Forest Ecology and Management 270 (2012) 78–84

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass – A comparative study

Hans Petersson [a,*], Sören Holm [a], Göran Ståhl [a], David Alger [a], Jonas Fridman [a], Aleksi Lehtonen [b], Anders Lundström [a], Raisa Mäkipää [b]

[a] Department of Forest Resource Management, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden
[b] Finnish Forest Research Institute, FI-01301 Vantaa, Finland

ARTICLE INFO

Article history:
Received 1 July 2011
Received in revised form 3 January 2012
Accepted 4 January 2012
Available online 9 February 2012

Keywords:
Greenhouse Gas Inventory
Kyoto Protocol
Stock change method
Sweden
Tree allometry

ABSTRACT

Signatory countries to the United Nations Framework Convention on Climate Change (UNFCCC) and its supplementary Kyoto Protocol (KP) are obliged to report greenhouse gas emissions and removals. Changes in the carbon stock of living biomass should be reported using either the default or stock change methods of the Intergovernmental Panel on Climate Change (IPCC) under the Land Use, Land-Use Change and Forestry sector. Traditionally, volume estimates are used as a forestry measures. Changes in living biomass may be assessed by first estimating the change in the volume of stem wood and then converting this volume to whole tree biomass using biomass expansion factors (BEFs). However, this conversion is often non-trivial because the proportion of stem wood increases with tree size at the expense of branches, foliage, stump and roots. Therefore, BEFs typically vary over time and their use may result in biased estimates. The objective of this study was to evaluate differences between biomass estimates obtained using biomass equations and BEFs with particular focus on uncertainty analysis. Assuming that the development of tree fractions in different ways can be handled by individual biomass equations, BEFs for standing stock were shown to overestimate the biomass sink capacity (Sweden). Although estimates for BEFs derived for changes in stock were found to be unbiased, the estimated BEFs varied substantially over time (0.85–1.22 ton CO_2/m^3). However, to some extent this variation may be due to random sampling errors rather than actual changes. The highest accuracy was obtained for estimates based on biomass equations for different tree fractions, applied to data from the Swedish National Forest Inventory using a permanent sample design (estimated change in stock 1990–2005: 420 million tons CO_2, with a standard error amounting to 26.7 million tons CO_2) Many countries have adopted such a design combined with the stock change method for reporting carbon stock changes under the UNFCCC/KP.

1. Introduction

Although signatory countries are obliged to report greenhouse gas emissions and removals according to the United Nations Framework Convention on Climate Change (UNFCCC) and its supplementary Kyoto Protocol (KP; United Nations, 1998), Löwe et al. (2000) have identified a lack of consistency in national reporting of changes in forest and other woody biomass stocks. In addition, calculation methods for converting forest data to carbon dioxide (CO_2) – the most important greenhouse gas – differ between countries. The accuracy of estimates of standing volume and volume of growth is often unknown, and the quality of data is sometimes poor. However, in recent years many countries have improved their National Forest Inventories (NFIs), which are typically used to provide data for UNFCCC/KP-reporting (Tomppo et al., 2010). Normally, these NFIs have a sample-based design with sample plots inventoried in the field. Thus in general, area-based estimators are used to estimate changes in carbon pools.

According to the Revised 1996 Guidelines for National Greenhouse Gas Inventories (IPCC, 1997) and the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003), the national reporting of changes of CO_2 equivalents (or Global Warming Potentials, see IPCC, 2003) in forest and other woody biomass stocks can be calculated by a default method as the difference between growth and drain (harvest, natural mortality and natural disturbances). Alternatively, these changes can be calculated by the stock change method as the change in stocks between two consecutive inventories. In NFIs, changes in growing stock are often quantified in terms of the volume of stem wood (merchantable). For the Greenhouse Gas Inventory, this change in volume is multiplied by constants (biomass expansion factors) to convert from stem wood volume to whole tree biomass and then CO_2

---

* Corresponding author.
E-mail address: Hans.Petersson@slu.se (H. Petersson).

0378-1127 © 2012 Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.foreco.2012.01.004

equivalents (e.g., see Formula (5)). Another approach is to directly estimate the biomass per tree fraction by applying biomass regression equations (BiEqs) to sample trees and then converting the biomass to CO_2 equivalents by scaling (see, for example, Formula (1); Somogyi et al., 2007).

When estimating changes in living biomass at a national scale, it is usually difficult to obtain a reliable value for the whole tree biomass from the stem volume because stem proportion increases with tree size at the expense of branches, foliage, stump and roots (Fig. 1). Hence, the use of biomass expansion factors (BEFs) may lead to biased estimates because BEFs vary with tree size (age, etc.) and tree populations change over time (e.g., Satoo and Madgwick, 1982; Albrektson and Valinger, 1985; Pajtík et al., 2011).

When using the stock change method, to reduce the risk of bias BEFs should reflect the actual change in stock by incorporating the accumulation of growth per tree fraction with the effects of harvest and natural thinning patterns in one constant. Such BEFs can be derived but need to be updated if the allocation of growth and harvest patterns change. For practical reasons, instead of representing the actual change in stock, BEFs are often derived for the standing stock, which introduces an unknown bias into the estimates. To reduce the risk of bias, age-dependent (e.g., Lehtonen et al., 2004, 2007; Tobin and Nieuwenhuis, 2007) or volume-dependent (e.g., Schroeder et al., 1997; Fang et al., 2001) BEFs have been developed, which enable the ratio of whole tree biomass to stem volume to change with tree size. Levy et al. (2004) performed regression and variance analyses of BEFs and found that tree height was a better predictor than age. Therefore, in summary, there is a growing body of evidence that estimates based on BEFs are not constant but vary with tree, site and stand conditions (e.g., Jalkanen et al., 2005; Guo et al., 2010).

