Multi-source inventory methods for quantifying carbon stocks and stock changes in European forests

# CarboInvent

# Compilation and Calculation of Soil Carbon Data according to the IPCC GHG Inventory Methodology

Subtitle:

**Requirements and frame conditions to consider soil carbon and litter in greenhouse gas reporting**

Final report (Deliverable 3.4)


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# CarboInvent

## Soil Carbon in the IPCC GHG Inventory – D3.4

**Document No.:** **WP3-D3.4-RUG**

**Date:** **January 19, 2006**

**Summary:** **This report summarizes the reporting options for litter and soil organic carbon. It provides an overview on the possibilities and requirements to report soil C changes, and gives examples based on existing reporting and research activities. The aim of the report is to provide a framework to the methodical results of this work package and to transport the findings into the context of the greenhouse gas reporting.**

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## List of Abbreviations

| | |
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| AFOLU | Agriculture, Forestry and Land Use |
| CP | Commitment period |
| GPG | Good Practice Guidance |
| FSCC | ICP Forests Soil Coordinating Centre |
| FSCDB | ICP Forests Soil Condition Data Base |
| GHG | Greenhouse Gas |
| ICP Forests | International Cooperative Programme on assessment and monitoring of air pollution effects on forests in the UN/ECE region (1985) |
| JRC | EU Joint Research Centre |
| KP | Kyoto Protocol |
| Level I | Forest Soil Condition Monitoring of the EU/ICP Forests Level I Network |
| LULUCF | Land use, land-use change and forestry |
| PTF | pedo-transfer function |
| SOC | soil organic carbon |
| UNFCCC | United Nations Framework Convention on Climate Change |

# 1. Introduction

The objective of this report is to view the results of work package 3 in the policy context of climate change reporting. The main objectives are:

- to test and compare soil organic carbon data for the reporting according to the IPCC Methodology
- to analyse the role of soil (carbon) inventories in the reporting

## 1.1 GREENHOUSE GAS REPORTING (UNFCCC, KP)

**Reporting greenhouse gas emissions and removals**

Countries regularly report their greenhouse gas emissions and removals under the United Nations Framework Convention on Climate Change (UNFCCC). After its adoption, reporting under the Kyoto Protocol (KP) of the convention refers to the first commitment period 2008-2012. In order to allow basic harmonization of reporting approaches, inventory guidelines have been made available (IPCC 1996). Beginning from the year 2005, all Parties to UNFCC should apply IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry - GPG LULUCF (IPCC 2003).

The practice of reporting is still far from perfect and some countries still use the above-mentioned IPCC 1996 (revised) methodology in their reporting. Currently, the drafting of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines) is ongoing. Guidelines on reporting on carbon sequestration in forests will be contained under the **Agriculture, Forestry and Other Land Use (AFOLU)** section of the guidelines. This section is mainly based on the methodological work developed in GPG LULUCF.

Figure 1 presents the general reporting scheme for AFOLU. It can be seen that reporting has to consider several non-CO2 gases as well, and that both managed forest land and land conversions are considered. For monitoring CO2 fluxes from AFOLU categories, changes of the carbon storage in pools has to be considered. This report concentrates on soil carbon in mineral and organic soils, as well as litter, because these pools are relevant in soil inventories.

With regard to the reporting under UNFCCC and Kyoto Protocol (KP): both reporting systems are integrated on the basis of the GPG (IPCC 2003). Both reportings are based on a land-use matrix, consider a key category analysis, and distinguish Tiers and pools. Under UNFCCC, wetlands, settlements and “Other” do not need to be reported. The proposed categories under UNFCCC are mostly recommendations; reporting of pools is based on available data and/or cost-efficient data assessments. Under the Kyoto Protocol, reporting is also not compulsory in all categories and pools if a pool is not a source for greenhouse gases. The minimal requirement thus is to proof whether a pool currently acts as a source or not.

Stronger reporting requirements result from the relative importance of a category (such as CO2 fluxes in managed forests) within the national greenhouse gas budget. If a category is considered “**key**”, the significance of the listed pools need to be assessed, and reported at a higher Tier.

← ***key categories***

if key, assess significance of sub-categories
(accounting for 25-30% of the emissions)

| $CO_2$ | $N_2O$ | $CH_4$ |
|---|---|---|
| - biomass | - fire | - fire |
| - dead organic matter | - SOM mineralization | |
| - soil | - fertilizer input | |
| | - cultivation of organic soils | |

The so-called **Tiers** refer to methodical options, which differ regarding requirements, quality and resolution of the data used. Tier-selection is based on the principle to use available data, models, evaluation procedures, etc. "*as efficiently as possible*".

