Methodological options for quantifying changes in carbon pools in Swedish forests

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Table of Contents

Executive summary

Background

Carbon uptake in terrestrial sinks is important in the global carbon balance and hence in limiting the concentration of carbon dioxide in the atmosphere. During the last decades the terrestrial ecosystems overall have served as a net sink for carbon dioxide, in spite of net emissions to the atmosphere from land-use change, primarily in the tropics. Northern forests appear to account for a major portion of the terrestrial sink, partly as a result of improved forest management. Parties that have signed the Kyoto Protocol have had different views to what extent sinks should be used to meet the commitments. The agreement reached in Marrakesh represents a complex compromise, in which anthropogenic sinks can be used to a limited and carefully regulated extent. The agreement requires thorough monitoring and complex accounting of sinks. For Sweden, the sink in forests is of major potential importance.

The Parties must report what areas have been used to meet commitments. Areas that have been included in one commitment period need to be monitored, reported and accounted for also in future commitment periods. The pools of carbon included are above ground biomass, below ground biomass, litter, dead wood, and soil organic carbon.

IPCC will elaborate methods to estimate, measure, monitor, and report changes in carbon stocks and anthropogenic greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change, and forestry activities and prepare a report on good practice guidance and uncertainty management. IPCC further will develop practicable methodologies to factor out direct human-induced changes from natural effects and indirect human-induced effects such as fertilization from deposition of nitrogen or increased CO_2 concentrations and the dynamic effects of age structure resulting from activities and practice before 1990.

Objectives

The objective of this study was to evaluate Sweden's methodological options for quantifying changes in forest carbon pools on a national scale to meet important reporting requirements of the Kyoto protocol. Our treatment of different methodological options has been general, since there will be a certain freedom for individual countries to develop suitable national methods. Also, since Sweden is a country with rather stable land-use, our focus has been on Article 3.4 in the Kyoto Protocol, rather than the activities afforestation, reforestation, and deforestation under Article 3.3. Thus, our ambition has been to study methods for quantifying changes in carbon pools in forest management areas. No attempts have been made to factor out natural and indirect human-induced effects or to estimate fluxes of non-CO_2-greenhouse gases.

The approach of the study has been to compile and synthesize current knowledge and practices in Sweden and to evaluate advantages and disadvantages of various methods in terms of requirements and availability of data, included carbon pools, uncertainty of the outcome, etc. The work has considered:

- What forest definition to use
- How to define different forest carbon pools in the Swedish case
- What methods are available for national accounting and the corresponding accuracy in national level estimates
- What methods are available for purposes of verification

4

- Needs for research and improvement of on-going national monitoring programmes to enhance the accuracy of the carbon pool change estimates

Forests and forest monitoring in Sweden

Since the middle of the 20th century, Sweden has undergone rather limited changes in land-use. Thus, currently there are no major transfers between different land-use categories, although some land is being exploited for purposes of expanded infrastructure, and some agricultural land has been converted to forest. Moreover, currently there is an increase in the proportion of protected forests.

Most of the Swedish forests are managed. Exceptions are the tree-covered lands on mires and rock outcrops, which are forest according to FAO's definition although not according to the Swedish definition. Using FAO's definition, the forested area in Sweden in about 27 Mha, while it is slightly less than 23 Mha using the national definition, which states that the potential productivity should exceed 1 m^3 stem-wood per hectare and year. We suggest the Swedish definition of forest to be used for reporting forest management under the Kyoto Protocol (Art 3.4). It remains to be discussed whether or not protected forest areas should be included.

Regarding monitoring of forest carbon pools, Sweden is well equipped with basic data due to the annual surveys within the National Forest Inventory (NFI) and the Swedish Forest Soil Inventory (MI). These two monitoring programmes share the same plots, and thus data can easily be integrated. Within the NFI, among other things measurements of trees and dead wood are conducted. Within the MI, soil samples are taken and analysed for carbon. During the last decade, the NFI has comprised about 12-15 000 sample plots annually. About 50% of these were located in forests. Soil samples within the MI are taken only on a small fraction of the NFI plots due to the high costs of sampling and analysis.

Different from the case in most other countries, the two national forest surveys cover the entire country on an annual basis and thus there is no major need for data extrapolation or interpolation when reporting for a specific period (some interpolation might be needed in the case of soil carbon, since soil data are collected in 10-year cycles). Moreover, permanent sample plots were established in the 1980s, providing a good foundation for change estimation by repeated measurements.

During the last decade, the annual growth in managed forests in Sweden has been estimated at about 100 Mm^3 per year, while the cuttings have been about 70-80 Mm^3. The annual sequestration of carbon in tree biomass has been 5-10 Mton C - a substantial proportion of the anthropogenic emissions of carbon. There are indications that some soil types are carbon sinks and that some are sources. Currently there is a lack of data for a full evaluation.

Methods for assessing changes in carbon pools

Considering methods for assessing carbon pools in Swedish forests, it is judged appropriate to make use of the data available from the NFI and the MI. Eddy-covariance measurements are carried out at some places in Sweden; these sites can be very useful for purposes of verification. With the national inventory programmes, it is convenient to make a separation between the

detailed measurements made of the carbon pools at the plot level, and then study the problem of scaling up for estimating national level total changes.

At the plot level, it is important to have clear definitions of the different carbon pools. Currently, above ground biomass in trees can be calculated from the detailed measurements of trees made at the sample plots of the NFI. Based on these measurements, contrary to the practice in many other countries – where biomass expansion factors are applied – individual tree biomass functions are used. With these functions, tree biomass (above ground) can be estimated for the fractions stem, branches, and needles and fine twigs. To convert from biomass to carbon, the factor 0.49 has been found to be rather stable in several studies. Currently, there are no procedures available for assessing the quantities of carbon in other above ground vegetation than trees. However, the latter carbon pool is judged to be small in comparison to the tree carbon pool.

Tree stumps and roots are considered part of the below ground biomass. Below ground biomass of trees is estimated at the individual tree level with the same kind of functions as the above ground biomass. However, due to the procedures used when developing these functions, there is currently most likely a slight under-estimation of below ground biomass of trees. No procedures are available for assessing the amount of other below ground biomass than living tree roots.

Dead wood is measured on a regular basis within the NFI. From these measurements, the volume of dead wood (with a diameter exceeding 10 cm) is obtained. Studies about how to convert these volume estimates to carbon estimates are ongoing. Information is lacking from finer fractions of dead wood (above ground) and biomass in dead roots.

Regarding the quantities of litter in Swedish forests, information is only available from literature sources and a limited number of research sites. Measurement of this carbon pool today is neither part of the NFI nor of the MI.

Regarding soil organic carbon, samples are regularly taken within the MI. These comprise humus layer cores as well as samples of fine fractions of mineral soil at different depths. Among other analyses, the samples are analysed for carbon concentration. Since the inventory originally was not designed for quantifying the amount of different compounds in the soil, some problems are encountered with estimating changes in soil carbon pools, although principally the survey is adequate for this purpose. The problems involve the principles for selecting humus cores, how to estimate the bulk density of the finer soil fractions (which are the ones that are analysed), lack of methods for assessing the amounts of stones and boulders in the soil, and a lack of samples from lands with deep peat layers.

Turning from the measurements at the plot level to the problem of scaling up to national level estimates, our main studies comprise the following methods regarding tree biomass (above and below ground):

1) Summation of growth minus removals over the years in a reporting period, along the principles used in the current Swedish reporting under the UNFCCC
2) Direct estimation of changes between the end and starting point of a reporting period based on (i) temporary sample plots and (ii) permanent sample plots
3) Combined estimation, using (1) and (2). In this case, the two original estimates are weighted in order to obtain a single estimate with a lower variance than any of the two original estimates

4) Satellite-data aided change estimation. In this case, satellite data were used as auxiliary data to the field data, and principles of post-stratification were applied.

A summary of the results regarding biomass in trees is given in Table S1 below. It can be seen that there are many methods that result in quite reasonable sizes of standard errors of estimated changes. The approach to sum annual growth-minus-cuttings, which is the one used in Sweden for reporting under the UNFCCC, results in fair levels of standard errors. Methods based on direct change estimation – averaging results over three year periods at the start and the end of the reporting period – result in quite low standard errors in case all the NFI plots were permanent (the plan is that two thirds will be permanent in the period 2008-2012). With temporary plots the standard error of the change estimate would be high, and there would also be a severe risk of systematic errors due to the difference being taken between two large pools. Slightly varying systematic error levels between the start and the end of the reporting period in this case could lead to a large systematic error of the change estimate. This risk is reduced if permanent plots are used, since a list of the trees from the first inventory is brought to the field at the point of time of the second inventory. To avoid systematic errors, it is important to carry out the inventories very carefully, and to have separate control teams that redo the measurements on a random sample of the original plots.

Table S1. Summary of important features of the proposed methods for estimating changes in carbon pools in trees (above and below ground carbon). The estimates are based on data from the Swedish NFI, and to some extent on assumptions.

Method	Standard error of an estimate of five years change, Mton C[*]	Risk for systematic errors	Ready for application?
Summation of growth minus cuttings ("IPCC")	11 - (25%)	Moderate	Yes
Direct change (temporary plots)	18 - (40%)	High	Yes
Direct change (permanent plots)	6 – (13%)	Moderate	Yes
Combined estimation ("IPCC" and permanent plots)	5 – (11%)	Moderate	Almost
Remote sensing aided change estimation (post-stratification)	5 – (10%)	Moderate	No

*) The total change of carbon in biomass for a 5-year period is set to be 43 Mton C, which is based on the change during the period 1990-2000. Approximate 95% confidence intervals are obtained as $43 \pm 2 *$ Standard error.

A challenge in applying remote sensing in the Swedish case is to improve the estimates obtained when using field data only. Since these have quite high accuracy, as described above, a major issue is to avoid introducing systematic errors when incorporating remote sensing data in the estimation procedures. One important basis is that remote sensing alone seldom is very useful for biomass estimation and similar purposes. Almost always there is a need for field reference data, so that the specific spectral signatures can be interpreted.

Theoretically, the combination of remote sensing and field data is not complicated. Many methods exist, e.g. stratification, multi-phase, or multi-stage sampling. However, working with satellite imagery for deriving estimates for forests we face problems with poor geometry of images as well as poor precision of geo-referenced field plots. Mismatches between field plots and satellite pixels may lead to biased estimates. Moreover, classification procedures, e.g. to estimate the forest area from satellite imagery, seldom are unbiased. Thus, care must be taken when applying remote sensing for purposes of estimating changes in carbon pools. The principle pointed out in this study was post-stratification, using medium resolution imagery.

The above discussion is specific to countries where the quality of field data is high. When field data are sparse or lacking, remote sensing has an important role of providing at least some basic information. Specifically, deforestation can often be identified with rather high accuracy.

Leaving carbon in biomass and turning to carbon in soils, the soil organic carbon is measured in the MI, and expressed as concentration and amount. The concentration is expressed as, e.g., percent C of dry weight of fine soil (<2 mm). The values are obtained from laboratory analyses of the soil samples collected. The content of C per volume unit is calculated as the concentration times the bulk density of the fine soil. To obtain amounts C per area unit, the density of C is multiplied with the soil volume down to a certain reference depth or within a certain layer. Layers are either defined as genetic soil horizons (such as O, E and B horizons) or as set depth layers (such as 0-5, 5-10 cm etc.). For soils containing mineral matter larger than 2 mm, i.e. coarse material, the volume has to be reduced with the volume of coarse material.

An important question for carbon estimation in mineral soils is the assessment of coarse material. Another important question is to what depths the stock should be accounted for. We suggest for Sweden that 0.5 m would be suitable in mineral soils.

The MI-dataset on carbon in the humus layers was used for determining changes in this carbon pool, and the corresponding uncertainties. The results, based on 1000 plots, indicate that this carbon pool has increased in southern Sweden during the last decades with approximately 0.5% per year. In central Sweden an increase is indicated, although not significant. For northern Sweden a slight decrease in humus layer carbon is indicated.

Regarding carbon in thick peat layers, data and methods are still lacking for making a thorough analysis. However, it is stressed that a large proportion of all soil carbon in Sweden occurs in peat-lands and that peat-land under forest might be a potential carbon source. Hence, it is important that methods to survey peat carbon stocks will be developed.

Due to high variation in carbon concentration in mineral soils, lack of data on stones and boulders, no reliable estimate of carbon stock changes in mineral soils have been made so far. If we assume an annual increase of 0.5% and apply the known variation in concentration, bulk density and stone and boulder content, the change over a 5-year period would for mineral soil material to a depth of 0.5 m be 21 Mton C, with a standard error of 8.5 Mton C. The estimate is based on the present number of analysed samples, which is 3500.

In Table S2, a summary of important features is given regarding the possibilities to use the MI for monitoring soil carbon pools.

Table S2. Summary of important features of soil monitoring for estimating changes in soil carbon pools. In this case, NSFSV data (and assumptions) are used for direct change estimation between two time points.

Method	Standard error[*] of an estimate of five years change, Mton C	Risk for systematic errors	Ready for application
Humus layer, south Sweden	0.75 - (25%)	High	Yes, with minor modifications
Mineral soils to 0.5m	8.5 - (40%)	High	Yes, with modifications

*) Approximative 95% confidence limits are obtained as the estimate ± 2*Standard error

A prominent feature in general of using sample-based approaches for the reporting under the Kyoto Protocol is that standard errors can be estimated based on the data collected. Thus, contrary to many other cases of reporting removals or emissions of greenhouse gases, there is no need to make qualified guesses regarding the precision of the data.

The Kyoto protocol states that the estimated changes in the carbon pools shall be verifiable, i.e. to verify that the changes are true. The closest we can come to verify an estimate of a change in carbon pools is probably to compare estimates made by independent methods that are designed to measure the same thing. The eddy-covariance method provides one possible means for such comparisons. With the eddy-covariance method the net flux of CO_2 between the atmosphere and a forest can be measured with a half-hourly time resolution. The integral over time of the flux plus the transport of dissolved organic carbon (DOC) out of the system shall be comparable to the change in the pools estimated over the same time period, provided all pools are measured. Since the DOC transport is known to be fairly small in most systems, it can be neglected in a first approximation and, thus, integrated fluxes measured by eddy-covariance can be directly compared to measured changes in the pools at the same site (if export of carbon as harvest also is included). Today, eddy-covariance measurements are ongoing at several forests in Sweden as part of different research projects but there exist no sites for continuous long-term monitoring. We suggest that a number of eddy-covariance sites are set up in a monitoring and verification program. At these sites, the methods applied for monitoring of carbon pools should be used exactly the same way as for the purpose of Kyoto Protocol reporting. Results from these measurements can be used for testing and development of methods based on modeling.

Conclusions

It is concluded that the current Swedish national forest monitoring programmes, the NFI and the MI, provide adequate bases for reporting changes of forest carbon pools under the Kyoto Protocol (Article 3.4). Also, with the permanent plots of the NFI it is likely that most of the requirements regarding reporting of afforestation, reforestation and deforestation (Article 3.3) can be fulfilled. Several methodological options are available for reporting changes in biomass

9

in trees; to some extent these methods are complementary and can be used for verification or for combining estimates. The most promising approach is judged to be direct change estimation based on permanent plots (although this might imply a need to recalculate the annually reported figures once the reporting period has ended). This principle might be combined with post-stratification using remote sensing auxiliary data, to slightly further improve the estimates. However, the routines for check assessments within the NFI need to be improved.

The existing soil survey (MI) can, after some modifications, be used for monitoring soil carbon stock changes in mineral soils to a depth of 0.5 m. New methods would be needed in order to include peat lands as well. An alternative to basing the reporting on repeated measurements of soils would be to develop soil carbon models. Since annual reporting is required to the Kyoto Protocol, such models might assist in deriving extrapolated values from the 10 yr change estimates obtained from the MI.

Dead wood is covered by the NFI, and once new functions for conversion from volume to carbon have been established it will be possible to include this pool in the reporting.

No measurements are made to estimate the carbon pool of litter. One possibility could be to expand the humus sampling of the MI to include litter as well. Especially, new methods would be required to survey fine woody debris (<10cm), which is included in this pool.

Eddy-covariance measurements are valuable means for verification and for further improving our understanding of greenhouse gas fluxes, for example regarding the temporal variability of fluxes. However, currently there is no possibility to use these measurements for improving the national level estimates of carbon pool changes. The reason is that the network of measurement stations is very sparse, and that there are no methods available for scaling up from the site level to the national level.

Overall, the precision of the carbon change estimates obtained in this synthesis study are reasonable in comparison to what has been reported in other studies.

Finally, although this report focuses on methods for change estimation based on current and past data, it is important to point out that scenario analyses are important tools for being able to act pro-actively with issues related to carbon sources and sinks in forests. Whether or not the forest ecosystem is a source or a sink is a result of complex ecological and socio-economical interactions, where tree growth and soil processes act on the one side, and the processes that lead to management decisions such as harvesting act on the other side. In Sweden, joint SLU-MISTRA funded projects (Heureka, LUSTRA, and others) aim at developing tools that can be applied for this kind of integrated analyses.

Introduction

Carbon uptake in terrestrial sinks is an important process in the global carbon balance and hence in limiting the concentration of carbon dioxide in the atmosphere. The agreement reached in Marrakesh (UNFCCC 2001), where some remaining issues in the Kyoto Protocol were sorted out, means that anthropogenic sinks can be used to a limited and carefully regulated extent by signatory parties to meet commitments. The agreement requires thorough monitoring and accounting of sinks and sources.

