convention, Part I: UNFCCC Reporting Guidelines for Annual inventories (following incorporation of the provisions of decision 13/CP.9), FCCC/SBSTA/2004/8, UNFCCC Secretariat, Bonn.
UNFCCC (2004b) National inventory submissions of Annex I Parties of the UNFCCC in 2004, UNFCCC Secretariat, Bonn. http://unfccc.int/national_reports/annex_i_ghg_inventories/ national_inventories_submissions/items/2761.php
Vanninen P, Mäkelä A (1999) Fine root biomass of Scots pine stands differing in age and soil fertility in southern Finland. Tree Phy. 19:823–830.
Viro P (1955) Investigations on forest litter. Communicationes instituti forestalis fenniae 45(6):1–142.
Winiwarter W, Rypdal K (2001) Assessing the uncertainty associated with national greenhouse gas emission inventories: a case study for Austria. Atmo. Envir. 35:5425–5440.
Zhang X-Q, and Xu D (2003) Potential carbon sequestration in China's forests. Envir. Sci. & Pol. 6:421–432