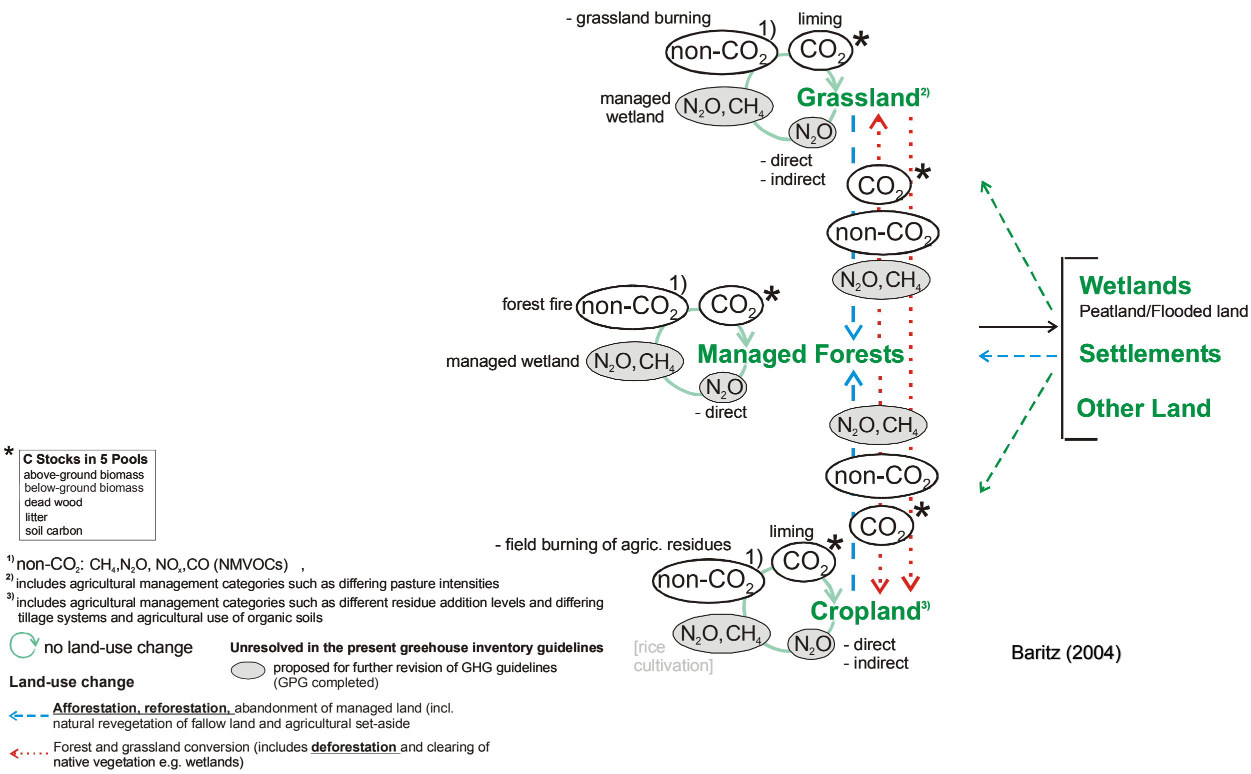


**Figure 1: Reporting scheme for AFOLU**

### Role of the European Community (EC)

The EC as a Party to the UNFCCC, via decision of the European Parliament and of the Council (280/2004/EC), defined as the "mechanism for monitoring Community greenhouse gas emissions and for implementing the Kyoto Protocol". The Commission Decision (2005/166/EC) laid down the rules for implementing the decision with regard to the Community inventory system. Therefore, the EC is also required to monitor and report direct human induced greenhouse gases (GHGs) emission by sources and removal by sinks, including sources and sinks related to forest activities (afforestation/reforestation, deforestation and forest management). Within the EC system, a burden sharing agreement between EU15 regulates the shares of emissions and removals allowed and targeted by the member states.

### Reporting approaches in AFOLU

GHG fluxes in the AFOLU sector are estimated in two ways:

| | | | |
|---|---|---|---|
| 1 | **net changes in C stocks over time** | used for most $CO_2$ fluxes | *a) inventory-based approach*<br>*b) process-based approach* |
| 2 | **direct gas flux rates to the atmosphere** | used for estimating non-$CO_2$ emissions and some $CO_2$ emissions | *emission factors*<br>(resemble change rates received from 1.a or 1.b) |



-

While emission factors (default values for fluxes) are used for reporting of direct gas flux rates, two basic mechanisms exist which apply to the monitoring of C stock changes in storage pools:

(a) comparing between two (or more) consecutive (repeated) inventories (inventory-based)

(b) applying change rates of the size of pools (process-based), for example:
  - annual increments of (stem volume, which needs to be expanded to biomass increment)
  - pool change factors received from repeated inventories (in combination with a) or chronosequence studies) or models

The use of C stock changes to represent $CO_2$ emissions and removals, is based on the fact that changes in ecosystem C stocks are predominately through $CO_2$ exchange between the land surface and the atmosphere. Hence, carbon sequestration (i.e. process of increasing the carbon content of a carbon pool other than the atmosphere) over time is equated with a net removal of $CO_2$ from the atmosphere. Non-$CO_2$ emissions (even if related to changes in carbon pools) are different from carbon sequestration and they largely result from microbiological processes and combustion of organic materials.

In 2006 IPCC Guidelines, the $CO_2$ exchange of terrestrial ecosystems is mainly monitored by tracing changes of carbon pools in forest ecosystems. These pools were defined in the GPG LULUCF, namely:

1. Above-ground biomass
2. Below-ground biomass
3. Dead wood
4. Litter
5. Soil organic matter

The following factors affect how the selected reporting schemes will look like:

- reporting under UNFCCC or KP
- decisions related to the Art. 3.4 of the KP
- availability of data
- relative importance of C sequestration in forests within each of the countries' national GHG inventory (as determined by the key category analysis)
- requirements for the applied reporting approaches (Tiers)
- selection of pools for the reporting.

## 1.2 GENERIC ASPECTS FOR REPORTING C SEQUESTRATION IN FORESTS

Up until now, within the UNFCCC Greenhouse Gas (GHG) Inventories of many central European countries, the LULUCF reporting is characterized by the following frame conditions:

- the reporting so far has concentrated on part 5A, biomass carbon changes, and no reporting on land use change (LUC) has been done due to the lack of representative data, soils are excluded, and no reporting on "non-CO2" gases has been done (except UK)
- no severe land use change is taking place
- in several countries data from different regional forest inventory sources data had to be compiled and "unified"
- the role of LULUCF as a key category in the overall national Greenhouse Gas Inventories is still often unknown
- within the nationally existing LULUCF reporting, reporting for forests is organizationally separated from agriculture ("land use"), and land use change

According to Matteucci and Seufert (2003), the most critical issues from which member states' reporting currently suffers are: forest definitions, definitions of expansion and conversion factors (e.g. biomass expansion from stem volume), and national thresholds and methodologies taken in the respective inventories. These factors lead to significant methodical differences among the member states (MS).

With regard to **forest definitions**, comparability among countries is currently not provided. It is currently under investigation within each countries' GHG inventory system preparation, whether a common definition for example as provided by FAO is possible. In some national forest inventories, crown cover is a monitored parameter. On the basis of quantitative information of the indicator parameters (such as crown cover, area dimensions and/or productivity index), harmonization of different definitons is expected to be rather unproblematic. However, in many countries, additional qualitative aspects play an important role (what is considered forest or not): unmanaged forests/forest reserves, forests/woodlands in unreachable areas, open woodlands, nurseries, etc.

The reporting format/tables consider **geographical "regions"** for forests (e.g. boreal, temperate). In forestry, climatic and physio-geographic aspects are considered to distinguish growth regions or other nationally-defined boundaries relevant for forest growth. These regions are important for the country-specific stratification of inventory data, and are difficult to harmonize across Europe.