IPCC will elaborate methods to estimate, measure, monitor, and report changes in carbon stocks and anthropogenic greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change and forestry activities. Further, IPCC is preparing a report on good practice guidance and uncertainty management relating to the measurement, estimation assessment of uncertainties, monitoring and reporting of net carbon stock changes and anthropogenic greenhouse gas emissions by sources and removals by sinks in the land use, land-use change and forestry sector, by the ninth conference (COP 9) of the UNFCCC Parties in 2003. Moreover, IPCC will develop practicable methodologies to factor out direct human-induced changes from natural effects and indirect human-induced effects such as fertilization from atmospheric deposition of nitrogen or increased CO_2 concentration and the dynamic effects of age structure resulting from activities and practices before 1990, by COP 10 in 2004.

Different methods can be used to account for changes in carbon stocks of different pools in forest ecosystems. All those methods have advantages and disadvantages and the usefulness of the results are strongly dependent on the objectives, the database, and the geographical scale. In general it is easy to get detailed information on greenhouse gas balances on a local level. The big challenge, however, is to develop and apply methods, which produce estimates on the national scale with acceptable accuracy in a cost-efficient way.

The objective of this report was to evaluate Sweden's methodological options for quantifying changes in forest carbon pools on a national scale to meet the requirements in the Kyoto protocol. Our treatment of different methodological options has been quite general, since there will be a certain freedom for individual countries to develop suitable national methods for the reporting. Also, since Sweden is a country with rather stable land-use, our focus has been on Article 3.4 in the Kyoto Protocol, rather than the activities afforestation, reforestation, and deforestation under Article 3.3. Thus, our focus has been on methods for quantifying changes in carbon pools in forest management areas. No attempts have been made to factor out natural and indirect human-induced effects, which is likely to be required in future reporting. Nor have we made any attempts to study methods for estimating fluxes of non-CO_2 greenhouse gases.

The approach of the study has been to compile and synthesize current knowledge and practises in Sweden and to evaluate advantages and disadvantages of various methods in terms of requirements and availability of data, included carbon pools, uncertainty of the outcome, etc. The work has considered:

- What forest definition to use
- How to define different forest carbon pools in the Swedish case
- What methods are available for assessment of carbon stock changes at the national level and the corresponding accuracy in the national level estimates
- What methods are available for purposes of verification
- Needs for research and improvement of on-going national monitoring programmes to enhance the accuracy of the carbon pool change estimates

International agreements

The issue

Carbon uptake in terrestrial sinks is important in the global carbon balance and hence in limiting the concentration of carbon dioxide in the atmosphere. During the last two decades, the terrestrial ecosystems have served as a small net sink for carbon dioxide. This terrestrial uptake has occurred in spite of net emissions into the atmosphere from land-use change, primarily in the tropics with 1.6 ± 0.8 Gt C/year (1 Gton = 10^9 ton. The uptake in terrestrial sinks was estimated to 2.3 ± 1.3 Gt C/year (IPCC 2000a). The magnitude of the net carbon flows (in Gt C/year) between the atmosphere, the oceans and the terrestrial ecosystems, averaged for 1989-1998, is shown in Fig. 1 (IPCC 2000a).
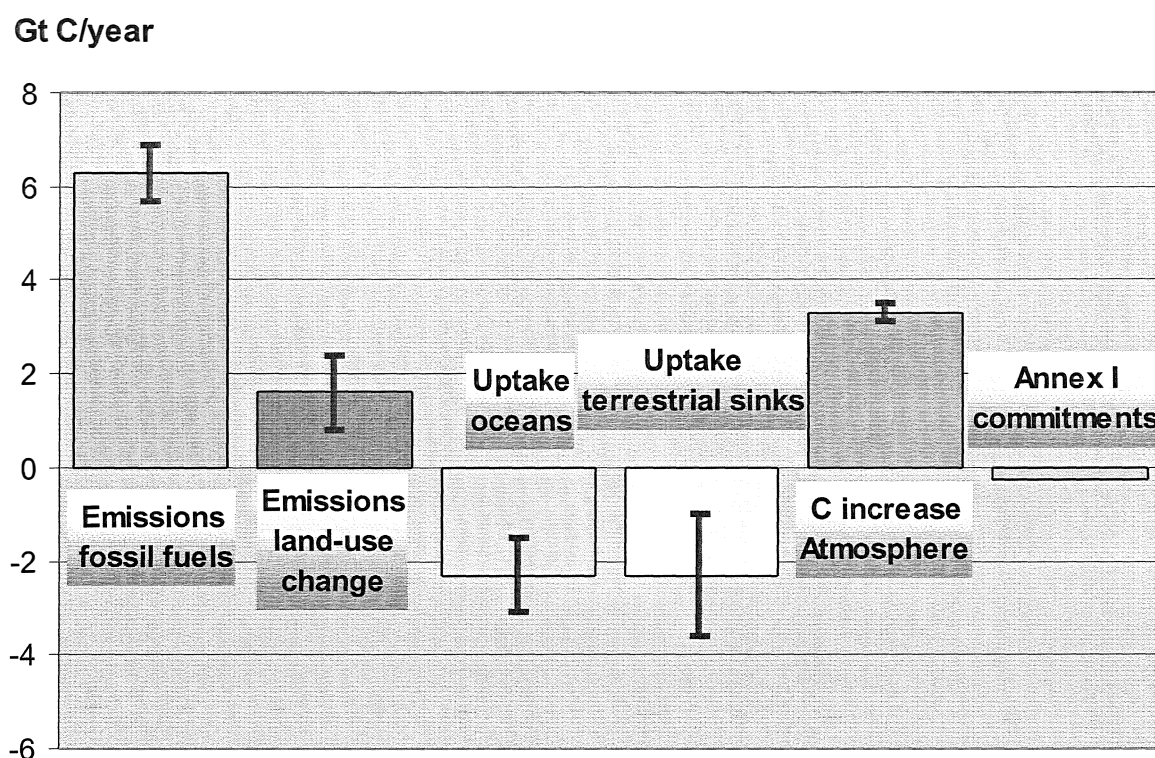

Figure 1. Annual carbon flows for the period 1989-1998 compared with Annex I commitments in the Kyoto Protocol of 250 Mt C/year for the period 2008-2012. (The vertical bars in the diagram show the uncertainty at an estimated 90% confidence interval)

The uptake in terrestrial ecosystems has been calculated as a residual term from emissions from fossil fuels and cement production, emissions from land-use change, storage in the atmosphere and uptake in the oceans, and is therefore often referred to as the residual terrestrial sink.

The terrestrial sink mainly is a result of (i) growth of forest and other vegetation and the accumulation of organic matter in soils including the effects of improved land and forest management, particularly in temperate and boreal forests of the northern hemisphere, (ii) indirect effects of human activities such as atmospheric CO_2 fertilization and nutrient deposition and (iii) changing climate, both due to natural and anthropogenic causes. It is presently not possible to determine the relative importance of these different processes (IPCC 2000a).

Satellite data combined with forest inventory data have indicated that forests in Europe, Russia and North America have been storing nearly 700 Mton C per year in forest biomass during the 1980s and 1990s (Myneni et al. 2001). Northern forests may account for a major portion of the residual terrestrial sink if also other pools, such as the soils, are included. The study indicated that most northern forests – with the exception of Canada's boreal forests – were storing carbon. Russia accounted for almost 40 % - or 280 Mton C per year – of this forest carbon sink, declining harvests being the most probable cause. In other areas, such as the Nordic countries and USA, current management practices are likely reasons for the net forest carbon sink. Forest fires and infestations are possible reasons for the net carbon loss from boreal forests in Canada (Myneni et al. 2001). This study report very high figures for the case of Sweden, as compared to previous studies (e.g. Eriksson 1991). Recently, the carbon sequestration in European forests was estimated at 880 Mton C/year, by the use of inventory data (Liski et al., 2003a).

In addition to the sources and sinks shown in Figure 1, also the sum of the commitments of the, so called, Annex I countries of the Kyoto Protocol is shown (250 Mton C/year). The agreement in Kyoto on commitment levels was reached on the understanding that there should be only a limited inclusion of sinks during the first commitment period and that focus should be on reduction of emissions. An unlimited inclusion of sinks could result in claims corresponding to a major portion of the residual terrestrial uptake.

The terrestrial carbon uptake has an important role in the global carbon cycle at present. The net uptake as a result of improved forest management may significantly increase the amount of carbon in a forest over a rotation period as compared with that of natural forests. The crucial matter is, however, the changes in a longer perspective. The net loss of the amount of carbon in terrestrial ecosystems since pre-industrial times is probably considerably less than 100 Gton C and the total net gains by deliberate human efforts to increase uptake by terrestrial ecosystems will probably be of the same magnitude during the 21st century. The foreseen accumulated emissions according to IPCC's scenarios during this period, as a result of burning of fossil fuels are, however, predicted to be an order of magnitude larger, 800 to 1500 Gton C, and emphasis must therefore be on emissions reduction in order to achieve stabilisation targets for CO_2 in the atmosphere.

Decisions on sinks in the Kyoto Protocol and the Marrakesh Accords

Parties have had different views to what extent sinks should be used in the first budget period, 2008-2012, to meet commitments. The agreement reached in Marrakesh (UNFCCC 2001), that makes the Kyoto protocol operational, represents a fairly complex compromise, in which anthropogenic sinks can be used to a limited and carefully regulated extent by Parties to meet

13

commitments. The agreement requires thorough monitoring and complex accounting of sinks in Annex I countries[1].

The issue of carbon sinks received attention only at a late stage in the negotiations of a protocol under the Climate Convention, and diverging views among Parties led to a fairly complicated compromise that was agreed in the Kyoto Protocol at the third conference of the Parties to UNFCCC (COP 3), held in Kyoto 1997. It was agreed that sinks could be used, but only to a certain limited extent, to meet commitments during the first period.

Article 3.3 in the protocol states that the net changes in carbon stock from the activities afforestation, reforestation and deforestation since 1990 shall be used to meet commitments. Article 3.4 states that Parties may choose to apply additional human-induced activities to be agreed within the agricultural and forestry sectors. Further negotiations were needed to make these paragraphs operational, e.g. the definition of forest, the definitions of the activities under Art. 3.3, and on the modalities, rules and guidelines for inclusion of new activities under Art. 3.4. A principal agreement was reached at COP 6 in Bonn in June 2001, that was made operational in the Marrakesh Accords agreed in Marrakesh at COP 7 in November 2001 (UNFCCC 2001). The Marrakesh Accords also set the rules for accounting and reporting of the carbon sinks.

The activities in Art. 3.3: afforestation, reforestation and deforestation, represent a change in land use and Parties have to account for the changes in carbon stock due to these activities. Reforestation activities for the first commitment period are limited to reforestation occurring on lands that were not forested on 31 December 1989. Reforestation activities in the normal harvesting- reforestation cycle thus are not included under Art 3.3. This means that for most Parties, including Sweden, Art 3.3 activities will only have a limited quantitative impact. Article 3.3 will have a large impact only in countries with plantation forestry, like New Zealand, and in countries where extensive afforestation programmes occur. Annex I Parties would, of course, also be responsible for decreases in carbon stock due to deforestation.

Under Art 3.4 the broadly defined activities forest management, cropland management, grassland management and the more narrowly defined revegetation can be used by Parties to meet commitments during the first commitment period. The three latter activities all concern agriculture, and carbon stock changes are compared on an annual basis with the corresponding carbon stock change during the base year (1990). Thus, credits are given to improvements relative to the base year (so-called net-net accounting). The agricultural activities will not be further analysed in this report.

Forest management is broadly defined as "a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner". The definition would basically include all forest areas under management in Sweden. For the forest definition, Parties have to select a forest definition from ranges given for tree crown cover, tree height and minimum land area, and keep that definition for the first commitment period. Parties need to justify the choice and show that its values are consistent with information that has historically been given to FAO and other international bodies or, if they differ, explain why and how the definition was chosen.

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[1] Parties that have quantified emission reduction or limitation commitments are listed in Annex I to the Kyoto Protocol (basically the industrialized countries including Russia and other Eastern Europe countries with economies in transition).

Accounting for forest management is based on the actual carbon uptake, not the uptake relative to the base year as for the agricultural activities. It was decided in the Marrakesh Accords that accounting of sinks should be guided by a number of principles, e.g. accounting and crediting of carbon uptake should exclude effects of indirect effects such as fertilization from atmospheric deposition of nitrogen or increased CO_2 concentration and the dynamic effects of age structure resulting from activities and practices before 1990.

Such adjustments should be based on scientific data, but for the first commitment period it was agreed to use a pragmatic, simplified basis for accounting: Numbers were calculated for each Annex I Party based on an 85 % discount factor and a 3 % (of 1990 greenhouse gas emissions) cap on forest management, using a combination of data provided by Parties and by the FAO. Some Parties were given higher numbers based on "national circumstances". This applied primarily to Canada and Japan, but also to Russia. The amount for Sweden is 0.58 Mton C/year. These numbers are in addition to a compensation for a net debit that may have been incurred under Art 3.3.

Parties shall report the areas that have been used to meet commitments. It is stated in the Decision 11/CP7, Land-use, land-use change and forestry (LULUCF decision) that "National inventory systems…shall ensure that areas of land subject to land use, land-use change and forestry activities under Article 3 paragraphs 3 and 4 are identifiable, and information about these areas should be provided by each Party included in Annex I in their national inventories…". The accounting provision states that information should be given on "the geographical location of the boundaries of the areas that encompasses (i) units of land subject to activities under Article 3, paragraph 3; (ii) units of lands subject to activities under Article 3, paragraph 3, which would otherwise be included in lands subject to elected activities under Article 3, Paragraph 4….; and land subject to elected activities under Article 3, Paragraph 4."

The text indicates that the exact geographical location of individual units of land with afforestation, reforestation or deforestation does not need to be identified, but statistical sampling within normal forest inventories can be employed. The key part of the decision is "geographical location of the boundaries of the areas that encompasses"…" units of lands subject to activities under Article 3, paragraph 3".

Areas that have been accounted and used to meet commitments during the first commitment period need to be monitored, reported and accounted for also in future commitments periods. The carbon pools included are above ground biomass, below ground biomass, litter, dead wood and soil organic carbon. A Party may choose not to account for a given pool in a commitment period, if transparent and verifiable information is provided that the pool is not a source.

Forests and forest monitoring in Sweden

Definition of Forest

The Swedish definition of forest implies that all areas – with no major other land use - where the potential production of wood is at least 1 m^3 per hectare and year are considered forests. The minimum patch size for an area to be a forest is 0.25 ha. This is different from the definition used by FAO in their last world forest resource assessment, FRA2000 (Anon 2001). According to FAO, all land areas not predominantly used for other purposes, where the crown cover is at least 10% and the tree height is at least 5 metres, are forests. Areas temporarily below these limits due to, e.g., clear-cutting or fire also are included. The minimum patch size is 0.5 ha.

In comparison to the FAO definition, the Swedish definition is narrower, i.e. less land areas are included. The forest area in Sweden is about 23 Mha with the national definition (Anon 2003), while the corresponding area according to FAO's definition is about 27 Mha. Areas added are mires and rock outcrops sparsely covered with trees, and alpine birch areas in the north-western part of the country.

For Kyoto Protocol reporting in general, each country's definition of forest must be selected within certain frames. The suggestion is that Sweden chooses a forest definition identical to FAO's definition. However, for reporting under Article 3.4 an additional definition of "forest management areas" must be given. Our proposal is that the Swedish definition of forest be used in this case. Whether or not productive forest areas within reserves should be reported under Article 3.4 remains an open question.

Forest and soil conditions in Sweden

The total stem volume in Swedish forests is about 3000 M m^3 (average 126 m^3 ha^{-1}); 39% is Scots pine, 42% Norway spruce, and 11% birch. The remaining 5 % is composed of other deciduous tree species such as aspen, oak and beech. The mean site capacity is around 5.3 m^3 ha yr^{-1} while the annual increment is 104 Mm^3 (Anon, 2003). This is almost 70% higher than the growth in the beginning of the 20th century. The areas of forest reserves currently increase, due to increased ambitions to preserve biological diversity.

The total carbon pool in tree biomass is about 1000 Mton C, which corresponds to an average of 45 ton C per hectare forest. There is a strong gradient, from an average of about 20 ton C ha^{-1} in the north to more than 60 ton ha^{-1} in the south. The annual gross accumulation in biomass is estimated at about 35 Mton C year^{-1}. The annual net accumulation of C in biomass is lower than the gross accumulation due to harvest removals and natural mortality. During the last decade the annual net increase has varied between 5-10 Mton C per year, depending mainly on the harvest level.

Of the forest land 66% can be classified as well drained upland soils with a groundwater table below 1 m, and 34% as poorly drained with a groundwater table closer than 1 m to the soil surface. The poorly drained soils often are peat lands with an organic horizon (histic) thicker than 30 cm. The forest area with peat amounts to about 1.8 Mha, which is 8% of the total forest area.

In the upland (drained) soils of Sweden the soil organic carbon generally occurs in an upper humus rich layer (O- or A horizon) and in the mineral soil down to at least 2 m (E, B and C

horizons). Approximately 25% of the total soil organic C stock occurs in the O or A horizon, 50% in the mineral soil to 1 m and the remaining 25% from 1 to 2 m. Additional small amounts may occur below 2 m (LUSTRA, 2002). The knowledge of the carbon distribution pattern below 2 m is very poor.

The average soil carbon pool for upland forest soils in Sweden is approximately 8.5 kg to a reference depth of 1 m (LUSTRA, 2002).

Under wet or moist conditions, i.e. a high groundwater table (0-1 m), decomposition of organic matter is hampered and soil carbon pools therefore have accumulated to a size that largely exceeds the soil carbon pool of the drained upland soils. The carbon can accumulate as a thick humus layer as well as in the underlying mineral soil. Peat layers may develop. In Sweden, peat is commonly classified as an organic horizon that is at least 30 cm thick.

The size of the carbon pool on wet and moist forest land is less well known than the carbon pools at the drained upland conditions but may amount in average from ca 15 kg to 50 kg C per m^2. Thus, a substantial part of the total carbon pool in forest soils in Sweden occurs at sites with high groundwater table.

In assessing the impact of wet or moist land on greenhouse gases also carbon losses as methane (CH_4) should be considered (e.g. Olsson et al., 2002). A wet soil may emit a small quantity of methane together with a net accumulation of carbon. Because methane has a much higher global warming potential (GWP) than carbon dioxide (ca 21:1), the net effect might be an emission of greenhouse gases, in terms of GWP, despite a net accumulation of carbon.

Large-scale inventories of Swedish forests

Sweden is well equipped with national forest monitoring programs that can be used for assessing changes in forest carbon pools. During the last decade, the National Forest Inventory (NFI) annually has comprised about 12-15 000 sample plots, about half of these in forest. Carbon related measurements within the NFI involve measurements of individual trees on sample plots and measurements of coarse woody debris. The inventory is composed of a combination of permanent and temporary plots, the permanent plots being revisited at 5-10 year intervals. On these plots, the Swedish Forest Soil Inventory (MI) is conducted. This inventory is closely related to the NFI and the two inventories share the same infrastructure. Among other things, the MI collects soil samples that are analysed for carbon. In addition to these two programs, a National Survey of Landscapes in Sweden (NILS) started in 2003. This inventory covers all parts of Sweden, and – from a carbon monitoring perspective – contributes with data from some types of areas that are currently not covered within the NFI and the MI, e.g. mountain birch forests. Below, the NFI and the MI are described in more detail.

The Swedish NFI started in 1923 as a county-wise survey focusing mainly on forests from a timber production point of view (Segebaden 1998). Over the years, there have been many changes both with regard to the scope and the design of the inventory. Especially during the last decades, many new variables have been introduced as a result of new requirements. From 1953 onwards, the inventory has been based on measurements on sample plots allocated in clusters (so called "tracts"). In 1983, permanent sample plots were introduced in addition to temporary plots, allowing for more efficient estimation of changes. At present, the time-interval between re-measurements of permanent plots is about 10 years; but in future this will be adjusted to 5 years for basic variables, including these needed to derive the carbon pools in trees.

17

From a carbon monitoring point of view, the careful measurements of trees on plots with 7 or 10 meters radii are important. From these measurements, the biomass of trees and thus also the quantity of carbon can be assessed. In addition, specific measurements of growth, mortality, and cuttings are made, as well as measurements of dead wood. This involves both standing and downed dead trees.

In total the MI comprises about 20 000 permanent plots, corresponding to the permanent plots (in forests) of the NFI. The first soil assessments on these plots were made in the period 1983 to 1987. Currently, the re-measurement interval is 10 years for the soil assessments. In general, soil pits and soil and site descriptions are made at one to two plots per tract. At each plot general site properties are described, such as vegetation type and occurrences of different species, type of soil parent material, and hydrological conditions. Specific variables are, e.g., thickness of the humus layer, humus form, soil unit (Swedish system and according to the FAO-Unesco legend) and thickness of the E horizon. The occurrence of stones and boulders is included from 2003 onwards.

The soil is sampled in O or A, E-, B-, B/C or C-horizons. For the O horizon, about 1 – 5 samples are taken per plot (depending on O horiozon thickness). The A to C horizons are sampled in one pit per plot. Samples are stored in a soil bank and analysed regarding, e.g., pH and concentration of C, N, aluminium, and exchangeable base cations. Bulk density is not determined.

The MI measures the carbon pool in the humus layer to a depth of 30 cm. Thus, peat layers below 30 cm are not sampled. However, from 2003 onwards, measurement of the total depth of peat-lands is made. Peat thickness and bulk density also have been measured by the Swedish Geological Survey, although not in a way that enables an evaluation of changes.

Until now, the NFI and the MI have been entirely field based. In the plans for the period starting 2003, estimates aided by remote sensing data will be introduced, mainly for enhancing the precision of estimates within smaller areas.

Methods for assessing changes in forest carbon pools

The underlying problem

An important part of the implementation of the Kyoto protocol is to develop methods, which are well suited for estimating changes in forest carbon pools as prescribed by the agreements. The pools included are above ground biomass, below ground biomass, litter, dead wood and soil organic carbon. When discussing different methods, it is important to note that it is not the change in the pools as such that is of interest from a climatic point of view but rather the net change of the amount of carbon dioxide in the atmosphere. The change in the amount of carbon dioxide in the atmosphere is mainly determined by the flux of gaseous carbon dioxide in and out of the atmosphere at the interface between the earth's surface and the atmosphere (omitting the direct effect of airborne vehicles' CO_2 emissions). This flux is the result of different processes in the ecosystem with photosynthesis, autotrophic and heterotrophic respiration as the dominant ones (Fig. 2). The net flux between the atmosphere and the ecosystem is called 'Net Ecosystem Exchange' (NEE) and it consists of the sum of the fluxes originating from the different processes. Typically, the flux is directed downwards from the atmosphere to the ecosystem during daytime when photosynthesis is larger than respiration and in the opposite direction during night when only respiration is ongoing.

Figure 2. Schematic figure showing the main compartments and fluxes in a forest ecosystem. (Removals due to harvesting is an additional component which is not included in this overview.)

The term 'carbon balance' often refers to a certain longer time period, and if the integrated flux is downwards during this period the ecosystem is a sink, and if the net flux is directed upwards, the system is a source. The NEE over a certain time period can in principle be measured in two ways: either by measuring the fluxes and integrating them over time or by

measuring the change in amount of carbon of all pools over the same time period. The latter has been chosen as a primary method for the reporting according to the international agreements.

Below, different techniques for estimating carbon balances are presented. First, methods based on estimation of changes in the different carbon pools are treated. This is followed by a discussion of flux measurements.

Measurement of changes in carbon pools

Assessment of changes in different forest carbon pools is the main methodological alternative identified in the international agreements (e.g. IPCC 1997). As pointed out above, this is an indirect way of estimating the NEE. Measuring changes in carbon pools can be made using many different methods. Default methods proposed by IPCC generally are based on separate assessment of emission factors and of areas, for which the emission factors apply. While, in the case of Sweden, detailed data are available from the national forest inventories, there is no need to make use of IPCC's default data. Nor it is judged to be a relevant approach to elaborate national default values, which is another methodological option. Instead, a relevant approach is to make use of existing data from the NFI and the MI. Even with these inventories, or similar inventories, there remain many methodological options regarding how to assess changes in the different carbon pools. However, regardless of method the procedures generally comprise two steps: The first step involves detailed measurements of the pools at a local scale (e.g. of the trees on a sample plot). The second step involves the scaling up from the measurements made at the local level to estimates for the entire country.

Below, the five forest carbon pools first are described in more detail, and the measurements related to these pools are outlined. Then, general aspects on sampling-based methods for the up-scaling part are given.

In all cases, our only ambition has been to quantify changes in the forest carbon pools between two time points. Thus, we do not consider the problem of what happens to harvested wood products etc. once trees have been cut and extracted from the forest.

The pools

According to the Kyoto Protocol, the following carbon pools are identified. Assessment of changes should be made for each one, unless it can be established that the pool is not a source of carbon.

- Above ground biomass
- Below ground biomass
- Litter
- Dead wood
- Soil organic carbon

The boundaries between the different pools not always are distinct. Below, it is discussed what carbon components might be part of each pool, given the current inventory practices in Sweden. The methods for measurements of the pools are described, as well as potential needs for improvements, both regarding definitions and measurement procedures.

20

Above ground biomass

This pool consists of biomass of trees - above stump height - including stem, bark, branches, and needles/twigs. For the majority of Swedish tree species, the biomass (dry matter) can be estimated using individual-tree regression functions derived by Marklund (1987, 1988) and Petersson (1999). These functions separate the biomass on stem, bark, branches, and needles/leaves. An alternative would be to use biomass expansion factors (e.g. IPCC 1997), which convert volume estimates to biomass estimates. Since such factors only in few cases make a distinction between trees of different ages (e.g. Lehtonen et al. 2003) or trees in stands of different density, application of individual-tree biomass functions is judged to be superior to using biomass expansion factors, provided data with adequate resolution are available. The data needed to use the functions typically are tree species, diameter, height, and geographical location. Different kinds of functions exist, so that the same principle can be applied under different conditions.

Currently the biomass in stumps is not considered as part of this carbon pool, due to the way the biomass functions are constructed. Moreover, the current knowledge about the amount of carbon in other above ground vegetation than trees is poor (e.g. Anon 2000). Work to include this part of the above ground pool could be motivated, although the amount is probably limited in comparison to the amount of carbon in trees. However, increasing density of trees generally implies decreasing density of other vegetation, and thus exclusion of carbon in other vegetation might lead to an overestimation of the build-up of carbon in above ground biomass when the density of trees increases (and vice versa). This would motivate the inclusion of carbon in other vegetation as well.

Below ground biomass

This pool consists of biomass in living roots of trees, and of the biomass in tree stems below 1% height (stump height). As for the above ground biomass, individual-tree regression functions for estimating the below ground biomass of trees exist (Marklund (1987, 1988) and Petersson (1999)). The functions are applied using the same kinds of basic data as for above ground biomass. However, currently functions are only available for pine and spruce, which is a limitation. In many applications, these functions are used also for other Swedish tree species.

Due to the procedures used for up-rooting trees when the material for these functions were collected (Marklund 1987), it is likely that the functions slightly under-estimate the below ground biomass.

Living roots of other vegetation than trees currently are not assessed as part of this pool according to the Swedish practices. Potentially, new procedures for soil sampling could be introduced where these roots could be sampled and measured separately.

Litter

This pool generally refers to the dead organic debris that is supplied to the soil as litter fall and root litter. It can be separated into three different pools – fine debris as leaves and needles, fine woody debris (<10 cm diameter) above ground, and root litter. Litter is generally distinguished from soil organic matter due to its low degree of decomposition or fragmentation. Litter is at least occasionally accumulated on top of the soil, but litter may also include newly died roots in the soil. Currently, the litter pool is rather poorly defined as according to Swedish large-scale monitoring practices. No measurements are carried out in the national inventories. An often problematic issue is to separate the lower parts of the litter layer from the upper parts of the humus layer (which are part of the soil organic carbon).

<u>Dead wood</u>

The definition of dead wood used in the NFI is that the diameter should be larger than 10 cm, and – in case of highly decomposed material – the stem form should be clearly distinguishable. Both standing and downed dead trees are included. On intact trees, measurements of breast height diameter and height are made, and ordinary functions applied to derive the volume (e.g. Näslund 1947). When trees are not intact, sectioning techniques are applied (e.g. Loetsch and Haller 1973). To convert from volume to amount of carbon, there is a need for conversion factors or functions. Research is ongoing in order to establish such results.

<u>Soil organic carbon</u>

The soil organic carbon pool is referred to as a mixture of dead plant and animal residues in various stages of decomposition, of substances synthesised microbially or chemically from the breakdown products, and of the remains of bodies of soil microorganisms in a more or less decomposed stage. Soil organic carbon occurs in the form of an organic distinct layer (ca. 35-45% C) on top of the mineral soil (O horizon) or blended with mineral matter (A or B horizons). Soil organic carbon is usually determined for the size fraction < 2 mm. Under wet conditions soil organic matter may occur in the form of peat layers.

The soil organic pool is difficult to delimit both upwards and downwards. Upwards, the boundary generally is set between the humus layer and the litter layer (a boundary that is not always clearly distinguishable). Downwards, a certain limit must be set from a practical point of view.

The decision on lower limit depth for carbon pool quantification is crucial. The soil carbon turnover rate is much higher in the upper soil horizons than in the lower horizons. The upper part of the soil therefore in the short run will respond more to forest management than the lower parts. On the other hand, the biggest carbon stocks are found in the underlying mineral soil, i.e. in the B horizon. The deeper the considered soil reference depth is, the more accurate the total soil carbon stock or stock change assessment is, but at the same time, the more expensive a high-precision inventory will be. Deep sampling enables a fair comparison between countries and sites with different vertical distribution of soil carbon. This can be illustrated by, on one hand, thin soils (Leptosols) where all organic carbon occurs in a 10-30 cm thick soil layer, and on the other hand, deep soils in which the same amount of soil carbon is distributed down to 1-2 m. Arguments against deep sampling are the high sampling costs and statistical uncertainties due to the measurements of low concentrations including small changes in concentration.

For Sweden, sampling of the humus layer and of the mineral soil to 0.5 m is suggested to be a good compromise. This depth would cover more than half of the total carbon pool, and the difficult sampling of the compact underlying and compact basement till is avoided.

Carbon in the humus layer can be directly sampled by taking bore cores of humus, which are weighted and analysed concerning carbon content. A problem is that large roots and stumps may prevent cores from being taken at certain spots. Quantification of carbon in the mineral soil is generally more difficult due to boulders and stones in this layer. Thus, to measure the carbon quantity in this soil layer, a two-step procedure must be followed. Firstly, soil core samples are taken at certain depths for analysis of carbon content and bulk density. Secondly, the amount of stones and boulders must be determined.

Determination of carbon in peat soils provides specific problems. It is not possible to delineate an upper part of the peat layer, e.g. 50 cm. Instead, the carbon in the whole peat layer must be determined.

Sampling methods

The NFI and the MI are based on sampling. A powerful feature of applying sampling is that is possible to estimate the uncertainty of the estimates, based on the data obtained (e.g. Thompson 1992). This stands in contrast to many of the methods used in connection with reporting greenhouse gas removals or emissions under other conditions. Some basic aspects and requirements on sampling methods are summarized below.

Objectivity

Two conceptually different kinds of sampling practices exist, one where measurement locations are selected in a subjective manner – subjective sampling – and one where the locations are determined following randomisation procedures – random sampling (cf. Thompson 1992, Schreuder et al. 1993). Although subjective procedures can be appropriate in some cases, it should be stressed that there is a severe risk of obtaining major systematic errors if such procedures are chosen. In cases when many different stakeholders are present and when there is a need for results that all parties can believe in, objective sampling is generally the solution (cf. Thompson 1992). Moreover, most of the existing sampling theory only works when random sampling is applied. Still, subjective sampling may be appropriate under conditions when very limited funds are available in order to obtain rough estimates of likely ranges of emissions or removals.

Well-defined population

Concerning carbon in trees, it is clear that the trees make up the target population. Regarding carbon in soils, the population no longer can be enumerated in distinct units, but an area frame for the sampling procedure must be used. In both cases, however, the important decision to be made is what areas should be defined as forest (if the results should only regard forests). Many different definitions exist and it is important that a clear and operative definition is used. Not least, it is important that the definition is useable from a fieldwork point of view, so that there will be no shifts between time-points regarding what type of areas are considered forest and non-forest. Such shifts would lead to biased estimates of carbon pool changes.

Strict measurement procedures

Just as it is important to have strict definitions, it is very important to have strict procedures for the measurements to be performed. Considering the carbon pools in trees, generally these are derived from basic measurements on trees, e.g. of the diameter at breast height. From the humus layer and from the mineral soil, samples are taken and the carbon quantity or concentration within these is determined in the laboratory. It this context, it is very important that the same view on, e.g., the boundary between the humus layer and the mineral soil, is maintained between different time points. Moreover, it is important that the procedures used in the lab are comparable between time points.

23

Cost-efficiency

Many different sampling procedures exist. Most of them have been derived since they, in some particular situation, have proved to result in estimates with better precision than "traditional" procedures. Thus there is a vast number of potential sampling procedures to choose between for carbon monitoring (e.g. Schreuder et al 1993). However, in many cases carbon monitoring will only be one part of some multipurpose forest inventory, like most national forest inventories of today (Lund 1998). In this case, the design of the NFI will limit the possibilities of selecting a sampling procedure efficient particularly for carbon monitoring. Still, within the framework of an NFI the specific samples taken solely for carbon estimation can be distributed in a way so that maximum precision is attained given the available budget.

Existing information of various kinds often can be used to improve the precision of estimates. One such example is use of remote sensing data.

Accurate estimates and check assessments

It is important to stress that it is the estimates of *changes* in different pools rather than the state estimates that are of prime importance when monitoring carbon pools in forests according to the Kyoto Protocol. Thus, sampling procedures must be set up that are efficient for change estimation rather than state estimation. Generally, this involves use of permanent plots. For soil sampling, use of permanent plots has some limitations since exactly the same plots cannot be used due to the destructive character of sampling in this case.

Flux measurements

Direct estimation of NEE can be made using flux measurements. Techniques for measurement of gas-fluxes from different types of surfaces have developed rapidly during the last decades (e.g. Aubinet et al 2000). The flux is often expressed as a flux density, i.e., it is expressed per unit area of an object. For flux measurements from separate components of an ecosystem, e.g., a leaf of a tree, it is most common to use some kind of chamber, which encloses the whole object under study. For measurements from whole ecosystems, micrometeorological methods are most commonly used. In the following a brief outline is given concerning the basic principles for these two types of flux measurement methods.