## 1.3 REPORTING OPTIONS REGARDING SOIL ORGANIC CARBON AND LITTER

- In general (UNFCCC 5A, KP3.4): if SOC changes in managed forests are to be reported, different forest management types do not have to be considered, except the basic Tier 1 stratification for deciduous and coniferous forests. The average SOC density for a country can be assessed, and its change over time extrapolated/estimated/modelled. Under common literature-based assumptions, no changes occur unless management and the disturbance regime change. If data are available, or can be made efficiently available, harvesting by clear felling or large disturbance has been recommended (IPCC 2003).
- UNFCCC 5.A
  Reporting SOC changes is completely optional even if changes in forest biomass carbon are considered a key category. Reporting is recommended if sufficient data are available
- KP3.4
  a: if KP 3.4 is not selected: no data about SOC changes under forest management is needed;
  b: if elected, carbon in storage pools only need to be reported if any of these pools is a source for greenhouse gases (GHG)
- KP3.3
  Any pool has to be reported which acts as a source for GHG.

(for the role of forests in GHG reporting, see Matteucci and Seufert 2003).

## 1.4 THE ROLE OF SOIL INVENTORIES

Table 1 lists the requirements if SOC from sampling would be included in the GHG inventory system. Due to the high spatial variability, and consequently the respective high uncertainties (e.g. difficulties to measure the rock content, or biased sampling of the plot network is not representative), soil stock changes can be monitored only if data the quality is high: this could be demanding for reporting/monitoring, input from research and long-term benchmark sites needed. A detailed overview of uncertainties and methodical aspects regarding sampling for SOC is presented in CarboInvent D3.5).

Specific data requirements result form the reporting needs for carbon sequestration in soils:

**Table 1: Data needs with regard to soil carbon in greenhouse gas reporting**

| requirements | Explanation |
|---|---|
| soil C stocks | determine soil C concentration, bulk density, and stone content, derive regionally validated pedo-transfer functions if bulk density cannot be analytically determined at Level I |
| soil C stock changes | ability to detect changes in soil C given the range of uncertainties derived from a specific inventory (repeated inventories, models, $CO_2$ emission rates from fluxes measurements) |
| reliability | quantify uncertainties including an estimate of bias (especially when comparing inventories at the EU scale) |
| verifiability | - to take more accurate measurements of soil C stocks<br>- to verify changes taken repeated measurements/chronosequences<br>- to verify projected changes with flux measurements<br>- to receive independent estimates and projections using (various) models |
| stratification | - managed peat land<br>- afforestation<br>- if possible: forest management types, unmanaged/managed forest |
| greenhouse gases | $CO_2$, $N_2O$, $CH_4$: combine C and N cycle |

With the availability of a national soil inventory which contains data on soil carbon, reporting at least allows the development of country-specific default data. With regard to change detection, several pathways are possible:

- application of default change or sequestration rates (taken from the literature or from repeated measurements at intensive observation/monitoring plots)
- repeated measurements in total or subsamples
- integration/coupling with modelling.

Figure 2 shows that extrapolation methods are needed at any rate to adjust the sampling dates to the reporting requirements (e.g. 2008-2012 as the first commitment period).

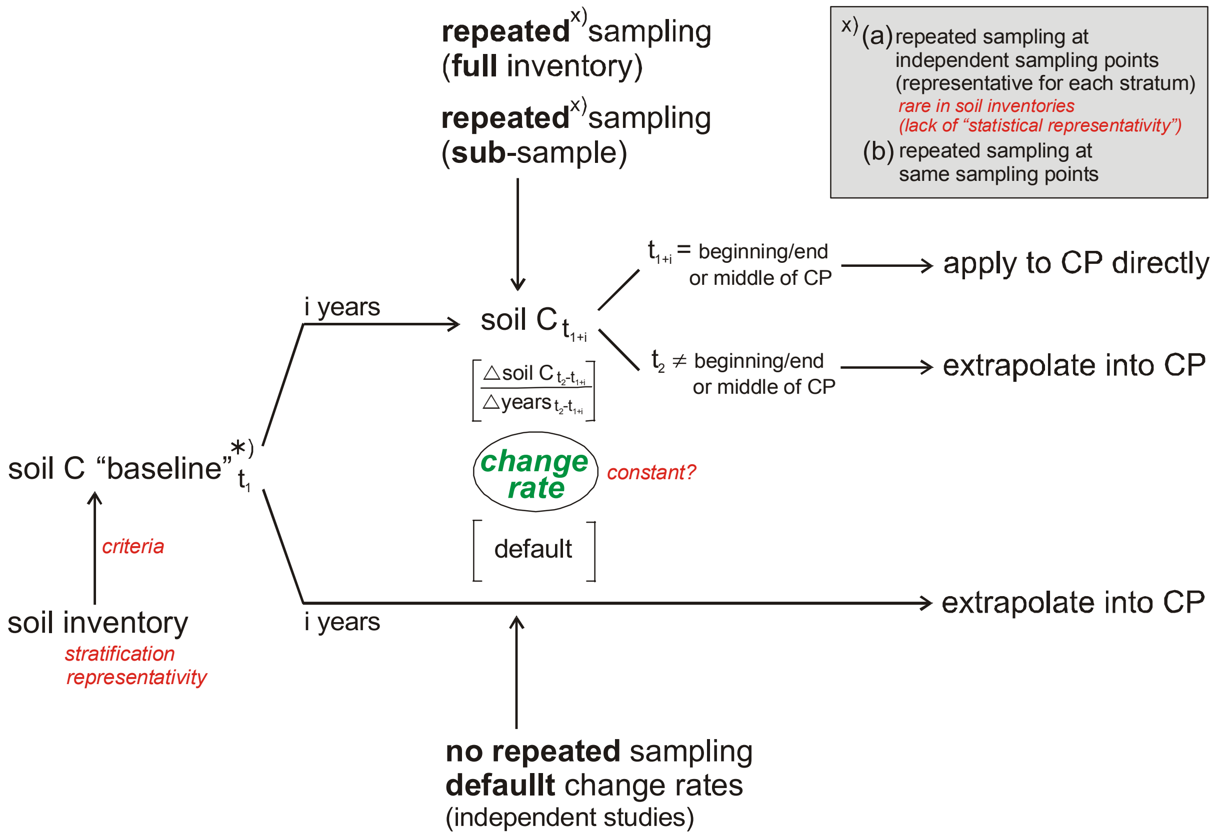


**Figure 2: Alternatives for using forest soil inventories to report SOC changes**

Reporting for forests under the Kyoto Protocol only requires annual changes rather than quantifying the difference between the gains and losses during the commitment period compared to the 1990 baseline. Nevertheless, a baseline is needed to which repeated inventories and model runs can be compared to. The various options to use a forest soil inventory for GHG reporting is illustrated in Figure 2 and in the following paragraph.