Fluxes by chamber techniques

The basic principle for almost all chamber measurements is simple; the object under study is enclosed in a chamber, transparent or dark depending on purpose, and then the concentration of CO_2 in the air entering the chamber, and leaving the chamber, is measured by a gas analyzer. By also measuring the mass flow of air passing the object, the flux of CO_2 can be calculated. These type of systems are called dynamic chambers and they can be 'open' or 'closed' depending on the technical solution. The main disadvantage is that the environment inside the chamber is often quite strongly affected, which in turn can affect the object itself and therefore create a bias. In advanced systems, the environment is controlled in order to avoid such biases. In static chambers, there is no circulation of the air and the flux is measured by measuring concentrations at different times and then from the rate of change of concentration per time unit and knowing air volume, the flux can be calculated. This type of system is common for measurement of flux of CO_2 from the soil (soil efflux). All soil efflux chamber measurements are hampered by the

adverse effect of pressure on the measurements plus the fact that the soil is disturbed by the chamber installment.

All methods that are based on measurement of component fluxes must be scaled up in order to achieve an estimate of NEE. This is a serious constraint and in particular, soil fluxes are difficult to scale up because of the heterogeneity of soils. It is, however, a relatively cheap method and it can be used widely giving important information about the variability of fluxes with local conditions.

Fluxes by micrometeorological methods

For studies of the planetary boundary layer, i.e., the part of the atmosphere that is in contact with the earth's surface, different methods have been developed for measurement of fluxes of heat, water vapour (evaporation) and momentum (wind friction). The sub-discipline of meteorology that works with development of such methods is called micrometeorology. The micrometeorological methods can, in principle, be used for measurement of the flux of any gas that exist in the air, i.e., methane or carbon dioxide. The methods are based on the fact that it is the wind that is carrying the 'properties' (e.g. concentration of a certain substance) that are transported between the earth's surface and the atmosphere. When the wind sweeps over the surface, mechanical turbulence develops because of the friction between the air and the underlying surface. Turbulence (which also can be caused by thermal effects) consists of seemingly chaotic wind movements in all three dimensions. This turbulent movement can be seen as parcels of air, 'eddies' that are of different size and moving with different speed and rotation. It is the vertical component of the movement of these 'eddies' that can cause a net upward or downward transport of a 'property'. However, in order for a net transport of a 'property' to take place, there must exist a difference in concentration of this 'property' in the vertical direction. If, for instance, the concentration of carbon dioxide is lower at the earth's surface compared to at some height above the surface, an eddy that is moving down will, on average, carry a higher concentration as compared to an eddy that is moving upwards. This will result in a net transport downwards of carbon dioxide. The difference in concentration with height can only be maintained as long as there is a sink or source somewhere. In the case of fluxes of carbon dioxide, the sink is caused by photosynthesis and the source is caused by respiration.

Different micrometeorological methods have been developed on basis of the principles described above. The most direct method of these is the so-called 'eddy-correlation' or eddy-covariance' method (e.g. Kramer et al 2002). In this method the vertical velocity of the respective eddies must be known together with the CO_2 concentration of the same eddies. This sounds fairly simple but it is rather complicated in practice. One problem is that the eddies have different sizes from less than metres to hundred of metres above, for instance, a forest canopy and they sometimes move with high speed. This means in particular that the sensors must be fast in response, down to typically 10 Hz, and also be sensitive enough to catch small differences. The wind speed is typically measured by a sonic anemometer, which do not have any moving parts and is very fast in response. With such sensors, the 3-dimensional movement of the wind can be measured very accurately. The CO_2 concentration is normally measured by an infrared gas analyser, i.e., an instrument that measures the absorption of light by CO_2 molecules in the infrared region of the spectrum. Recent technical development has made such instruments fast enough to be used routinely for this type of measurements. With this methodology fluxes can be measured with a time resolution of about 30 minutes. This means that the method gives very detailed information about the processes concerned and is therefore particularly suitable for

research aiming at providing a better understanding of the interaction between climatic parameters and the NEE.

With the method described above, it is in principle possible to measure a flux of CO_2 at any point in space but since in our case, the purpose is to measure the NEE, it must be placed above the forest concerned. The higher the instruments are located above the forest the larger area is covered by the instruments. It is also important to understand that the area measured by the instruments is located at a distance upwind from the sensors (because of the horizontal movement of the wind) and that the size of the area varies with conditions in the atmosphere and depends on the height of the sensors. The higher the sensors are placed above the forest, the further and larger becomes the measured area. At night when the atmosphere is stable, the measured area is larger than in daytime. The area representing each measured flux is called 'footprint'. In a typical setup, the sensors are placed, say, 5 m above the canopy and the footprint is in the range 50-300 m upwind of the sensors. This will put restrictions on the type of forests that can be measured with this method. It must be fairly homogeneous in all directions and quite large in extent.

Scaling up from individual sites to the national level would require that a large number of micro-meteorological sites be established. Due to the high costs, currently this is not a feasible approach for obtaining national level carbon budgets.

Modeling

Although models of various kinds are involved both when change estimates are obtained from sample surveys and from flux measurements, we consider these methods being based on actual measurements of the quantities of interest; the measurement parts dominate over the model parts in the assessments.

With modeling approaches, generally measurement data are only utilized for obtaining initial conditions. Then, models are used to predict the carbon stock changes for a given period of time (e.g. Mollicone et al. 2003), perhaps incorporating easily obtained weather data during this period of time as additional input data.

Model approaches can be of many different kinds. Examples of different kinds of models will be given in the next chapter.

Methodological options – analyses for the case of Sweden

In this chapter, different methods for determining the changes in carbon pools in Swedish forests are presented and discussed. It is shown what can be achieved with these methods based on the data currently available in Sweden. A separation is made between methods for estimating changes in carbon stocks in *tree biomass* and corresponding methods for estimating *soil carbon*. The carbon pools in litter and dead wood are only briefly discussed. In addition to the methods for carbon pool change assessments, eddy-covariance methods for measuring fluxes are discussed in the context of verification.

Uncertainties in estimates of changes in carbon pools

Uncertainties in carbon pool change estimates are of two different kinds. *Systematic errors* express the average difference between the true change and the estimated change, if an inventory is repeated many times. This kind of error typically stems from incorrect measurements, subjectively located sites, model errors, etc. Some sources of this kind of error can be checked (e.g. the measurement errors) and be corrected for. However, in practice it is generally impossible to determine the size of systematic errors. Instead, procedures must be chosen in order to avoid this type of error as far as practicable (e.g. IPCC 2000b).

Random errors express the variation around the average estimate, in case an inventory is repeated many times. These errors occur in sampling due to the fact that only a sample of the entire population is measured. Moreover they may be a result of variable quality of the measurements. Random errors commonly are expressed as standard errors (i.e. the estimated standard deviation of an estimate).

In case an estimate is unbiased (i.e. it has no systematic error), 95% confidence interval can be set up as the change estimate ± 2 times the standard error. This means that in about 95 times of a hundred the confidence interval will comprise the true value of the change.

According to the recommendations from IPCC (IPCC 2000b), systematic errors and random errors can be combined into a single uncertainty estimate, which is treated as a random error (although somewhat inadequate from a statistical point of view). Confidence intervals are then constructed that include both random and systematic errors. In this case, the size of systematic errors generally has to be assessed by subjective judgement.

Dealing with carbon estimates, different kinds of models are used, for example biomass functions to calculate the biomass of individual trees from basic measurements. As long as these functions provide unbiased results at the plot level, the estimated standard errors will reflect the model errors as well as the errors due to the sample selection (e.g. Bondesson 1990). This is an important example where the approach suggested by IPCC might be misleading, and where standard sampling procedures for estimating standard errors instead should be used.

In the analyses to follow, we concentrate on a formal analysis of the random errors of the change estimates, and only make subjective assessments of the likely sizes of systematic errors.

Sampling for tree biomass change estimation

With forest inventory data, changes in the total quantity of carbon in living trees between two time points can be assessed in different ways. Below, different methods are treated in more detail for the case of Sweden. The examples shown are based on data from the period 1990 to 2000. During this period, the annual increase of carbon in tree vegetation (including roots) has been 8.7 Mton C per year (in forests outside protected areas). The total amount of carbon in forest trees in Sweden is about 1 Gton C. The figures on standard errors etc. are obtained from analyses of the NFI material.

The field sampling based procedures for estimating changes in tree biomass, to be described and discussed, are:

- Summation of biomass growth minus removals, along the basic principles of IPCC (1997).

- Direct estimation of change between the end and the start of a reporting period.
  a) using temporary sample plots
  b) using permanent sample plots

- Combined estimation; using (1) and (2)

Summation of growth minus removals

In forest inventories, estimation of growth generally is made from measurement of annual rings on bore cores (Svensson 1988) as well as repeated measurements of trees on permanent plots. This typically provides a growth estimate for the last five years. Cuttings may be estimated from measurement on stumps from harvested trees. This procedure is used in Sweden, but is less common in other countries. However, most countries have industrial consumption statistics as well as figures on export and import, whereby annual harvested volumes can be estimated. In the latter case, only growth and natural mortality is estimated on a sampling basis.

In principle, this is the procedure used for Sweden's past reporting under the UNFCCC. The approach is suitable for annual reporting although a problem (seldom addressed) is that the growth figures implicitly will be based on assumptions of steady state since they are generally taken as averages for a certain period of time before the actual reporting year.

In formal terms, the basic principle is to estimate the change for a five years period, Δ, as:

$$(1) \qquad \hat{\Delta} = \sum_{t=1}^{5} \widehat{Growth}_t - \widehat{Cuttings}_t - \widehat{Mortality}_t$$

Every year in the evaluation period, growth, cuttings, and natural mortality are estimated. Since these estimates commonly are obtained as volumes, they must be converted to amounts of carbon through the use of expansion and conversion factors (e.g. IPCC 1997). Then a sum is calculated as according to equation (1). The different components can be based on the separate assessments of growth, cuttings and natural mortality that often are part of NFIs. Due to a likely under-estimation of cuttings in the NFI (e.g. Daamen 1980), it is advised that Swedish industrial consumption statistics (Anon 2002) be used for estimating harvests.

28

Regarding the precision of this method, the standard error of the estimates of yearly cuttings is generally poor; the standard error is in the order of 5-10% in NFI data. The uncertainty of industrial consumption statistics is not known, but this estimate is likely to have a somewhat smaller standard error. Growth estimates have better precision; usually the standard error is in the order 1-3% of the annual growth. Using equation (1) for estimating the total change in carbon quantity, the variance will be a sum of variances of the estimates for the single years (e.g. Cochran 1977). The standard error of the change estimate for a five-year period is likely to be in the order of 25%. In this case the standard error of the consumption statistics has been set at a level slightly better than the precision of the corresponding NFI estimate.

A conclusion is that this method results in reasonable precision, but that there is a risk of systematic errors, which may be quite large. Partly, this is due to the many conversion and expansion factors that must be applied in obtaining biomass and carbon estimates from the basic volume estimates that the method relies on. Another methodological problem is the time lag between the growth estimate and the estimate of cuttings. For a five-year period, one solution would be to use the growth figures from the inventory at the end-point of the period, while the annual harvest estimates should be summed. This would require recalculation at the end of the reporting period, of the figures reported for the single years.

Direct estimation of change between two time points

If the main objective of the change reporting is a certain evaluation period - e.g. five years long - rather than providing annual figures, forest inventory data can be used for estimating the change in carbon pools directly instead of estimating and summing annual changes. The total carbon pool is simply estimated at two different time points, and the change is taken as the difference. With this approach, use of permanent sample plots is superior to the use of temporary plots (e.g. Ranneby et al. 1987), although with a large number of plots this procedure can be meaningfully applied also with temporary plots (i.e. plots that are visited only once).

This approach can be used for assessing changes in all the different carbon pools, not only the carbon pools in trees.

In formal terms, an estimator of the change, Δ, is set up according to equation (2), where Y_2 is the carbon quantity at time point 2 and Y_1 the quantity at time point 1.

(2) $$\hat{\Delta} = \hat{Y}_2 - \hat{Y}_1$$

The estimators of Y_1 and Y_2 will depend on what sampling procedures are adopted. A generally applicable estimator of the carbon quantity at any of the two points of time is the Horvitz-Thompson estimator (e.g. Thompson 1992), which is obtained as a sum over all sampled trees, of the carbon quantity in a tree divided by the tree's probability of inclusion in the sample. With plot-based inventories such as the Swedish NFI, all trees (within a certain stratum) will have the same probability of inclusion.

Use of temporary plots
If temporary plots are used, the variance of (2) will be:

(3) $$Var(\hat{\Delta}) = Var(\hat{Y}_2) + Var(\hat{Y}_1)$$

If all plots in the Swedish NFI were temporary, and the change estimate for the five year evaluation period is based on three-year averages at the starting point and the end point, the standard error would be 18 Mton C, or about 40% of the change (an annual increase of 8.7 Mton C is assumed), which is relatively large.

A conclusion is that, as expected, use of temporary plots for assessing the changes in carbon pools in forest trees over a five-year period will result in quite unreliable estimates. However, the precision can be enhanced by increasing the number of sample plots.

In addition to large random errors, there is also a risk for substantial systematic errors when this approach is used. This is the case since small systematic errors in assessing the initial and end point carbon stock is likely to result in a large systematic error in the change estimate.

Use of permanent plots

In estimating changes, it is well known that permanent plots generally will result in higher precision than temporary plots. The background principle for this is shown below, in estimating the same quantity as above. Using permanent plots, the variance of the estimator (2) will be:

(4) $\quad Var(\hat{\Delta}) = Var(\hat{Y}_2) + Var(\hat{Y}_1) - 2Cov(\hat{Y}_2, \hat{Y}_1)$

Compared to the case of using only temporary plots, the covariance between the estimates at time point 1 and time point 2 will lead to considerably reduced variance of the change estimator. Assuming the same variance at both occasions (which will generally be a good approximation) the formula can be simplified to:

(5) $\quad\quad\quad Var(\hat{\Delta}) = 2Var(\hat{Y})(1 - \rho)$

Here, ρ is the correlation between the two estimates, which generally is very high in applications of this kind. Typically in estimating the amount of biomass, the correlation will be at least 0.9 over a five-year period and thus the variance of the change estimate will be only 10% of what it would have been, had the plots been temporary.

Assuming that all NFI plots were permanent, and that the change for a five-year period is calculated based on three-year averages at the beginning and the end of the evaluation period, the standard error of the change estimator would be only 6 Mton C, or about 13% of the change. This can be judged to be quite sufficient precision.

Compared to the case of using temporary plots only, the risk of systematic errors in the change estimate due to variable systematic errors at the two time points is reduced. This is the case since the trees are marked at the initial inventory and then revisited at the second inventory. Thus, problems with missed trees at one of the two time points can be avoided. On the other hand, there is a risk that the management of permanent plots is different from the management of the rest of the forest if these plots are too clearly marked. Thus, it is important that permanent plots be marked very discretely, so that forest managers will not be able to detect the plot locations.

A conclusion is that if all NFI plots were permanent the precision in carbon mass change estimates over a five-year period would be quite high.

Combining permanent and temporary plots

Most likely the NFI in the period 2008 to 2012 will be based on a combination of permanent and temporary sample plots. Using such a combination, the precision of the estimates will be

intermediate to the ones presented under (2a) and (2b) above. However, since the majority of the plots (two thirds) probably will be permanent, the figures will be close to the ones presented under (2b), i.e. the standard error can be expected to be about 15% of the change.

Combined estimation using a mix of permanent and temporary plots (e.g. Scott and Köhl 1994) is rather complicated from a theoretical point of view, especially when it comes to the estimation of standard errors. However, approximate methods for estimating the standard errors exist.

Concluding remarks on direct change estimation
Some concluding remarks on change estimation from repeated measurements are given below:

- With permanent sample plots, the size of random errors will be reasonably small, while with temporary plots the errors will be much larger. Calculating changes for a five-year period based on three-year averages at the starting point of time and the end point will result in quite high precision using NFI data.

- It is important that the re-measurement interval of permanent plots matches the evaluation period, otherwise the gain from using permanent plots is somewhat reduced.

- The change is estimated as a difference between two large numbers. It must be ensured that the size of systematic errors will not differ between the two time points. (Systematic errors of equal size at both time points are, however, not problematic.) The risk for changes in systematic error levels probably is much larger when temporary plots are used than when permanent plots are used, since the risk for varying levels of systematic errors in the latter case is reduced due to the coordinates of all trees being recorded.

- Check assessments should be carried out to control the size of systematic errors. To stress the importance of check assessments, a 1% difference in systematic errors between the two points of time would correspond to 10 Mton C or almost 25% of the expected change over a five-year period. Results from check assessments within the Swedish NFI (e.g. Daamen 1980), point towards systematic errors levels for biomass estimates in the order of 1-2%.

- Detailed biomass conversion factors can be applied, i.e. functions that give the amount of carbon for single trees from basic measurements on the trees. The application of biomass functions is straightforward in this case, while it is impossible to apply in the case of summing growth minus cuttings.

Sometimes, as was assumed in the examples above, there is a need to use data from more than one year to obtain reliable averages. For example, for the reporting period 2008-2012, data might be needed for the period 2007/2009 to assess the state in 2008 and from the period 2011/2013 to assess the state in 2012. In such cases, there will be a delay in the reporting due to the need to wait for data from the year after the end of the reporting period. Another possibility would be to instead assess changes on the basis of data between 2006/2008 and 2010/2012 and by extrapolation correct for the slight mismatch.

Finally, the size of random errors can always be reduced by increasing the number of sample plots. However, there is a limit beyond which further decrease of the size of random errors is not meaningful, since the systematic errors will then tend to be very large in comparison to the

random errors. Thus, dimensioning of inventories should not aim solely at reducing the statistical errors (random errors), but also at controlling the size of systematic errors by adequate use of control procedures, such as control inventories.

Combined estimation

In cases when different estimates are available for the same parameter – in this case the total change in carbon stocks over a certain period – the different estimates can be used in two principally different ways:

- Verification
- Combined estimation

In the first case one of the figures is considered superior, and the other(s) used for verifying the plausibility of the first figure.

In combined estimation, different estimates of a certain quantity are consolidated into one single estimate. For example, if estimates are obtained both using the "growth minus removals" approach and direct change estimation, the two estimates can be combined into a single estimate in a way that minimizes the variance (cf. Raj 1968, Ståhl 1992). For combined estimation to be meaningful, the different single estimates should be reasonably unbiased, and their variances should be possible to estimate. With sampling based approaches, these criteria generally are met.

A combined estimator is set up according to (example for the case with two different estimates available):

(6) $$\hat{\Delta}_c = a\hat{\Delta}_1 + (1-a)\hat{\Delta}_2$$

With uncorrelated estimates of equal precision, the variance of the combined estimator will be only 50% of the variance of any of the two separate estimators (e.g. Raj 1968).

The details of how to set up a combined estimator have not been explored in the case of estimating forest carbon pools. Application of combined estimation – using estimates from methods 1 and 2 as input – would require some further development before it could be implemented. However, with combined estimation there is a potential to further improve the precision of carbon change estimates. Considering a case where two thirds of the NFI plots are permanent, it is likely that the increased precision from combined estimation would be quite limited. A coarse estimate is that the standard error would be about 5 Mton C or 10% of the change.

Sampling for soil carbon change estimation

Assessing changes in soil carbon pools with sampling approaches follows the same principles as outlined above for assessing changes in biomass. The pools are assessed repeatedly and the change taken as the difference between two subsequent assessments. However, for soils there exists no counterpart to the "growth minus removals" approach for biomass, since inputs and outputs of carbon from the soil system cannot be measured without applying very advanced and expensive methods.

Depending on soil layer, different methodological approaches are used for assessing the carbon stock. The approaches apply to the methods used in the Swedish Forest Soil Inventory (MI).

- For carbon in the humus layer, sample cores are taken by random sampling. The dry weight of humus per unit area of forest land is determined and from lab analyses the mass of carbon per dry weight unit of humus is estimated.

- The amount of carbon in peat soils currently cannot be determined, since no cores are taken from different depths of the peat soils. Further, measurement of the depth of peat layers (below 1 m depth) in the MI has started only in 2003.

- The amount of carbon in mineral soils is assessed by taking soil samples at different depths from soil fraction < 2 mm. The carbon concentration in these fractions is determined in the lab.

In the following, the accuracy of estimates of changes of carbon in humus and mineral soils based on MI data is discussed. No analyses are provided for carbon in peat lands due to lack of data.

Carbon stock changes in the humus layer

Analyses of changes in humus layer carbon can be made based on repeated sampling of plots. The re-measurement interval currently is 10 years. In total about 3000 plots in the whole country (and about 1000 plots in southern Sweden) has been included in the analyses presented here. Each basic sample plot has a radius of 10 m. About 3-5 small sample cores per plot were acquired and merged into a composite sample, which was then analysed for carbon concentration in the lab.

The humus layer carbon stock at an individual plot is obtained as:

(7) $$C_{stock} = C_{conc} \cdot D \cdot L \cdot A$$

Here, C_{stock} is the stock of carbon on a sample plot, C_{conc} the concentration of carbon in the humus layer, D the bulk density of the humus, L the average depth of the humus layer on the plot, and A the area of the sample plot. Roots and similar material thicker than 2 mm are removed from the cores, and thus not included in the analyses. To derive overall national level estimates from the plot values, standard sampling theory are applied to the specific design of the MI (e.g. Ranneby et al. 1987).

However, no formal analyses of carbon stock changes, covering the entire country, have been made for the humus layer carbon. Instead, results from investigations limited to certain soil types are used to conclude what sample sizes would be necessary to detect changes in the humus layer carbon stock.

The standard deviation of plot-wise values of changes was found to be 1.2 kg C m^{-2} for the whole country and 1.4 kg C m^{-2} in southern Sweden – equal to a coefficient of variation around 50%. From these values approximate 95% confidence intervals were constructed (Fig 3). Half the (expected) length of a confidence interval was plotted versus the number of plots.
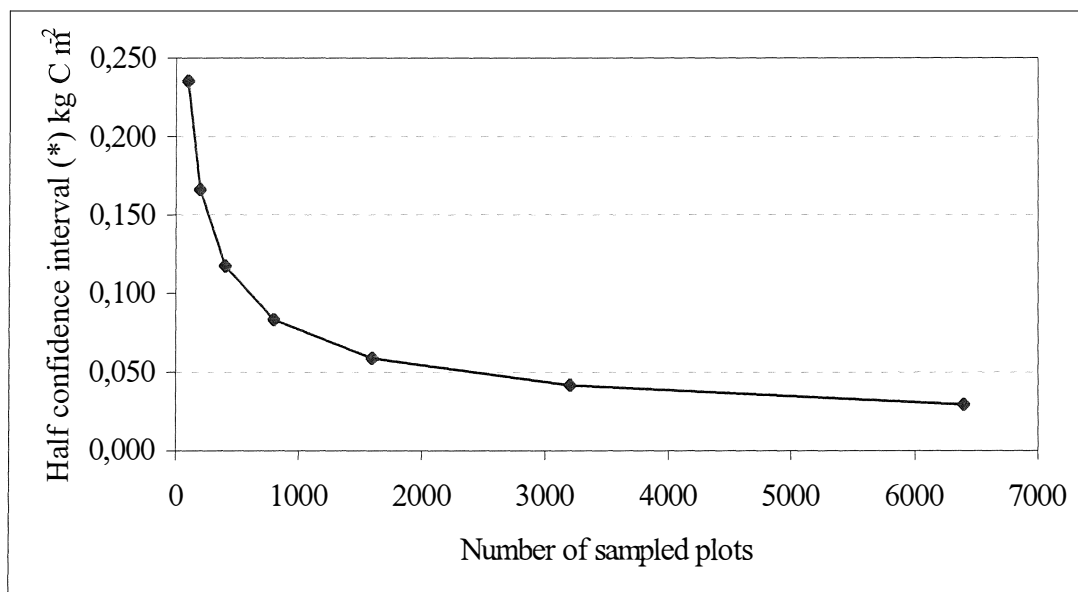
Figure 3. The approximate relation between the confidence interval and the number of plots used (for a STD of 1.2 kg m^{-2}).

We can assume an annual increase in humus-layer C content that might amount to 0.5-1.0% of present stock, at least in southern Sweden. This value is based on repeated measurements in the MI, modelling by COUP and by results from the soil model YASSO in Finland (LUSTRA 2002). The mean content is about 2-3 kg C m^{-2}. Consequently, the possible change that should be verified is about 0.02 kg C m^{-2} year^{-1} or 0.10 kg C m^{-2} for a 5 yrs monitoring period. From Fig. 3 it can be deduced that 700 plots would result in a confidence interval of about ± 0.099 kg C m^{-2}, i.e, the change would be significantly larger than 0.

Based on 3000 plots for 3 million ha in southern Sweden we can for a 5 yrs period assume a change of 3 ± 1.5 Mton C. This conclusion requires that sampling procedures and analytical methods are equal between the two different sampling periods, so that there are no distortions due to varying levels of systematic errors. Potential sources of systematic errors in this case are:

- The selection of humus sample cores may not be entirely objective. Specifically, some sample locations (e.g. close to stumps, large roots or boulders) may be impossible to assess.

- The boundaries between the litter layer and the humus layer, as well as between the humus layer and the mineral soil layer, are difficult to determine. The principles for determining these boundaries may vary between surveyors as well as between years.

- Difficulties to separate dead and living roots during sampling preparation

- Erroneous estimates of bulk densities, particularly in compact subsoil horizons

- Carbon analyses – particularly change in method during the monitoring period, sometimes due to small sample volumes and poorly homogenised samples.

Carbon stock changes in the mineral soil

At about 3500 plots within the MI survey, soil pits are dug and soil samples taken from various depths and layers in the mineral soil. However, the analyses of these samples only comprise soil fractions finer than 2 mm. Measurements are repeated at 10 yrs intervals from the same plots; the new soil pit is dug at a few metres distance from the old one at a given plot.

The C stock on a plot, in a given layer or horizon, can be obtained as:

$$(8) \qquad C_{stock} = C_{conc} \cdot D \cdot f \cdot L \cdot A$$

In this formula, C_{stock} is the stock of carbon per area unit, C_{conc} the concentration of carbon in < 2 mm fraction, D the bulk density of the < 2 mm fraction, f the proportion of soil volume < 2 mm in the layer studied, L the depth of the layer, and A the area of the sample plot.

So far, no comprehensive analyses of carbon stock changes in the mineral soils have been carried out on the Swedish MI data. This is due to the many problems that remain in determining bulk densities of the fractions analysed, and to infer the total carbon stock at a site where samples have only been taken within a few specific mineral soil horizons. Thus, the sample size discussion below is largely hypothetical. It is based on information of variation in C concentration from one measurement only.

Since L and A in formula (8) are constants, the coefficient of variation (e.g. Cochran 1977) for the plot level values of carbon in the mineral soil can be approximated as:

$$(9) \qquad CV = \sqrt{CV_C^2 + CV_D^2 + CV_f^2}$$

Here, CV_C is the coefficient of variation for carbon concentration, CV_D is the coefficient of variation of the bulk density of finer fractions, and CV_f is the coefficient of variation of the proportion of soil volume finer than 2 mm.

In general, with a variation coefficient of 30% for bulk density, 40% for the proportion of fine material, and 80% for carbon concentration, the total CV at the plot level would be around 95%.

A 0.5% annual change in amounts of C in the mineral soils is assumed. This change is slightly less than the one in the humus layer (see above) and reasonable at least in southern Sweden. The present mean content in mineral soils to a depth of 0.5 m is around 4 kg C m^{-2}. Consequently, the possible change that should be verified is 0.02 kg C m^{-2} year^{-1}. During a 5-year monitoring period this corresponds to 0.10 kg C m^{-2}. These assumptions were inserted in formula (4) assuming the covariance between the estimates at time point 1 and time point 2 to be 0.7 when estimating a change over a five-year period For a sampling density of 3200 samples the 95% confidence interval would be the estimate ± 0.095 kg C m^{-2}, thus enough to verify that the change in carbon stock is larger than 0. A sampling density of presently around 3500 samples in Sweden gives a change of 0.10 ± 0.08 kg C m^{-2}.

However, this calculation has not considered systematic errors between sampling occasions whereby the uncertainties might be very much increased.

Sources of systematic errors in carbon stock estimation in mineral soils

Many problems remain regarding how to assess carbon stock changes from repeated measurements in the mineral soil.

Determination of the proportion of coarse material is a major uncertainty in countries where glacial tills or similar soil types dominate. Little data on this issue seem to occur in the Nordic countries. In Norway, NISK roughly estimate the stone and boulder content to 30%. However, the variation between sites was extremely large. In Sweden, the technique with stone index according to Viro or Tamminen is commonly used.

Determination of bulk density is less problematic. However, knowledge and techniques for assessing bulk density in deep layers are poor.

Another problem is the definition and recognition of dead organic matter under decomposition. Living roots of any size is not included in the soil organic pool. However, it is generally difficult to separate living roots from recently dead roots when the tissue structure is still preserved. Different scientists have different tradition to separate living root-C from dead organic-matter C. Also, the practise to include coarse organic matter seems to be different among scientists. By definition it should be included in the soil organic matter C-pool, but sometimes it seems to be excluded in the sieving process, i.e. before analysis the soil is passed through a 2mm sieve and coarser material is excluded.

To conclude, some major potential sources of systematic errors are:

- Erroneous assessment of volume coarse material, i.e. stones and boulders that are not included in the soil samples, but either neglected, guessed or estimated by other techniques.

- Inconsistent identification of soil horizons or reference depth – particularly if there is a change in field staff between the measurements.

- No sampling beneath stones and big roots (slight underestimation of C concentrations)

- Erroneous estimates of bulk densities, particularly in compact subsoil horizons.

- Overestimation of organic C on calcareous soils (minor problem in Sweden)

- Carbon analyses – particularly change in method during the monitoring period, sometimes due to small sample volumes and poorly homogenised samples.

Spatial variation and sampling density

It is of interest to know the spatial autocorrelation in data when designing sampling surveys. A study carried out with the LUSTRA research programme at Knottåsen in Sweden (Fig. 4) indicated that the autocorrelation was very low for distances longer than 3 m for O horizons and 20 m for mineral soil horizons (B horizon). For the mineral soil horizon, the autocorrelation was limited even at short distances. However, these results depend on the scale at which the processes are observed, and the reliability of data obtained in single samples. For example, measurement errors will decrease the autocorrelation.
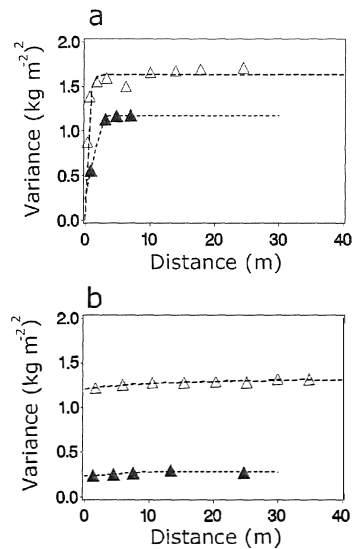
Figure 4. Variograms for moist and fresh classes: (a) O-horizon; (b) B-horizon. Moist and fresh classes are indicated by empty and solid symbols, respectively.

Apart from spatial variation of carbon concentration in fine soil (< 2 mm) one should also consider the spatial variation in bulk density and content of coarse mineral material, i.e. stones and boulders. However, this variation is probably smaller than for the concentration of C.

There is not very much information on the spatial variation of stones and boulders. A study from glacial till in central Sweden (Eriksson & Holmgren, 1996) showed that the variation coefficient was in the range 25 to 75%, with a mean around 40%. The study was conducted by measuring the volume percentage of material > 2 cm in 5 sample plots 0.5 x 0.5m at each one of 10 different sites.

Stratified sampling for improving carbon stock change estimation in soils

Within the MI, soil samples are taken at rather few plots due to the high costs associated with the fieldwork and the subsequent analyses in the lab. Thus, in this case it could be wise to consider the opportunity to allocate the soil sampling effort to the plots, within the MI, where they are most useful, i.e. where they contribute most to the precision of the assessment of change in soil carbon over a given period. One approach to solving this would be to use the principle of stratification (or two-phase sampling for stratification, e.g. Thompson (1992)) to allocate the soil sampling efforts in an optimal manner. The basic principle would be to stratify the existing MI plots based on characteristics that are believed to covariate with soil carbon change, and then allocate sampling efforts to the different strata in proportion to the expected variability of carbon changes. Below, a general presentation of the principle first is given. Secondly, an example is

given based on rather crude assumptions regarding the variability in soil carbon changes between different kinds of soils.

Allocating Observations to Strata

Given a total sample size *n,* one may choose how to allocate it among the strata. The interest is in finding the best choice of sample sizes, n_h, in each stratum to obtain the best precision. If each stratum has the same size and there is no prior information about the population, a reasonable choice would be to assign equal sample sizes to the strata, so that for stratum *h* the sample size would be

$$(10) \qquad n_h = \frac{n}{L} \, .$$

This corresponds to *proportional allocation.* If the strata differ in size, proportional allocation could be used to maintain a steady sampling fraction throughout the population. If stratum *h* has N_h units, the sample size allocated to it would be

$$(11) \qquad n_h = \frac{n N_h}{N} \, ,$$

where *N* is the population size. When the strata are large enough, the population standard deviation under proportional allocation is usually smaller than the standard deviation achieved with ordinary simple random sampling.

The objective in sampling generally is to gain the most information possible for the least cost. Let *C* represent the total cost, c_0 represent overhead costs, and c_h represent the cost of taking an observation in stratum *h*. The objective is to allocate observations to strata in order to minimize the variance for a given total cost *C* or to minimize *C* for a given variance. If we suppose that the costs $c_1, c_2, \cdots, c_L$ are fixed than the allocation scheme, which estimates the population mean or total, with the lowest variance for a fixed sample size *n* and fixed cost under stratified random sampling is *optimum allocation*:

$$(12) \qquad n_h = \frac{n N_h S_h / \sqrt{c_h}}{\sum_{k=1}^{L} N_k S_k / \sqrt{c_k}} \, ,$$

where S_h is the population standard deviation in stratum *h.* This leads to the following rules. In a given stratum, take a larger sample if

1. The stratum is larger.
2. The stratum is more variable internally.
3. Sampling is cheaper in the stratum.

If the standard deviations are more or less equal across all the strata, proportional allocation is probably the best allocation for increasing the precision. In cases where the S_h varies greatly, optimal allocation can result in increased precision. Optimal allocation is of course only possible when we have some prior information about the standard deviation in each stratum. In the case of monitoring soil carbon stocks, it is likely that the standard deviations of carbon stock changes vary between different soil types, e.g. peat soils and upland soils.