### Definition *baseline*

(1) A soil inventory (with measured C content) has been conducted at a certain time before the CP, or at/around 1990 (national level soil inventories usually stretch out over several years):

- historical management effects (negatively affecting SOC) are neglected; natural status or the equilibrium with low management impact is not known; the inventory reflects the status of current management (cannot be treated as $C_{Ref\ native}$).

FCCC/KP reporting investigates soil C changes under management change:

- The baseline reflects the status of soil C under a specific management regime, and allows quantification of changes under management change.
- The degree of historical SOC loss is not known. Thus, the potential for sustainable C sequestration is also not known.
- Soil C changes need to be verified (requires intensive monitoring at least at some plots).

(2) The reference date of a soil inventory is not connected to the CP, or at/around 1990; data need to be extrapolated to 1990, or to the KP commitment period:



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- Verification is more requiring; it needs to be demonstrated that show that the extrapolation results are plausible.

Use of baseline date:
(a) change rates derived from the use of models; baseline as start-up;
(b) change rates from default values; baseline as start-up

If repeated measurements exist, change rates can be directly assessed; uncertainties result from the changes over time, which are not linear (literature based from long-term experiments), depending on prior land use/management type.

According to Lal et al. (2003), the development of reliable SOC baselines still belongs to one of the knowledge gaps to obtain reliable information about carbon sequestration in forest soils. Chertov et al. (2002) also argue that the initial SOC levels may reflect important uncertainty sources for the model application.

In soil (C) inventories in forests of European countries, mostly only one inventory has been conducted, mostly not directly connected to 1990. Not only have these inventories been conducted with objectives **not** related to detect changes in soil C, **repeated measurements are rare**. Changes can therefore only be assessed using/evaluating the existing inventories as a *baseline*, and then looking into changes derived from[1]:

(a) models (refer to WP6, to-down modelling), or

(b) by connecting to soil C change rates as defaults (derived from literature, supplementary studies, ecosystem research sites with repeated measurement)

**Broad-scale (national) soil C change**

Alriksson et al. (2002) have investigated SOC changes within the National Survey of Soils and Vegetation in Sweden. Data from repeated sampling over a 10-yr. interval were available, 1983-1985 and 1993-96). They found an increase of C in the O-layer in south-western Sweden (2.4 ± 1.1 t C/ha), but losses in south-eastern and northern Sweden (-0.50 ± 1.98, -1.4 ± 1.1 t C/ha, respectively). For the whole country, soils have lost C with a rate of -0.56 ± 0.86 t C/ha. With regard to the reliability of the estimate, the authors have referred to systematic errors introduced by the change of the analytical scheme (see also D3.5) and changes in the quality of the sampling of the O-layer. However, no method or correction factor was found to extract the systematic error from these numbers.

According to the model-based projections by Liski et al. (2002), forest soils of western Europe (EU14, Norway, Switzerland) have been gaining 26 Tg C per year in 1990. This equals about 32 or 48 % of the biomass sink. Until 2040, the rate is expected to increase to 43 Tg, corresponding to 61 or 69 % of the biomass sink. Looking at the stock, forest soils at average contribute more than biomass, although regional differences occur: less in the Mediterranean countries, about equal in central Europe, and higher in soils in northern Europe.

A close look at the recent results from an inventory-based change assessment in the UK reveals that forest are loosing carbon in soils (Bellamy et al. 2005): coniferous forests loose ca. 1 g/kg C annually in 0-15 cm, the O-layer not sampled (deciduous forests ca. 0.5 g/kg). Similar results were found from a model exercise using the SOMM model (Chertov and Komarov 1997). Chertov et al. (2002) estimated SOC gains in the Leningrad area of north-western Russia of 0.08% annually over a 100 yr. modelling period.

[1] A 1990 baseline is not needed for Kyoto Protocol reporting in the case of forest management. However, a baseline, not necessarily for 1990, inventory is needed in case soil carbon changes are derived from forest inventories.

Boettcher and Springob (2001) have applied a simple carbon balance model to the L and O - layer in a forest ecosystem in central-northern Germany (CABOLA). The found high variability of C stocks (t/ha), with CV often > 50%. As for the L layer: no correlation to stand age was found. However, an $R^2$ = 0.78 was found for the O-layer. The overall increase rate was: 0.6 g C dm-2 yr-1 (600,000 g/ha, 600 kg, 0.6 t/ha). They did not find any correlations for mineral soil carbon.

**SOC change from management change**

A recent review regarding soil C changes in forests is contained in Baritz et al. (2004). The authors conclude that the vast and intensive cultivation throughout Europe (deforestation, drainage, deflation and erosion) has caused immense historical losses of SOM (in extreme case even up to 70%). Even in many nowadays forested areas, SOM degraded soils are abundant and offer a tremendous potential to restore SOM given the proper management, and therefore to sequester carbon (with typically slow rates over a long but limited time perspective). The effectiveness of management change in forestry (suspension of liming, restoration after drainage, ecological silviculture instead of plantation forestry, etc.) depends on the degradation level, soil properties and climate, which means that different SOC change if any can only be regionally assessed or observed (e.g. Vesterdal et al. 1995).

With regard to GHG reporting under land use (where reporting SOC and litter change will most like take place), emission or SOC change rates would be required for a specific set of nationally typical management changes:

- afforestation/reforestation of grassland
- afforestation/reforestation of crop land

both modified by afforested species, site type, fertilizer used, water regime changed or not.

By applying the YASSO model Eggers (cited in CarboInvent D3.3) found SOC changes during stand development after clear cut. Since the change is non-linear, it is advisable to consider **stand age** in stratifying and evaluating soil inventories. A similar result was recently presented by Takahashi et al. (2005) who used the CENTURY model. However, the changes received from the modelling exercise could not be validated with *in situ* measurements from monitoring. Even in the case of afforestation, SOC changes in the mineral were not detectable (although changes in the O-layer are typical, but more difficult to measure) (Vesterdal et al. 1995, 2002). On the other hand, Paul et al. (2001) have conducted an intensive world-wide review and concluded a trend for SOC losses in the mineral soil, and gains in the O-layer (during the stand development following afforestation). Paul et al. (2001) have also indicated the limitations by inadequate experimental design and sampling techniques.

Proposed forest management changes which may be considered in GHG reporting:

(1) disturbance: storm, avalanches, beetle damage, clear-cut
(cleared sites: important factors to consider are degree of salvage logging, slash treatment, replanting or national regeneration)

(2) permanent crown cover (no mechanical soil/litter disturbance, except harvesting operations with varying litter/debris compartment: litter – silvo-genetical stand development; debris: same plus slash dynamics typical for silvicultural treatments)



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## 1.5 THE ROLE OF MODELS

Currently, UNFCCC reporting has mostly relied on national forest inventories, and concentrated on detecting biomass-C changes. However, with the requirements of the Kyoto Protocol reporting and pools to consider, the demand for well-calibrated models will increase. So far, the UK greenhouse gas inventory has been based on modelling.