A case study was conducted to study what could be achieved by using stratified sampling for estimating the change in the soil carbon pool in Swedish forests. In this case, the population (all soils) can, e.g., be stratified into podsols on well-drained soils, brown forest soils at well-drained conditions, thin well-drained soils, and soils under wet or moist conditions. However, to keep the example simple only two strata were identified: well-drained soils and peat-lands.

There are 591 measurements for the carbon stock changes on well-drained soils from 1983-1987 to 10 (or 11) years later from the MI. The mean carbon stock changes for these measurements are 0.2864 kg/m^2 with standard deviation 2.767.

Two datasets were constructed, each with 745 simulated measurements for the carbon stock changes on peat-land for the same time period as there were data available for well-drained soils. The mean carbon stock changes in these 2 datasets were 3.1034 kg/m^2 with standard deviation 4.1480 (dataset 1) and 9.1153 kg/m^2 with standard deviation 2.6960 (dataset 2).

Assume a random sample of 100 observations of carbon stock changes (kg C/m^2) with proportional allocation. Since $N_1 = 591$ and $N_2 = 745$, we get $n_1 = 44$ and $n_2 = 56$. The estimated mean value of the carbon stock changes ($\overline{C}$) and the estimated standard deviation (s) of $\overline{C}$ for the two different datasets with simple random sampling (SRS) and stratified sampling became:

Table 1. The precision in change estimates using stratified sampling and simple random sampling.

	$\overline{C}$ (SRS)	s (SRS)	$\overline{C}$ (Strat.)	s (Strat.)
Dataset 1	1.7562	0.3947	1.5127	0.3356
Dataset 2	4.7926	0.4389	4.8216	0.2512

As seen in Table 1, stratified sampling gives a lower standard deviation, 15% for dataset 1 and 52% for dataset 2, compared to SRS. Thus, the case study indicates that stratified sampling would be a means of improving the precision considerably within soil monitoring programs.

Modelling approaches based on survey data

The preceding sections have treated cases where carbon stock changes were estimated from repeated measurements, or from separately assessing growth and removals of biomass. In these cases sampling data have been used to assess the changes in the carbon pools. To some extent models have also been involved, for example for converting basic measurements on trees to

39

biomass (e.g. Marklund 1987). However, these models have generally played a minor role in the analysis.

Moving one step further, models can be used as a major component in analyses of carbon stock changes. Moreover, the models can be applied directly to data describing the present state of forests; thus there is no need to make repeated measurements.

In general, it can be argued that very precise repeated measurements always will give the best estimates. However, the costs for applying models may be much lower, and some potential sources of systematic errors in repeated measurements can be avoided. The choice between applying models or repeated measurements should be made considering the cost and accuracy of the approaches (cf. Ståhl 1994).

Below, separate sections are devoted to model based assessment of changes in the 5 carbon pools to be reported under the Kyoto Protocol.

Model based estimation of change in above ground biomass carbon

The baseline approach in this case would be to separately estimate gross growth, natural mortality, and removals due to harvesting. Overall changes in biomass then would be converted to change in carbon. The basic data upon which the models would be applied would be data from the NFI.

Gross growth can be estimated with many different models (e.g. Ekö 1985, Söderberg 1986). In case models for single trees are applied, static individual tree biomass functions (Marklund 1987) can be used to obtain growth directly in terms of biomass rather than volume. Most Swedish growth functions have been established to provide growth for a 5 yrs period. Even if the functions of the above kind are known to be rather accurate on average, large fluctuations in growth appear between different years.

Specific functions (e.g. Söderberg 1986, Fridman & Ståhl 2001) can be used for estimating the natural mortality. For natural mortality, there is an even larger variation between years as compared to gross growth.

Removals due to harvesting typically would be taken from industrial consumption statistics (Anon 2002), rather than from models. The accuracy of such figures is unknown, but probably reasonably high.

The overall accuracy of a modeling approach of the above kind is difficult to assess. It might result in quite large systematic errors for a five-year evaluation period.

An advantage with modelling approaches is that yearly values easily can be derived. Such values are needed although the reporting period for the Kyoto Protocol is five years.

Model based estimation of change in below ground biomass carbon

Presently, no specific growth functions are available for estimating the growth of below ground biomass. However, applying individual tree growth models (Söderberg 1986) together with biomass functions (Marklund 1987), the gross growth of below ground biomass of trees can be

estimated. Alternatively, a fixed ratio between above and below ground biomass can be assumed, and any kind of model for the growth of above ground biomass be used for assessing also the growth of below ground biomass.

Assessment of this pool also needs to consider natural mortality of trees and harvests. In both cases the roots will die and thus be part of another pool. These components need to be assessed along the same lines as above ground biomass.

Model based estimation of change in dead wood

Creation of new dead wood can be modelled using mortality functions (e.g. Söderberg 1986, Fridman & Ståhl, 2001). The likely amount of dead wood left in the forest after harvesting can be obtained from the NFI.

However, presently only very crude models are available regarding the decomposition rates of dead wood.

Model based estimation of change in litter and soil organic carbon

Models for predicting litter and soil C changes are either ecosystem models that consider different C fluxes in the entire ecosystem or decomposition models that focus on the turnover over the soil C pool. Examples on ecosystem models are the CO2Fix model developed at EFI in Finland (Masera et al., 2003) or the Coup model developed at the research program LUSTRA in Sweden (Jansson and Moon, 2001). The CO2Fix V.2 is a multi-cohort ecosystem-level model based on carbon accounting of forest stands, including forest biomass, soils and products. Carbon stored in living biomass is estimated with a forest cohort model that allows for competition, natural mortality, logging, and mortality due to logging damage. Soil carbon is modeled using five stock pools, three for litter and two for humus. The Coup model is a process based model driven by abiotic factors.

Examples on decompopsition models are Yasso (e.g. Liski et al. 1999, Liski et al., 2003b) and the Q model (Ågren and Hyvenön, 2002). However, decomposition models need to be supplemented with data on biomass and litter production. The potential use of models in combination with micro-meteorological measurements is further described in the section "Carbon fluxes – eddy covariance measurements and modeling".

A limitation with most of the models is that they do not pay full attention to the distribution of carbon fluxes to and from the various different soil horizons. This reduces the reliability and usefulness of models to predict changes. The reason is that the carbon pools in different horizons are affected by different conditions and thus respond on management and environmental changes in different ways.

Concluding remarks on modeling

Many different kinds of models can be applied for assessing changes in carbon pools. Some of them were outlined above. In addition, modeling approaches in connection with eddy covariance measurements will be treated in a later section.

Moreover, although this report focuses on methods for change estimation based on current and past data, it is important to point out that scenario analyses are important tools for being able to act pro-actively with issues related to carbon sources and sinks in forests. To make such analyses, forecasting models of various kinds are needed.

Whether or not the forest ecosystem is a source or a sink is a result of complex ecological and socio-economical interactions, where tree growth and soil processes act on the one side, and the processes that lead to management decisions such as harvesting act on the other side. In Sweden, projects such as Heureka (e.g. Lämås and Eriksson 2003) and LUSTRA (e.g. LUSTRA 2002) aim at developing tools that can be applied for this kind of integrated analyses.

Remote sensing aided carbon change estimation

Use of remote sensing data is often proposed as a means to improve the accuracy of estimates of carbon pools and fluxes. In this section, some procedures for remote sensing based estimation are outlined, and possibilities and problems are discussed. The challenge in the Swedish case is to improve the estimates that are obtained using field sampling only. Since these have reasonably high accuracy, as described above, a major issue is to avoid introducing systematic errors when incorporating remote sensing data in the estimation procedures.

Use of remote sensing offers many possibilities; a comprehensive coverage would require a separate report. Thus the treatment is limited to a few cases where medium resolution satellite remote sensing (SPOT, Landsat, Terra MODIS) is combined with field sampling in a statistical manner. In addition, comments on other kinds of applications are given.

One important basis is that remote sensing alone seldom is very useful for biomass estimation and similar purposes. Almost always, there is a need for field reference data, so that the specific spectral signature can be given an interpretation (e.g. Tomppo 1993, Olsson 1994, Nilsson 1997).

Possibilities and problems

Theoretically, the combination of remote sensing and field data is by no means complicated. Many methods exist, e.g. stratification, multi-phase, or multi-stage sampling (e.g. Cochran 1977). However, working with satellite imagery for deriving estimates for forests we face a number of practical problems:

- The geometry of images as well as the level of precision of geo-referencing with GPS-equipment implies problems to tie an individual pixel in the image to a specific field reference plot. Mismatches may in some cases lead to biased estimates.

- In pixel-based image estimation approaches we also face problems with mixed pixels, especially when some of the features in a pixel have much higher reflectance than others. Field reference data for mixed pixels seldom are available to cover all cases that may be encountered.

- Our existing digital maps only provide rough estimates of what areas are forest and what areas are non-forest. Thus, to derive estimates for forests based on image data, classification procedures must be adopted. In general, it is problematic (impossible

42

without a proper set of field reference data!) to set up classification procedures that lead to unbiased area estimates. This is a common problem, and source of mistake, in cases when satellite imagery is used for deriving statistics for some larger region (cf. Bååth et al. 2002)

Different methods

Three different approaches to utilizing satellite data for change estimation will be discussed:

1) Stratification
2) Ratio- or Regression estimation
3) kNN estimation

Stratification

A simple and robust approach of using remote sensing auxiliary data is to perform stratified sampling or post-stratification (e.g. Thompson 1992). In this case, all pixels or segments of pixels from the image are classified as belonging to a certain stratum, and the fieldwork may then be allocated in an efficient manner to these. The general principle is that strata with large internal variation receive large samples.

If a network of plots already exists, like the case with the Swedish NFI, post-stratification can be applied. Post-stratification will generally not be as efficient as stratification, since there is no longer any opportunity to allocate the plots in an efficient manner. Nevertheless, post-stratification may lead to major enhancements in the precision in comparison to using field data only.

A pilot study was conducted (Ståhl et al. 2002) to evaluate to what extent post-stratification increases the accuracy of estimates in comparison to using field data only. Three different procedures were compared in a region corresponding roughly to the county of Västerbotten:

- Stratification using image segments (clustered pixels with equal properties) with 1 ha minimum size (derived from Landsat TM)

- Stratification using segments with 5 ha minimum size (derived from Landsat TM)

- Stratification based on Terra MODIS pixels, 25 ha large.

With small segments, the theoretical efficiency can be expected to be high, whereas the amount of practical problems arising from assigning plots close to a boundary to a certain segment also can be expected to be high. With larger segments, the practical problems will be less pronounced. The motivation for also using entire MODIS pixels as units in the stratification was the simplicity of such a procedure, especially the simplicity whereby the stratification for a large region can be set up. However, since a certain reflectance value does not imply the same forest conditions in different eco-regions, stratification based on MODIS should also be based on some broad delineation of eco-regions with similar forest conditions within them.

Compared to using NFI field data only for the estimation within the region, the standard errors for key parameters were reduced with 20-50% using post-stratification. The best results were obtained when the segmentation was based on Landsat TM data, and segments down to 1 ha in size were allowed. Examples of results are shown in Table 2.

43

Table 2. Standard errors of biomass estimates for all tree species, for deciduous trees, and for dead wood using NFI data only and using different kinds of post-stratification.

Method	Total St err (%)	Deciduous St err (%)	Dead wood St err (%)
NFI	5,4	9,2	11,5
MODIS*	3,6	6,7	9,5
Landsat, 5ha	2,9	6,6	8,5
Landsat, 1ha	2,8	6,6	8,3

The above study concerned state estimation, in contrast to change estimation. Taking the figures in the table as valid for the entire country, the estimates of change would also be improved using post-stratification. However, at the national scale the gain in precision would be less pronounced. Thus, use of remote sensing auxiliary data mainly can be motivated from the point of view of obtaining accurate estimates for smaller regions.

The relative efficiency of using permanent plots will be somewhat reduced when stratification is applied. This is due to the strata being similar, and thus the correlation between the states on a plot at two different time points will be lower. The magnitude of this depends on how homogeneous the strata will be.

Ratio- or Regression estimation

A similar use of satellite data as in the case of stratification could be used also for purposes of ratio- or regression estimation (e.g. Cochran 1977). In this case, some crude estimate of the total carbon quantity in each segment should also be derived, and used as auxiliary information. Although not studied, it is likely that such procedures would lead to slight improvements in comparison to stratification, without risking any (major) bias.

In the context of regression estimation, a study by Myneni et al. (2001) will be used as a basis for a further discussion on potential risks with satellite-aided carbon change estimates. In this study, satellite data were used for estimating the carbon sinks in forest vegetation in northern regions; the result of the study was that the sink is much larger than previously expected.

In the study, regression models were developed linking satellite spectral values to certain values of carbon pools on the ground. Regression functions of this kind typically show quite large random variability; this variability by no means is entirely random, but the errors are likely to be very much spatially correlated – implying that estimates for a certain region may have systematic errors. To estimate the total carbon pool over a large area, the regression models were applied to all pixels covering that area. In the specific study, the target area was a major part of the northern hemisphere.

If state estimates are made at two successive time points, the change in carbon pools can be estimated. This was the approach adopted in the study. Thus, even small systematic errors of carbon stock estimates may have large impact on the change estimates. For example, in Sweden the carbon stock in the forest vegetation is about 1 Gton C. A 10% systematic error implies 100 Mton C. If a change estimate is based on the difference between two state estimates, one of them being 10% biased; the change estimate will be extremely biased.

44

In addition to the general problems outlined above, e.g. that we do not know from the satellite images what areas are forest, there are certain other problems present in an application of this kind as well:

- A certain spectral value in a satellite image means different things in different parts of a region, a nation, or the world. In the study, in addition to spectral values latitude was incorporated in the regression models for assessing the total biomass. Thus, implicitly it was assumed that, given a certain spectral value, the biomass in forest vegetation is the same in different parts of the world sharing the same latitude. With field samples objectively balanced over the entire region to be assessed, this might not be a problem. However, it is a major problem when the conditions are different in the areas where field data are available compared to the conditions in areas where field data are not available.

- With large pixels like the ones used in the study (order of 1x1 km), most pixels will be mixed, i.e. they contain both forest and other land-cover classes. Thus, other land-cover classes than forests contribute to the spectral values in an often poorly known manner. This causes the regression functions to be even more uncertain. In addition, the impact of other land-cover classes may be different in different parts of the world, which adds to the unknown bias of the estimates.

kNN estimation

In recent years kNN estimation (Tomppo 1990, Nilsson 1997) has become a popular method for various purposes of estimation using medium resolution images. The principle is that field data are assigned to all pixels in an image, based on the nearness in the spectral feature space, between the pixel of interest and all the pixels for which field reference data are available.

The kNN method is straightforward to apply, but it is quite difficult to assess the formal properties (bias, standard error) of the resulting estimates. Especially since it is difficult to control the systematic error component, use of kNN for purposes of monitoring changes is carbon stocks is not recommended in case there is an option to derive high-precision unbiased estimates from field data only. Of course, with only limited amounts of field data available, kNN or similar techniques would be meaningful.

Modeling NEE with satellite data

Today there is no remote sensing based method that can estimate NEE from satellite data only. In this context satellite data have mainly been used to estimate leaf area index, which is a key parameter in most causal models. Leaf area index may be estimated using remotely sensed data, in particular for agricultural vegetation and grasslands but also to some extent for forests. The relationship between a reflectance index, NDVI, and leaf area index is fairly strong and general for agricultural crops and deciduous forests but does not work well for coniferous forests. However, there are other indices, which are promising also for conifers (Eklundh et al., 2001). It is realistic to assume that leaf area index can be obtained from remote sensing, although it is known that images are saturated at rather low index values, and it is difficult to separate high values from intermediate values of leaf area index.

Another option is to estimate NPP (Net Primary Productivity) using satellite data and then combine this with a model for heterotrophic soil respiration in order to obtain NEE. It is well

known that photosynthesis is strongly correlated to the amount of light absorbed in the visible part of the spectrum. On basis of this, Monteith (1972,1977) introduced the so-called Production Efficiency Method (PEM), which is very simple and well suited for exploiting reflectance data provided by satellites. In PEM, NPP is estimated as the product of an efficiency coefficient, times the amount of absorbed radiation (APAR) minus the maintenance respiration. The APAR can be estimated from satellite reflectance data while the efficiency coefficient must be determined from empirical data. The latter is probably dependent on stress factors such as soil moisture deficit and high and low temperatures. Attempts have been made to correlate the efficiency coefficient with threshold values of vapour pressure deficit and temperature and there is some promise in these attempts. However, more work must be done to develop this concept before it can be used for operational purposes.

Conclusions regarding the use of remote sensing

In countries like Sweden, where a network of permanent forest inventory plots exist, the basic estimates of change using field data will generally have reasonably high precision. In this case crude regression-type estimates based on satellite data generally are not very useful, since they are likely to have lower accuracy. For example, the sizes of systematic errors are generally unknown.

Still, satellite data may be used to improve the quality of the estimates under these conditions, but care must be taken in order to use procedures that do not lead to deteriorated estimates. One possibility to improve estimates in this case is post-stratification, where image data are first segmented to reduce the problem of mismatches between satellite and field data.