The carbon accounting model of Dewar and Cannell (1992) calculated the mass of carbon in trees, litter, soil and wood products from harvested material in new even-aged plantations that were clearfelled and then replanted: Two types of input data and two parameter sets were required for the model (Cannell and Dewar, 1995). The input data are a) area of new forest planted in each year in the past, and b) the stemwood growth rate and harvesting pattern. Parameter values were required to estimate i) stemwood, foliage, branch and root masses from the stemwood volume and ii) the decomposition rates of litter, soil carbon and wood products. The decay of litter and soil matter was assumed to be controlled only by tree species and Yield Class and unaffected by other factors that varied with location. Additional litter was generated at times of thinning and felling: $CO_2$ Emissions and Removals from Soils (5D) were reported with that.

More detailed example on the importance of modelling in the GHG reporting are contained below in Chapter 3.3 “Tier 3 national soil C change estimates from soil inventories”. Details about practical models, advantages and disadvantages when applying for forest soils, and test within CarboInvent are provided in the report D3.3 (Chapter 3: “Role of Modelling in detecting forest soil carbon changes”, and Appendix II: Application of the Roth-C model in the CarboInvent test area Catalonia).

# 2. Method description for reporting Tiers according to the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF)

In the context of soil inventories, three different reporting categories can be distinguished: SOC for mineral soils, for organic soils, dead organic carbon in litter. The following basic calculatory schemes of the GPG for LULUCF (IPCC 2003) and the draft reporting guidelines for AFOLU (IPCC 2006) are presented below:

**Box: Generic methods in detecting SOC and litter changes**
(cited from IPCC 2006)

## Mineral Soil Carbon

$$\Delta C_{Mineral} = (SOC_0 - SOC_{0-T}) / D \qquad \text{Eq.1}$$

$$SOC = \sum_c \sum_s \sum_i (SOC_{\text{Ref}} \bullet F_{LU} \bullet F_{MG} \bullet F_I \bullet A) \qquad \text{Eq.2}$$

where:
$\Delta C_{Mineral}$ = annual soil carbon stock change, tonnes C yr$^{-1}$
$SOC_0$ = stable soil organic carbon stock, under state "*i*", tonnes C ha$^{-1}$
$SOC_{0-T}$ = stable soil organic carbon stock, under state "*j*", tonnes C ha$^{-1}$
D = time dependence of stock change factors (default time period between equilibrium SOC values; commonly 20 yrs.)
T = inventory time, yr
c, s, i = climatic zone, soil type, management system, respectively
$SOC_{ref}$ = reference carbon stock, tonnes C ha$^{-1}$
$F_{LU}$ = stock change factor for land-use systems, dimensionless (change associated with type of land use)
$F_{MG}$ = stock change factor for management regime, dimensionless (e.g. different tillage practices in croplands)
$F_I$ = stock change factor for input of organic matter, dimensionless
A = land area of the stratum being considered, ha

## Litter and dead wood

Process-based method:

$$\Delta C_{DW/LT} = A \bullet [(B_{\text{int}o} - B_{out}) \bullet CF] \qquad \text{Eq.3}$$

where:
$\Delta C_{DW/LT}$ = annual change in carbon stocks in the dead wood/litter pool, tonnes C yr$^{-1}$
A = area of managed land, ha
$B_{into}$ = average annual transfer of biomass into the dead wood/litter pool due to annual processes and disturbances, tonnes d.m. ha$^{-1}$ yr$^{-1}$
$B_{out}$ = average annual decay and disturbance carbon loss out of the dead wood/litter pool, tonnes C ha$^{-1}$ yr$^{-1}$
CF = carbon fraction of dry matter, tones C (tonne d.m.)$^{-1}$

Stock change method:

$$\Delta C_{DW/LT} = [A \bullet (B_{t1} - B_{t2}) / T] \bullet CF \qquad \text{Eq.4}$$

where:
$\Delta C_{DW/LT}$ = annual change in carbon stocks in the dead wood/litter pool, tonnes C yr$^{-1}$
A = area of managed land, ha
$B_{t1}$ = dead wood/litter stock at time $t_1$ for managed land, tonnes d.m. ha$^{-1}$ yr$^{-1}$
$B_{t2}$ = dead wood/litter stock at time $t_2$ for managed land, tonnes d.m. ha$^{-1}$ yr$^{-1}$
T (= $t_1$ - $t_2$) = time period between time of the forst and second stock estimate, yr
CF = carbon fraction of dry matter (0.37 for litter), tones C (tonne d.m.)$^{-1}$

## Organic soils

$$L_{organic} = \sum_c (A \bullet EF)_c \qquad \text{Eq.5}$$

where:
$L_{organic}$ = annual carbon loss from drained organic soils, tonnes C yr$^{-1}$
A = area of drained organic soils in climate type c, ha
EF = emission factor for climate type c, tonnes C ha$^{-1}$ yr$^{-1}$

-

The central idea behind reporting soil C changes is the difference of the SOC stock between two different reference years. IPCC (2003) refers to a native SOC stock as the reference condition. Another broad assumption is that SOC is assumed to be "spatially-average" and stable for the respective inventory stratum (a certain soil, climate, land use and management practice). Tier 2 may be based on a similar methodical approach for mineral and organic soils with Tier 1, but with country-specific data. When working with Tier 2 or 3 approaches, IPCC (2003, 2006 draft) recommends the development of proper inventory stratifications (management systems, climate regions, soil types). Reference SOC stocks do not necessarily refer to native soils, but can be derived on the basis of measurements of the current state. The reference condition can be native land, or any other land use.

The assessment of dead organic matter (including litter and dead wood) requires detailed inventory data for higher Tiers, and considers:
- age-dependent dynamics (silvo-genetical cycles/disturbances)
- estimates of transfer and decay rates

It is expected that the Tiers chosen for soils are likely to depend on the methods chosen for the biomass assessment.

From the existing reporting, two primary methodical approaches to detecting SOC changes are known**, soil inventories** and **modelled stock changes**, both referring to equations 1 and 4. In the following, some recent examples are discussed.