On the other hand, in countries void of other forest inventory data, use of satellite information can, of course, be very useful for obtaining estimates of, e.g., afforestation, reforestation, and deforestation.

Carbon fluxes – eddy covariance measurements and modelling

Even if the NEE can be measured very accurately for a single stand with the eddy covariance method it is still not feasible to have enough systems so that scaling up to national level becomes meaningful. The costs for such micro-meteorological measurements of this kind are too high.

It is, however, interesting to use such systems in combination with modeling. The fluxes measured by a number of eddy covariance systems can be used to test, develop and calibrate different models, which then in turn are used in conjunction with other available data to scale up to the required area. This will give a large flexibility and the models can be adapted to the type of data available. It also allows building up a prediction system where for instance different scenarios for management aiming at increasing the sink strength can be tested or the effect of future climate change on the carbon balance can be analyzed and quantified. Another advantage with a modeling system is that the carbon balance can be estimated with much higher time resolution as compared to an inventory based system. This means that the annual development, or even monthly or daily progress can be followed.

A scheme for how such a model-based system could be built up is shown in Fig.5. It is recommendable to use different types of models and also to base the up-scaling on different type

46

of data. This will provide a range of estimates for the NEE of Swedish forests, which will give an indication of the uncertainty of the estimates. In a first step, the models shall be tested against measured NEE data by eddy covariance at as many sites as possible. Here, historical data can be used and also data from other sites than Swedish, especially those from other Nordic countries where site conditions are comparable. Today, there are flux measurements ongoing in ca. 15 Nordic forests and many of them have multi-annual time series of data. In this step of the scheme, local weather data is used if the model requires that as input. In the second step, after the models have been verified and calibrated, up-scaling to the Swedish forest will take place. Depending on type of model, either forest inventory data or remotely sensed data can be used. In both cases additional information about soil conditions will be needed. If the model requires weather data as input, such data can be provided by a regional climate model driven by analysed data. Such a model is available in Sweden through the Rossby centre at the Swedish Meteorological and Hydrological Institute (SMHI). The model gives weather data with a spatial resolution of 44 km and a temporal resolution of 6 hours. The choice of model must be made considering the availability of data. Below, some examples of models are given, which could potentially be suitable for this type of application. There are, however, several other models that could be used too.
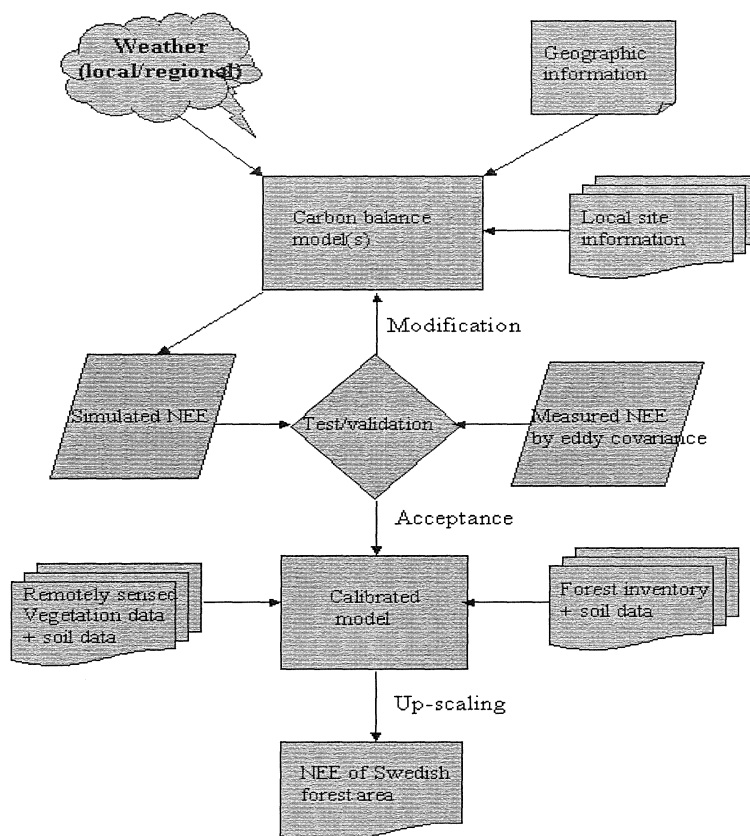

Figure 5. A scheme of how a model based system for estimation of NEE for the Swedish forest area could be organised.

An example of a causal model

Biome-BGC is a process-based model that simulates the storage and fluxes of water, carbon and nitrogen between the different components of the ecosystem and the atmosphere. The model was initially developed for forests, Forest-BGC (Running and Coughlan, 1988) but has now been developed into a more general 'biome' type of model. The time step is daily which is a good compromise between time resolution and time demand for simulations when applications are large scale. Models with a daily time-step are recognized to satisfactory describe the day-to-day variation (Kimball et al., 1997). Daily maximum, daily minimum and daylight temperature, precipitation, daylight vapour pressure deficit, daylight radiation and day-length are input variables. The soil is treated as one layer and so is canopy. The canopy is, however, divided into shaded and sunlit fractions. The photosynthesis is based on the Farquhar model (Farquhar et al., 1980). The canopy conductance to CO_2 and water vapour is controlled by air temperature, vapour pressure deficit, radiation and soil water potential. Stocks of carbon in the different compartments must be given as initial values. The amount of nitrogen is given by the C:N-ratios of the different compartments. The most resent version of the model (4.1.1) can be found at the Biome-BGC homepage: http://www.forestry.umt.edu/ntsg/EcosystemModeling/BiomeBGC/

An advantage with this model is that it is widely used and will continuously be developed. A comprehensive literature study has been done to identify values of ecophysiological parameters that are representative for the major biomes on the earth (White et al., 2000). Work is ongoing in Sweden to parameterise and test this model for boreal conditions. Even if this is a fairly simple model, it requires 43 parameters to be determined for each biome. Most of these are biome specific and need not to be changed for different stands but, for instance, leaf area index is a key parameter, which is needed for each stand.

Current status of eddy covariance measurements in Swedish forests

All eddy covariance measurements going on today are part of different research projects. These are normally short-term, i.e., 2-3 years at the most. There are two sites that have been able to run for as long as 8 respectively 6 years by now. These sites are Norunda in northern Uppland and Flakaliden in Västerbotten. Today NEE is measured at an additional 5 sites all of which are located in coniferous forests of different age and species composition. The measurements in Norunda, which is a drained site, show interestingly that forests can also be sources over long periods of time. A recent analysis of the total greenhouse gas exchange of drained forest show that even if the drained area is small in comparison to the total forest area, the global warming effect is large and need to be considered (Klemedtsson et al., 2002).

The measurements in Norunda also show that the variation between years is quite large. During the period 1995 to 2000 the mean annual NEE was +55.9 g C m^{-2} with a standard deviation of ±48.6 g C m^{-2} (Lankreijer at al., 2003). The variation between years was of similar size in Flakaliden and Hyytiälä in Finland although these two forests showed mean uptakes of -139 and -235 g C m^{-2}, respectively. The first preliminary results from NEE measurements in a chronosequence of stands show that the stand age is a key parameter in determining annual NEE. It is, thus, important that the stands that are used for calibration of the models are representative for age distribution but also for soil properties, which is another sensitive factor in the simulations.

Errors in eddy-covariance measurements

As with all methods, there are uncertainties and errors associated also with the eddy-covariance measurements. It is quite complex to perform a full error analysis without introducing the theoretical background for the measurements and therefore a more qualitative outline is given here. The errors in eddy-covariance measurements can be classified into systematic and random errors as summarized by Grelle (1997) (Table 3).

Table 3. Errors in eddy covariance measurements (after Grelle 1997).

Random errors	Systematic errors
One-point measurement Surface heterogeneity Inadequate average time Random signal noise Non-stationarity	Instrumental calibration error Inadequate correction function Inadequate functioning during stable conditions Inadequate sensor height Sensor separation Flow distortion

The division into random and systematic errors is not as clear as it might appear in Table 3. Some of the errors can be of both types, for instance, inadequate sensor height can cause a systematic error if the sensor is above the constant flux layer and, thus, 'sees' another area than the one that is supposed to be measure while if the sensor is located within the constant flux layer but to close to the surface, and, hence is located in the roughness sub-layer, then the error will be of the random type. For long-term measurements as is discussed here the random errors will be diminishing and for CO_2 flux on an annual basis, a typical random error above forest will be 2% (Grelle, 1997). If for instance, a 5-year value is sought for, the random error will be practically negligible. This relates to the errors for the estimates at the single location.

As in all types of measurements, systematic errors are always more difficult to handle and also more serious since they can cause an unknown bias in the estimate. One of the unresolved problems when it concern flux measurements is the so-called night-time problem. It shows up during stable night-time conditions when the flux measurements can indicate a zero flux even when the respiration process is fully active and, thus, should produce a positive flux. Part of this bias between the observed flux above the canopy and the production rate of CO_2 can be explained by increasing storage of CO_2 below the measurement level. Part of this discrepancy have been suggested to be caused by a katabatic flow in the trunk space but so far, no one have been able to show this convincingly. Our own results from analysis of the night-time problem indicate that the method is functioning adequately during stable conditions and that this problem might be exaggerated. However, care should be taken and more research is needed to resolve this matter.

Grelle (1997) estimated the systematic instrumental error for the CO_2 flux to 5.3% for a typical forest set-up and assuming that the errors are independent, the total error on an annual basis would be typically in the order of 6%. This estimate is without consideration to the potential night-time error and it should probably be considered a minimum error.

Accuracy of different methods for determining changes in forest carbon pools –a summary

Below, a summary of qualitative and quantitative aspects of the different methods for estimating changes in forest carbon pools is given. The summary comprises most of the methods outlined in the earlier sections of this chapter. Statements are given from the point of view of the currently available monitoring programs and systems. The summary is given in Table 4.

Table 4. Summary of important features of the proposed methods for estimating changes in carbon pools in Swedish forests. The estimates are based on data from currently available monitoring programmes and systems in Sweden, and to some extent on assumption.

Method	Standard error of an estimate of five years change, Mton C	Risk for systematic errors	Ready for application?
Tree biomass - Summation of growth minus cuttings ("IPCC")	11 - (25%)[*]	Moderate	Yes
Tree biomass - Direct change estimation (temporary plots)	18 - (40%)[*]	High	Yes
Tree biomass - Direct change estimation (permanent plots)	6 – (13%)[*]	Moderate	Yes
Tree biomass - Combined estimation ("IPCC" and permanent plots)	5 – (11%)[*]	Moderate	Almost
Tree biomass - Remote sensing aided change estimation (post-stratification)	5 – (10%)[*]	Moderate	No
Humus layer (example for south Sweden) – Direct change estimation	0.75 - (25%)	High	Yes, after minor modifications
Mineral soils to 0.5m – Direct change estimation	8.5 - (40%)	High	Yes, after major modifications
Eddy covariance measurements – all pools	Not assessable	Moderate-High	No

*) The total change of carbon in biomass for a 5-year period is set to be 43 Mton C, which is based on the change during the period 1990-2000. 95% confidence intervals are obtained as 43 ± 2 * Standard error.

50

Discussion and conclusions

General issues

The study shows that there are several options available for assessing changes in forest carbon pools in Sweden, and also that there are many possibilities for improving the current Swedish reporting. Looking at the different pools of the Kyoto Protocol, adequate data and methods are available for assessing changes in above and below ground biomass. For these pools, only minor improvement of the methodology is needed. Further, most of the data required for this purpose are available from the Swedish National Forest Inventory (NFI). The traditional method for reporting changes in this case has been to separately estimate growth and removals of tree volume, and convert the difference thus obtained to amount of carbon by applying various conversion and expansion factors. An interesting alternative to this approach is found to be direct estimation of change based on data from repeated measurements of permanent sample plots. This method probably is more accurate than the one currently used. Ideally, both methods can be applied and combined into a single estimate by appropriate weighting of the two different estimates.

Regarding soil carbon changes, further improvements of methods and monitoring principles are needed if these changes should be based on repeated measurements. Current practices and methods are promising, but it is unclear if the systematic error component of change estimates can be kept at low enough levels. In an international perspective, very few countries have a long-term monitoring programme like the Swedish Forest Soil Inventory (MI). Thus, in this perspective Sweden has an opportunity to set standards regarding how soil sampling programmes should be set up in order to assess changes in soil organic carbon. An alternative to repeated soil sampling would be to base the reporting on modeling. However, since the Swedish MI will continue to be operational regardless of Kyoto reporting, data on stock changes will continue to be available.

Although assessment of dead wood volume is conducted within the NFI, currently there is a lack of knowledge for assessing changes in these carbon stocks. However, work is ongoing, and within a couple of years functional relationships that relate volume and decomposition status of dead trees to carbon amounts will be available.

Regarding the carbon pools in litter there are currently no national level data available.

Eddy-covariance measurements are valuable means for verification and for further improving our understanding of fluxes of greenhouse gases, for example regarding the temporal variability of fluxes. In addition, these measurements provide information about non-CO_2 gases. However, presently it is not possible to use this kind of measurements for improving the national level estimates of changes in carbon pools. The reason is that the network of measurement stations is very sparse, and that there are no methods available for up-scaling from the site level to the national level.

The accuracies found in our studies of changes in forest biomass and soils are generally lower than what is found for other sources and sinks of greenhouse gases in national inventories (e.g. Rypdal and Winiwarter, 2001). Whether or not these accuracies are sufficient or not is a difficult question. Currently there are no recommendations from IPCC stating that a certain level of accuracy need to be obtained. Nor are such recommendations likely to be presented in the near future. Instead, each country is requested to provide as accurate estimates as possible, considering national circumstances (cf. IPCC 2000b).

Although this can be considered reassuring, we would like to propose an alternative approach where information about the uncertainty of estimates is actually utilized. This approach would be that only sinks that are "certain" would be allowed for inclusion in the reporting. This could be based on 95% confidence intervals of estimated changes. If such an interval overlaps 0, the conclusion would be that the pool cannot be accounted for as a sink. Otherwise, the lower limit of the confidence interval could be used as the accountable part of the sink. For example, if a country reports a confidence interval 5 ± 3 Mton C as the change in forest management areas, only 2 Mton C – instead of 5 Mton – would be allowed in the accounting. A prerequisite for this would be that careful checks be made in order to ascertain that there are no systematic errors in data.

Needs for improvement of the national monitoring programmes

For estimating changes of the forest carbon pools in Sweden, the NFI and the MI are of prime importance. However, no major changes of these inventories are foreseen as a result of the requirements to improve the reporting of changes in carbon pools under the Kyoto Protocol. The basic measurements will continue to be very useful. However, a number of minor modifications and developments would contribute to making the inventories better suited for carbon reporting. For the NFI, such modifications include:

- The reporting of changes in biomass carbon pools would benefit from a higher share of permanent plots. Such a shift from temporary plots to permanent plots is, however, already scheduled for the inventory that starts in 2003. This shift is planned in order to meet the demands for change estimates also in other areas than carbon reporting.

- New routines for control assessments need to be established, in order to obtain scientifically sound estimates of the systematic errors of the estimates. To achieve high precision in the control, an increased number of sample plots should be checked.

- The estimates of harvested volumes need to be improved, by introducing stricter routines for these assessments. The ambition must be to obtain unbiased harvest estimates, although the random errors in estimates for single years may continue to be high.

- The biomass functions used to calculate biomass of individual trees from the basic measurements should be improved, and be developed for all major species. Currently there is a lack of functions, especially for the root biomass.

- Functions need to be developed for the assessment of carbon in dead wood. Currently, only the volume of dead wood is assessed. Estimating the carbon mass in dead wood is somewhat complicated, since the density of carbon varies depending on decomposition stage of the wood. However, it is judged that it will be sufficient to use rather crude conversion functions.

- New routines could potentially be introduced in order to quantify changes in the carbon pools in other above ground vegetation than trees. This also would require the development of a set of regression functions for this purpose.

- If needed, coarse litter could be assessed by specific local line intersect sampling techniques. However, such measurements would be rather expensive.

The Forest Soil Inventory can be used for monitoring carbon stocks and stock changes in forest land on a national and regional level in Sweden. However, the system is not optimised for meeting the Kyoto Protocol demands and some modifications in field sampling procedures should be undertaken.

A stratified sampling design of permanent plots is suggested as one option. The number of plots should be optimised with respect to expected changes. However, since the MI is conducted for a number of reasons other than carbon change assessment, our recommendation is to keep the current allocation of plots where soil samples are taken.

It is suggested that the amount of carbon be monitored in the humus layer and in the mineral soils down to a reference depth of 50 cm. However, in case of peat soils with an organic horizon deeper than 50 cm, it is suggested that the entire peat layer be included in the monitoring.

Concrete suggestions for modifications of the MI are:

- Humus layer cores should be taken in a more objective manner, to avoid potential systematic errors from purposive selection of core locations. Litter samples might be taken simultaneously with the humus samples, using the same basic approach.

- Mineral soil samples would continue to be taken from certain predefined layers and depths in randomly located soil pits. However, inclusion of a new soil sample at a randomly located depth would improve the possibilities to quantify various compounds in the soil.

- Measurement of the amount of stones and boulders should be made according to the principles of Viro.

- The total thickness of peat layers should be measured. In addition, peat samples should be taken at different depths on peat lands.