**(a) Soil inventories**

The most recent example of results from a repeated inventory is that of Bellamy et al. (2005). The National Soil Inventory of England and Wales (5 km grid) has been repeated in a representative subsample 12 to 25 years after the original sampling (ca. 40 % of the original ca. 6,000 plots). The authors have detected an average SOC loss of 0.6 % relative to the existing soil C content. It has to be noted that losses only occur on soils having > 5 % SOC in 0-15 cm. There is a trend for SOC gains in soils < 2 % SOC. The results fully support the structure of the IPCC greenhouse gas reporting, which requires reporting of managed wet soils. The management of near-native soils (such as upland grassland) as well as plantation forestry (O-layers were not considered) appear to be non-C-sustainable management systems. The large losses of peat land must be either dependent on changes of the ground water levels (artificial ground water reductions) or changed climate (and interaction of both). However, SOC changes of peaty soils are extremely to detect (see below under "Organic Soils"), especially if only the top 15 cm are considered.

Indirect derivation of SOC changes on the basis of existing broad-scale soil inventories were recently presented by Lettens et al. 2005 for all of Belgium, and Sleutel et al. 2003 for cropland and grassland in Flanders. Sleutel et al (2003) have found a general declining trend in SOC. Regions dominated by sandy soils have been suffering from the largest losses. C changes in both studies are based on measured soil C change per "stratum" change (e.g. stratum definition by Lettens et al. 2005) by soil association (small-scale map, e.g. 1:500,000, or 1:1,000,000) divided by land use).

If no repeated measurements are available, then (a) can be integrated with other approach e.g. modelling (then serving as the baseline information).

**Organic soils**

A detailed investigation of greenhouse gas emissions from drained soils in Sweden has been presented by Klemedtsson et al. (2002). Despite the vast information available for Swedish drained soils, accurate data for $CO_2$ and $N_2O$ emissions are still lacking and mostly still based on expert judgement. The longer measurement series are available the higher the precision of the emission factors derived. There are also no data about the sink/source behaviour of intact peat soils which are needed to interpret the net effect of drainage. The most difficult problem is the separation of SOC oxidation from physical changes (compaction after drainage) and vertical redistribution of SOC in form of DOC.

Another approach has been presented by Alm (1997, cited in Sievanen 2004). Baseline data for Irish peat soils were recently presented by Tomlinson (2005), who impressively presents the complexity of peat types and the difficulties of deriving reliable SOC stock estimates given the tremendous variability induced by historical human impact.

**(b) Modelled stock changes/fluxes**

Modelling SOC changes mostly concentrates on forest management practices. With regard to GHG reporting, a combined approach has recently been presented for Japan (Takahashi et al. 2004). Baseline SOC stocks were derived from field sampling (Morisada et al. 2004). With regard to SOC, no changes under regular forest management are expected. However, the effect of forest management on SOC was investigated using the CENTURY model (Colorado State University, http://www.nrel.colostate.deu/projects/centruy5). The model has predicted SOC losses from repeated harvesting and thinning (after running it for 100 years). However, no such changes were observed within a few years of actual monitoring in the field. The authors conclude that verification or cross-validation between modelling and soil inventories will be difficult.

National SOC stocks based on modelling were calculated in CarboInvent Work Package 6 ("top-down approach"). The model Yasso has been used, which requires data on tree carbon and litter input to the soil, and simulates decomposition and SOC accumulation in several soil storage compartments. The results are presented in Ch. 3.4.1 (Table xy). The results also contain the inventory-based calculations conducted in Work Package 3 and illustrate once more the difficulties to compare the various approaches. Given the high accuracy of the inventory upscaling approach, the model greatly overestimates the baseline SOC for all test countries (except Spain and Ireland, where no direct comparisons are possible).

**Table 2: Reporting categories in the context of soil inventories**
(overlapping cells for Tier 2 or 3 mean that the same methodical approach can be done, but with increasing specifications and data density towards Tier 3)

| | **Mineral soil organic carbon**[2] | **Organic soils** | **Litter** (FWD, L, Of, Oh)[1] |
|---|---|---|---|
| **Tier 1** | – SOC stocks do not change with management<br>– default depth =30cm<br>– current C stock = $C_{REF}$ with soil C factors set to 1<br>– detailed description of the default climate regions and soils is needed | – default emission factor for drained peat land | – **no pool change** reported<br>– in case of significant changes in management /disturbance, apply Tier 2 |
| generic Tier 2 and Tier 3 methods | (a) refined Tier 1 based on country-specific data (only Tier 2)<br>(b) measurement-based (Tier 2 or Tier 3)<br>(c) model-based (mostly Tier 3) | | |
| **Tier 2** | – default depth =30cm, or lower<br>– $C_{REF}$ = C stock native land (Tier 2) or land use (mostly Tier 3) (= country-specific reference stock)<br>– country-specific stock change factors (measurements/experimental data, model simulations) | – cumulative loss of organic C throughout the profile due to drainage<br>– country-specific emission factors<br>– stratification (climate, management<br>– consideration of variable levels of drainage and decomposition | domestic (default) data[3]<br>(a) **process-based**: requires the tracking of inputs and outputs<br>(b) **stock change method** repeated inventories<br>(c) **model-based**: model input data needed; knowledge of DOM/litter dynamics<br><br>disturbance matrix recommended (Tier 2)<br>complex forest carbon accounting model (Tier 3; to track rates of input and loss) |
| | – more detailed stratification than default strata (management is at least: “intensive”, “extensive”)<br>– data may be preferably linked with NFI data (and/or wirth national and climate data bases); basic forest management changes can be addressed | | |
| **Tier 3** | – mostly done if SOC is key source<br>– yr-to-yr estimations of input parameters<br>– SIC<br>– addresses non-linearity of change<br>– advanced model application<br>– advanced stratification<br>– long-term effects of land-use and management based on measurements<br>– C transfers between pools may be represented<br>– estimation of human-induced effects<br>– establishment of permanent benchmark monitoring sites | approaches as above, but<br>– more sophisticated models<br>– improved parameterization<br>– improved input data<br>– higher stratification | |
| **Land-use change** | – general: converts land by climate region and soil type | *see above* | – the development of a disturbance matrix is recommended |
| | **Tier 1 (see above)**<br>– $SOC_{0-T}$= pre-conversion SOC<br>– $SOC_0$= SOC at last year during inventory time period<br>– both $SOC_{0-T}$ and $SOC_0$ require common set of $SOC_{Ref}$ and default stock change factors | | – **Tier 1**: defaults for the respective land-use categories<br>– requires values for the old and new land-use category |
| | – *Tier 1 refined, otherwise see above under Tier 2 and Tier 3* | | – **Tier2/3**: stratify are acc. to prior land use<br>– apply equation 3 and 4 |

[1] Dead organic matter (DOM) consists of litter (LT) and dead wood (DW); litter includes FWD up to a threshold (10cm) (IPCC 2006)
[2] including dead fine roots
[3] difference between Tier 2 and 3 depends on the quality of input data; model-based approach may be most likely Tier 3

In the following subchapters (2.1-2.3), some general aspects with regard to methods under the various Tiers are presented (see also Table 2).

## 2.1 TIER 1

Tier 1 estimates for CO2 emissions and removals use country-specific area estimates (land-area and changes in land area by categories) and default values of estimation parameters (SOC stock, or basic parameters such as C concentration, bulk density, stones). The **uncertainty** of Tier 1 values is expected to be highest and general because the available default parameters may not totally match the conditions of the country of concern. Uncertainty estimate are not quantified but expert-based (IPCC 2003). Default values can from the literature (Good Practice Guidance) are suggested to be used, and are partly provided in the GPG LULUCF (IPCC 2003).

Under Tier 1, no changes of SOC are assumed for forest remaining forest.

## 2.2 TIER 2

Tier 2 methods use country specific data (national default values). Activity data show little stratification, for example according to climate/management/disturbance categories. The calculations are mostly based on top-down approaches. The data sources often come from published data tables and are unlikely to be representative.

National SOC reference values (national default SOC stocks) should be stratified as much as possible (e.g. forest types, climate, site index, disturbance types etc.). The assessment of change is then based on area changes among the strata, as well as afforestation and deforestation. An example is provided by (VandenBygaart et al. 2004). They have investigated the sink strength of the Canadian agricultural sector over a 10-yr. period was quantified including a Tier 2 (IPCC 2000) quantification of uncertainties.

It is expected that Tier 2 reduces **uncertainty** of the sink/source estimate by providing country specific, representative data. IPCC (2003) expects inventory makers to identify and discuss more specific error sources (for example, those associated with data collection/measurements and sampling). Partial quantitative assessments can be provided for the uncertainty associated with statistical errors.

## 2.3 TIER 3

Tier 3 is completely based on representative country-specific information on carbon stock changes in the relevant storage pools The uncertainties of all estimation parameters are identified and quantified including possible systematic errors. The specific errors introduced by the sampling, the analysis, and the calculatory schemes (of pool size from a set of estimation parameters) have to be considered and added (see also CarboInvent D3.5). Depending on the national Tier 3 approach, the important driving factors for the carbon cycle might be identified and parameterised. Change assessment may be based on repeated sampling or modelling based on refined national This allows the application of dynamic models for extrapolation and verification purposes

# 3. Examples for considering SOC in UNFCCC and KP reporting systems

Under UNFCCC (before the new inventory guidelines (IPCC 2003) and the currently drafted 2006 AFOLU guidelines), soil reporting specifically addresses under land-use change and managed peat land. Stratification of soil C according to soil grouping, climate types and major forest types was already foreseen. Soil C from land-use change was mainly foreseen under cropland management.

Under the Kyoto Protocol (Articles 3.3 and 3.4), carbon stock changes shall be addressed for all 5 pools (see above). A pool does not need to be reported if the pool is not a source (which needs to be demonstrated in a transparent and verifiable way).

## 3.1 Tier 1 national soil C change estimates

Since according to Tier 1, SOC and litter do not change, no data were reported by most of the countries. However, reporting of “Tier 1 changes” using default data which can be applied to the afforested area is possible. Aspects of land use in European countries were often ignored because only small changes occur (except in southern Europe).

## 3.2 Tier 2 national soil C change estimates

Many European countries refer to the ICP countries Level I inventory to be used in GHG reporting. So far only one inventory (1990-1995) has been conducted (Vanmechelen et al. 1995).

For example, in France, SOC-change after land use change has been reported. The methodical approach is described in Pignard (2004). In France, the above-mentioned Level I inventory has been extended to all land uses (Arrouays et al. 2001). From that inventory the current typical soil C stocks according to land use can be derived ($C_t$). The reporting then applies a model to calculate the new soil C developing after land-use change considering the previous and consecutive land use.

$$C_{i(t-\Delta t)} = E_i + (C_{i(t)} - E_i) \bullet e^{(-k_i \bullet d_t)} \qquad \text{Eq. 6}$$

where:

$C_t$ = C tonnes/ha at time $t$
E = steady state SOC stock for new land use
k = kinetic decomposition factor specific for each land-use category
$i$ = SOC type (light and stable fraction)

The model distinguishes two organic matter types, with a fast and slow turnover rate. Because the initial SOC condition is assumed at steady state, the authors assume that this method overestimates the SOC change.

New Zealand is currently reporting SOC changes based on a Tier 2 assessment. With regard to the Kyoto Protocol, the inventory is intended to become improved by establishing a new national grid-based system. Especially with regard to soil carbon, the inventory is expected to become a Tier 3 approach which includes the coupling between inventories and above- and belowground C-cycling with models (Trotter et al. 2005). Soil C sampling is conducted through the above-mentioned forest inventories. So far, in order to come to baseline SOC estimates, national soil pedon data (national soil C database) are being used and stratified according to various land-use types and climate regions (N=39 strata).

Chronosequence studies coupled with soil sampling have been proven successful to demonstrate whether the SOC and litter pools act as a source or sink. For example Vesterdal et al. (2002) have shown for Denmark, that no significant changes in the mineral soil could be detected. On the other hand, in some cases, changes (gains) in the forest floor were significant. Since no soil losses were detected, SOC and litter do not have to be reported (unless the country decides to report the gains.

## 3.3 TIER 3 NATIONAL SOIL C CHANGE ESTIMATES FROM SOIL INVENTORIES

In all CarboInvent test countries, no distinction is made between managed and unmanaged forest land. In fact these decisions need to be taken nationally and are part of the GHG reporting system. Until then, all the forested land area is assumed to be managed. In none of the investigated countries, inventory data can be stratified according to forest management types (regeneration types, disturbance, plantations, etc.). The data in Table 3 present national soil C stock baseline estimates. The results presented here and in D3.5 are intended to provide a methodical basis for any country to investigate the ability of its soil inventory system to detect SOC change at a national level.