Intercomparison of methods – a tool for verification

The Kyoto Protocol states that the estimated changes in carbon pools shall be verifiable. To verify means to make certain that something is true and the closest we can come to verify an estimate of a change in carbon pools is probably to compare estimates made by independent methods that are designed to measure the same thing. The eddy-covariance method provides a means for such comparisons. With the eddy-covariance method the net flux of CO_2 between the atmosphere and a forest can be measured with a half-hourly time resolution. The integral over time of the flux plus the transport of dissolved organic carbon (DOC) out of the system shall be comparable to the change in the pools estimated over the same time period, provided all pools are measured. Since the DOC transport is known to be fairly small in most systems, it can be neglected in a first approximation and, thus, integrated fluxes measured by eddy-covariance can be directly compared to measured changes in the pools at the same site. Today, eddy-covariance measurements are ongoing at several forests in Sweden as part of different research projects but there exist no sites for continuous long-term monitoring.

We suggest that a number of eddy-covariance sites are set up in a monitoring and verification program. At these sites, the methods applied for monitoring of carbon pools should be used exactly the same way as done for the purpose of reporting. Results from these measurements can be used for testing and development of other methods based on modeling and remote sensing.

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Acknowledgments

Annex – Summary of the Nordic workshop *"Monitoring and reporting of carbon stock changes in forest land"*

The workshop was held in Krusenberg, Sweden, 02-10-31—02-11-01. The aim was to discuss a preliminary version of the study presented in this report. Conclusions from the workshop sessions are provided below.

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Background to the workshop

The Swedish Energy Agency has granted a study on "Quantification of changes in forest carbon pools- methodological options for Sweden". As an integrated part of the project a workshop was organized, October 31st to November 1st, 2002. The aim of the workshop was to evaluate the conclusions in a background report and to put the results into an international perspective.

Most of the time was spent in three working groups, which focused on: i) evaluation of available methods/ systems-, their strengths and weaknesses in terms of accuracy, reliability, regional applicability, costs, verifiability etc., ii) possible improvements and the need for future research.

The working group reports are summarized below.

Working group 1:
Inventory of carbon stock changes- biomass and dead wood.

Q 1. Which methods are suitable for application in national accounting systems? The WG focused on Tier 3-like methods (cf. IPCC reports on Good Practice Guidance) and the situation in the northern part of Europe.

National Forest Inventories (NFIs), based either on estimation of growth minus drain or measurements of the stocks at two different times.
NFIs can be used for aboveground and belowground biomass. Both pools can be covered either through BEFs (Biomass expansion factors) or individual tree biomass functions

Dead wood is included in some inventories, but the methodology needs improvement, particularly in terms of conversion from volume to mass of carbon.

Resolution in space and time depends on the sampling scheme, but in general the NFIs can be used only for larger areas (regions) and through interpolations and extrapolations over several years (3-5 years).

NFI in combination with remote sensing can improve the resolution in time and space.

Remote sensing, models and flux measurements: These methods should not be used alone, if there is an NFI, due to difficulties to achieve enough degree of accuracy, but they are complementary tools in using the results from inventory methods. (See further Working Group 3)

Q 2. What is the accuracy and reliability of the methods? What is acceptable accuracy? This question was addressed in relation to measurement of stock changes (NFI).

The accuracy for stem volume is highly accurate and can be estimated (In Nordic NFIs typically in the order of 1% standard error). The estimates for non-stemwood biomass (belowground biomass, ground vegetation) are less accurate, as BEFs (Biomass expansion factors/functions) are used. These could be a function of tree age, diameter, site fertility and other factors. This pool is sometimes underestimated, but it can be improved through (labour intensive) studies.

Dead wood estimates could be very inaccurate.

In terms of acceptable accuracy, anything is acceptable as long as the best available methods and data are used (according to IPPC- guidelines), which is a matter of national circumstances. Requirements focus more on documentation. Verifiers need to be able to track what has been done.

Q 3. Which are the main sources of error (random and systematic)?

The main errors are partly different if you use: i) NFI- change estimates from 2 measurements; ii) NFI – growth minus drain. Some of the problems listed below make less difference in approach ii) than i), because they cancel out when comparing two times. It is often good to combine the two methods, as this will improve the understanding of why a certain change has happened.

Some major errors in using NFIs- growth minus drain were discussed:

- Harvested trees are of different age and biomass expansion factors are averaged over the whole growing stocks
- Uncertainty in the harvest statistics (e.g. underreporting due to tax reasons). Non-commercial (e.g. fuelwood) uses of wood are only guessed
- Import and export is difficult to handle in terms of accuracy, which will affect the harvest statistics

Q 4. Which methods are applicable in which regions?

Some major conclusions: Direct measurement methods can only be applied where frequent NFI is carried out. The systems used are i) continuous inventories (the Nordic countries) or ii) rotating inventories (over 2-3 years and then a break for some years (as applied in Germany and Austria), has implications for the results and the accuracy.

In areas void of NFI data, the use of flux measurements, remote sensing and modelling approaches may be useful in national accounting systems. The choice of method will depend on the density of activities and on the size of the country.

Q5. What are the visions/potentials for improvements of the outcome in a 4- 10-years perspective?

It is crucial to meet the forthcoming reporting requirements and their timescales. Further R&D should address two different time frames: i) short term issues(e.g. IPCC Good Practise Guidance). It is important to feed in Nordic experiences; ii) long term issues with the aim to address the needs in a second commitment period from 2012 onwards.

Some of the conclusions regarding R&D needs in a 4-years perspective were:
- Improved biomass expansion factors and biomass functions through research projects.
- Methods for estimating rate of stock changes in dead wood and litter.
- More useful remote sensing methods, both for up-scaling and for detection of change
- Better knowledge of all types of errors, and particularly systematic errors
- Improved information on removals (harvest and fuelwood)
- Established links to international monitoring systems (for example FAO, ICP Forest)

- A closer link between the UNFCCC inventory people, national forest inventory people, and the research community.
- Those issues were also identified as urgent topics for research , aiming at an improvement of the monitoring and reporting system.

Some conclusions in a 10-years perspective were:

- Possibility to control systematic errors in general
- Independent verification methods are available
- Other environmental effects of LULUCF activities (e.g. biodiversity, groundwater) are considered

Working group 2:
Inventory of carbon stock changes- soil and litter.

Q1. Which methods are suitable for application in national accounting systems?

There are no harmonized methods used to estimate carbons stock changes in soils over time. The ideal way to plan a suitable inventory is to i) determine the expected change rate, and ii) to determine the spatial variability of the change rate. With this information and a given or wanted degree of precision the level of density of an inventory grid can be determined. However, today we are confronted with existing soil monitoring systems, which represent various methodologies and purposes. One approach to improve the accuracy and to increase the cost-effectivity is to apply a stratification scheme.

Repeated intervals of inventory of 10-30 years are necessary to detect soil changes. The reporting system requires an accounting system by the end of 2006. Soil inventories do not fulfil that requirement, due to a common repeated inventory period of 10 years. However, interpolation and extrapolation can be used.

With stratification, sampling might be adapted to reduce the time interval required to detect changes.

Peat soils, which cover large areas in some countries, are not included in inventories, not even in the Nordic countries.

The sampling procedure needs standardization in terms of i) soil depth to be sampled; ii) sampling of litter, which should be included in the inventory of soils; iii) approaches to handle coarse organic material and stoniness.

Q 2. What is the accuracy and reliability of the methods? What is acceptable accuracy?

For Sweden, according to the background report the existing inventory (provided a return interval of 10 years) is able to detect C stock changes in a reliable manner. The standard error is estimated to 25-40 %. A similar assessment is not known from other countries. Other conclusions are:

- An integrated approach should be investigated. Mostly additional information beyond the scope of national soil inventory (e.g. models, scenarios long-term experimental sites etc) is necessary to provide the necessary information.
- There is no soil inventory available which distinguishes the various sources of error. Rather the overall statistics are determined for the various strata (soil types, productive class, forest stand type, climate region)
- Repetitive sampling should be conducted at permanent plots

Q3. What are the visions/potentials for improvements of the outcome in a 4- 10-years perspective?

- Initiate a systematic cooperation within the Nordic countries to improve the monitoring methods, particularly how to deal with stones and coarse organic material.

- Develop methods to stratify according to the reporting requirements in order to improve the accuracy of regional soil carbon estimates.
- Integrate different approaches (e.g. modelling of humus dynamics) to meet the requirements.
- There is a great need to monitor carbon stock changes in peatlands, as these might change from sinks to sources (drainage, climate change).

Working group 3:
Other methodologies- their role in the implementation of accounting systems

The working group focused its discussions on the role of non-statistical methods (modelling, remote sensing, flux measurements and manipulation experiments) and how the results could be used for accounting, verification and/or as targeted information with the aim to be complementary to those inventory methods, discussed in the working groups 1 and 2.

Q 1. What are the characteristics of these methods- their role and usefulness?

Modelling cannot be used for reporting alone, but could be applied for up-scaling and updating of inventory data through interpolation and extrapolation in space and in time (fill gaps between inventories). Other uses are:

- System studies- understanding the processes
- Scenario analysis and sensitivity analysis
- Help in sampling design (statistical sampling, choice of pools etc)
- Inclusion of other trace gases
- Models are used in combination with flux measurements, remote sensing and manipulation experiments. Different models are used in different regions in Europe.

Flux measurements cannot be used to cover regions or countries, but they are useful for:

- Understanding the processes (e.g. interannual variation), particularly if other aspects are studied at the same time and for up-scaling from compartment studies.
- Validation of pool changes (inventories); quality control
- Quantification of the impact of various silvicultural measures (e.g. thinning)
- Verification whether changes are natural or human-induced
- Test and development basis for modelling efforts
- Results could be used in data assimilation (Flux, NFI, Remote sensing, Modelling)

Remote sensing should not be used to estimate carbon directly if NFIs are available, but it is useful for:

- Pre- and post-stratification to enhance the accuracy of inventory data. It might not help to estimate NFI tree biomass, but in can be used for updating of accounting results to annual intervals
- Stratification of landscapes for soil inventories
- Updating of field-measurement based estimates (together with growth models)
- Area estimation, including independent estimates of clear-cut areas
- Accounting of stock changes in areas where NFIs are not available (estimation of Leaf Area Index and direct measurements of carbon stock changes, but the accuracy is often low).

Manipulation experiments do not aim at national reporting, but could help to:

- Quantify effects of different silvicultural measures and the impact of environmental changes (e.g. Nitrogen and CO_2-fertilization)
- Factor out direct and indirect human effects
- Understand processes

Q2. Are these methods suitable for application in national accounting systems?

In regions with an NFI these methods should not be used alone, due to difficulties to achieve high enough accuracy in scaling up to national level, but the current inventories are not sufficient alone either. These other methods could be used to improve the quality of inventory data. National accounting systems need to have an integrated approach, where these methods can be complementary (sampling strategy, understanding processes, factoring out natural and direct and indirect human induced effects, verification, etc).

In regions void of NFI data, the use of satellite information, flux measurements and modelling approaches may be useful in national accounting systems. Remote sensing can be used if combined with field sampling. Combining different inventories with models is also a way to use available sources in a better way.

Q 3. Which are the major R&D challenges?

- Development of a better integration between disciplines and approaches is needed. It is also urgent to have a close link between scientists and practical people, working with national inventories
- Creation and maintenance of common databases and common protocols (harmonisation of data and methods)
- Develop better biomass expansion factors and equations; better information on deadwood, soil carbon and litter; more input data for models with spatial and temporal resolution;
- Use of common test sites for validation of different methods/approaches
- Nordic countries should collaborate to cover e.g. main forest site types, below ground biomass, and making joint contribution to the whole boreal region.

Serien Arbetsrapporter utges i första hand för institutionens eget behov av viss dokumentation. Rapporterna är indelade i följande grupper: Riksskogstaxeringen, Planering och inventering, Biometri, Fjärranalys, Kompendier och undervisningsmaterial, Examensarbeten samt internationellt. Författarna svarar själva för rapporternas vetenskapliga innehåll.

This series of Working Papers reflects the activity of this Department of Forest Resource Management and Geomatics. The sole responsibility for the scientific content of each Working Paper relies on the respective author.

Riksskogstaxeringen: (*The Swedish National Forest Inventory*)

1995	1	Kempe, G. Hjälpmedel för bestämning av slutenhet i plant- och ungskog. ISRN SLU-SRG-AR--1--SE
	2	Riksskogstaxeringen och Ståndortskarteringen vid regional miljöövervakning. - metoder för att förbättra upplösningen vid inventering i skogliga avrinningsområden. ISRN SLU-SRG-AR--2--SE.
1997	23	Lundström, A., Nilsson, P. & Ståhl, G. Certifieringens konsekvenser för möjliga uttag av industri- och energived. - En pilotstudie. ISRN SLU-SRG-AR--23--SE.
	24	Fridman, J. & Walheim, M. Död ved i Sverige. - Statistik från Riksskogstaxeringen. ISRN SLU-SRG-AR--24--SE.
1998	30	Fridman, J. & Kihlblom, D. & Söderberg, U. Förslag till miljöindexsystem för naturtypen skog. ISRN SLU-SRG-AR--30--SE.
	34	Löfgren, P. Skogsmark, samt träd- och buskmark inom fjällområdet. En skattning av arealer enligt internationella ägoslagsdefinitioner. ISRN SLU-SRG-AR--34--SE.
	37	Odell, G. & Ståhl, G. Vegetationsförändringar i svensk skogsmark mellan 1980- och 90-talet. -En studie grundad på Ståndortskarteringen. ISRN SLU-SRG-AR--37--SE.
	38	Lind, T. Quantifying the area of edge zones in Swedish forest to assess the impact of nature conservation on timber yields. ISRN SLU-SRG-AR--38--SE.
1999	50	Ståhl, G., Walheim, M. & Löfgren, P. Fjällinventering. - En utredning av innehåll och design. ISRN SLU-SRG--AR--50--SE.
	52	Riksskogstaxeringen inför 2000-talet. - Utredningar avseende innehåll och omfattning i en framtida Riksskogstaxering. Redaktörer: Jonas Fridman & Göran Ståhl. ISRN SLU-SRG-AR--52--SE.
	54	Fridman, J. m.fl. Sveriges skogsmarksarealer enligt internationella ägoslagsdefinitioner. ISRN SLU-SRG-AR--54--SE.
	56	Nilsson, P. & Gustafsson, K. Skogsskötseln vid 90-talets mitt - läge och trender. ISRN SLU-SRG-AR--56--SE.

57   Nilsson, P. & Söderberg, U. Trender i svensk skogsskötsel - en intervjuundersökning. ISRN SLU-SRG-AR--57--SE.

1999 61   Broman, N & Christoffersson, J. Mätfel i provträdsvariabler och dess inverkan på precision och noggrannhet i volymskattningar. ISRN SLU-SRG-AR--61--SE.

65   Hallsby, G m.fl. Metodik för skattning av lokala skogsbränsleresurser. ISRN SLU-SRG-AR--65--SE.

75   von Segebaden, G. Komplement till "RIKSTAXEN 75 ÅR". ISRN SLU-SRG-AR--75--SE.

2001 86   Lind, T. Kolinnehåll i skog och mark i Sverige - Baserat på Riksskogstaxeringens data. ISRN SLU-SRG-AR--86--SE

2003 110   Berg Lejon, S. Studie av mätmetoder vid Riksskogstaxeringens årsringsmätning. ISRN SLU-SRG-AR--110--SE.

117   Ståhl, G., Blomquist, g. & Eriksson, A. Mögelproblem i samband med risrensning inom Riksskogstaxeringen. - En studie för att kartlägga eventuella arbetsmiljörisker. ISRN SLU-SRG-AR--117--SE.

Inventering och planering: *(Forest inventory and planning)*

1995 3   Holmgren, P. & Thuresson, T. Skoglig planering på amerikanska västkusten - intryck från en studieresa till Oregon, Washington och British Columbia 1-14 augusti 1995. ISRN SLU-SRG-AR--3--SE.

4   Ståhl, G. The Transect Relascope - An Instrument for the Quantification of Coarse Woody Debris. ISRN SLU-SRG-AR--4--SE

1996 15   van Kerkvoorde, M. A sequential approach in mathematical programming to include spatial aspects of biodiversity in long range forest management planning. ISRN SLU-SRG-AR--15--SE.

1997 18   Christoffersson, P. & Jonsson, P. Avdelningsfri inventering - tillvägagångssätt och tidsåtgång. ISRN SLU-SRG-AR--18--SE.

19   Ståhl, G., Ringvall, A. & Lämås, T. Guided transect sampling - An outline of the principle. ISRN SLU-SRGL-AR--19--SE.

25   Lämås, T. & Ståhl, G. Skattning av tillstånd och förändringar genom inventerings-simulering - En handledning till programpaketet "NVSIM". ISRN SLU-SRG-AR--25--SE.

26   Lämås, T. & Ståhl, G. Om dektering av förändringar av populationer i begränsade områden. ISRN SLU-SRG-AR--26--SE.

1999 59   Petersson, H. Biomassafunktioner för trädfraktioner av tall, gran och björk i Sverige. ISRN SLU-SRG-AR--59--SE.

63   Fridman, J., Löfstrand, R & Roos, S. Stickprovsvis landskapsövervakning - En förstudie. ISRN SLU-SRG-AR--63--SE.

2000 68   Nyström, K. Funktioner för att skatta höjdtillväxten i ungskog. ISRN SLU-SRG-AR--68--SE.

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