**Table 3: Results from the baseline stock estimates for the CarboInvent test countries (CarboInvent D3.5 using regression kriging)**

| | Germany | | | Austria | | | Spain | | |
|---|---|---|---|---|---|---|---|---|---|
| | total | STD | area km² | total | STD | area km² | total | STD | area km² |
| **O** | 228,264,774.32 (mean: 21.0) | 10.8 | 103,761.89 | 60,155,974.4 (mean: 16.3) | 8.6 | 36,883.3 | no data[2)] | | |
| **0-20** | 673,107,629.1 (mean 64.9)[1)] | 27.1 | 103,737.41 | 465,182,714.1 (mean: 124.0)[3)] | 43.1 | 37,505.6 | 680,378,675.2 (mean: 73.5) | 25.7 | 92,530.2 |
| **total** | 901,113,924.2 (mean 86.9) | 29.7 | 103,715.18 | 505,893,105.2 (mean: 141.4) | 45.5 | 35,776.5 | --- | --- | --- |

[1)] 0-30 cm
[2)] The regression model fort he O-layer was not sufficient due to the lack of forest stand tree species composition at the Level I inventory plots
[3)] 0-50 cm

Because for many inventories, very high numbers of plots are needed to detect SOC changes, Wilding et al. (2001) also suggest to work with lower confidence limits, for example 80 % instead of 95%. 95% certainty for SOC change estimate is recommended by the GPG LULUCF (IPCC 2004).

The only national inventory-based SOC change assessment is that of Bellamy et al. (2005), which is not yet part of the GHG reporting system, but which demonstrates the frame conditions of this approach. The results have been discussed above (Ch. 2). Combining the experience made by Bellamy et al. (2005) the findings in this project it can be concluded that a pure inventory based assessment of all soils (including organic soils) is difficult, and not possible within the uncertainty range and time frame set by the reporting requirements. Lowering the reliability of the change estimates may have to be accepted given that a Tier 1 assessment can always be applied which completely lacks a statistical basis to detect change.

Sweden is likely to take a Tier 3 reporting approach because a large quantity of NFI plots is sampled for soils as well, also in repeated inventories.

The inventory also considers shallow and thicker peat layers (covered by forest; mires not covered by forest belong to the category “wetland”), although the sampling procedures does not specifically address the sampling requirements to address SOC stock changes in peat, rather than changes in the C concentration of the measured top 30 cm. (give citations Stahl et al. 2004, 2005). However, it is not expected that the inventory dates match the reporting dates of the KP commitment period. This requires extrapolation of the measured stock differences to the respective dates. The application of models is expected to support the verification of SOC changes (reporting SOC changes for cropland and grassland will also be based on modelling).

## 3.4 TIER 3 NATIONAL SOIL C CHANGE ESTIMATES FROM MODELLING

Most countries known to develop reporting systems striving for Tier 3 pursue the use of modelling. For example in Finland, a recent research programme has been launched with the objective to develop an integrated system that combines measured data from inventories with models (YASSO), accompanied by a careful sensitivity and uncertainty analysis. The verification is achieved by cross-validation and comparison with micro-meteorological eddy flux data. The approach achieves a Tier 3 assessment. As mentioned above, New Zealand is developing a similar approach, so does Japan (see above). A similar system has already been in place for Canada (citation – see Tokyo proceedings).

**Table 4:CarboInvent results for test countries: SOC inventory and model-based assessment**

| mean [t C/ha] | Germany | Austria | Finland | Spain | Sweden | Ireland | Thuringia |
|---|---|---|---|---|---|---|---|
| geo-/class matching[1)] | 79.2 | 84.9 | 46.7 | 75.3 | 56.8 | 259.0 | 96.3 |
| YASSO | 128.5 | 131.9 | 77.4 | 59.9 | 86.6 | 70.6 | 118.0 |

[1)] Inventory reference period: 1990-1995
[2)] Reference year: 1995

It can be concluded from Table 4 that for managed forests, YASSO may not be capable to balance SOC stocks and stock changes for larger regions, rather than individual sites or ecosystem study sites with the proper input data. There is a strong need for further investigations regarding forest types, stand age, and effects of site class, for example.

A model approach has also been established in UK’s GHG reporting, thus separately accounting for annual C stock changes in trees, litter, soil and products (Cannell et al. 1999; Milne et al. 2002). UK started to have a full terrestrial C stock accounting in 1993. carbon gains and losses were reported for soils as well. The resolution was 20x 20 km grids, and average values for land use and land-use change were applied – which may be regarded a Tier 2 GHG reporting. By 1997 the inventory has been improved, and on the basis of the CORINE land cover map, a map resolution of 1 km was achieved. SOC changes were estimated using the C-Flow model (which covers all five terrestrial carbon storage pools).

# 4. Conclusions about the role of soil inventories in Kyoto Protocol reporting

CarboInvent WP3 has compiled the current knowledge about the ability and restrictions of existing soil inventories to monitor SOC changes. It has been found that there is a substantial lack of experience with change detection and uncertainty assessment in soil inventories. Some recent projects have been reviewed which focus on the integration of soil inventories with other approaches such as flux measurements. For example, in the Swedish LUSTRA programme, Berggren et al. (2002) have found agreement between SCO changes indirectly derived from eddy flux measurements, but the results did not correspond the a model exercise which came to the opposite result. Lettens et al. (2005) have found that the sink/source behaviour of soils for carbon may become reversed solely by correcting the data for the systematic error received from erroneous recovery factors for wet oxidation to determine the carbon concentration. Total national SOC stock estimates received from modelling and different upscaling approaches with soil inventory data also deviate. These findings motivate the conclusion that variability aspects as well as systematic errors are known but not satisfactorily addressed. The ability of models to reflect the SOC dynamics of forest soils, and vice versa, the ability of soil inventories to provide generate proper input data for modelling, are still very limited. Berggren et al. (2002) conclude that *long-term measurements of important components of the whole plant-soil system* are needed.

- Peatlands play a relevant role in the carbon balance of Nordic/Oceanic countries. If managed, they become a substantial source for $CO_2$, if unmanaged, it is a relevant source for $CH_4$. Definitions and treatment for peat vary as strongly as for no other land category. There is also a lack of methods about how to include peat into the forest soil monitoring, especially if soil C stock changes are to be detected. Additionally, reporting has to cover non-$CO_2$ trace gases, which increases the monitoring requirements.
- Changes in soil C are occurring in the medium-long term: problem/conflict for annual reporting?

Matthews and Broadmeadow (2003) conclude that any cost-efficient system to detect forest C stocks and stock changes (including SOC changes) will have to rely on models. Direct monitoring seems to be impractical given the uncertainties and cost involved with the number of plots needed. They do fulfil an important function for verification.

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