Currently, BEFs are frequently used for greenhouse gas reporting because the volumes of growing stock and stem-wood growth are usually the most reliable estimates in traditional forest inventories. However, only a few investigations have assessed the magnitude of potential error that may be introduced if the BEFs are incorrect (e.g., Lehtonen et al., 2007; Albaugh et al., 2009).

Using the Intergovernmental Panel on Climate Change (IPCC) stock change method (IPCC, 2003), the aims of this study were as follows:

(i) To compare differences between carbon stock change estimates of living biomass pools calculated using either individual tree volume equations combined with BEFs or individual tree biomass equations.
(ii) To assess differences between variances of estimators based on independent samples (temporary sample plots) and paired samples (permanent sample plots) in the BEF and in biomass equation approaches, respectively, and consider systematic errors.
(iii) To determine whether BEFs derived for change in stock (cf., BEFs for standing stock) are invariant over time.

2. Materials and methods

Data from the Swedish NFI (NFI; Ranneby et al., 1987; Axelsson et al., 2010) were used for greenhouse gas predictions. These data were suitable for two reasons: (i) they comprise individual tree data from about 30,000 permanent sample plots first inventoried before 1990 (base year of the KP) and re-inventoried every 5–10 years thereafter, (ii) national representative BiEqs and volume equations are available for all three species (Näslund, 1947; Marklund, 1987, 1988; Petersson and Ståhl, 2006). The data are summarized in Table 1.

The Swedish NFI (Axelsson et al., 2010) is a systematic cluster sample inventory that includes annual data for all land and fresh water areas (ca. 45 mill. ha), except for the high mountains in the northwest (ca. 2.3 mill. ha), which are not covered by trees, and urban areas (ca. 1.1 mill. ha). The clusters are square-shaped with sample plots along each side and are distributed throughout the country but have a higher density in southern than northern Sweden. Each year, about 6000 permanent sample plots are inventoried. For each circular sample plot (radius 10 m), extensive information is collected about the trees, stand and site. The main purpose of the Swedish NFI is to monitor forests for timber production and environmental factors.

In the present study, the FAO definition (FAO, 2004) of forest land was used, i.e., land areas spanning more than 0.5 ha with a tree crown cover of at least 10% and a minimum height of trees of 5 m. The values for crown cover and minimum height refers to trees maturing *in situ*, and the predominant land use must be forestry.

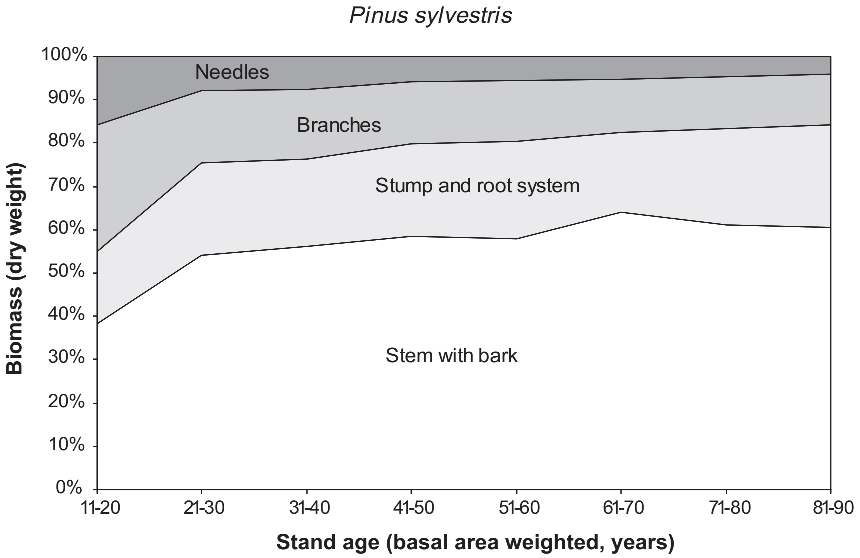

Fig. 1. Data showing the tree fractions for about 315 Scots pine sample trees collected during the summers of 1983–1985 (Marklund, 1987, 1988). The ratio stem with bark biomass (or volume) to whole tree biomass is normally not constant to tree or stand age (size).

Table 1
The stem volume of living trees in Sweden per stem diameter (dbh) for different species over time. Scots pine and Norway spruce were the dominant species. The proportion of larger trees and birch increased during the period 1998–2007. Values for 1998, 2003 and 2007 are based on moving average data for 1996–2000, 2001–2005 and 2005–2009, respectively (SLU, 2001, 2006, 2010).

Year	Species	dbh (cm)									Share by species
		0–9	10–14	15–19	20–24	25–29	30–34	35–44	45–	All	
		Volume (mill. m^3)									
1998	Scots pine	54.2	120.4	201.1	229.2	211.4	164.0	155.4	31.9	1167.7	38.8%
	Norway spruce	89.9	160.9	232.6	246.6	211.2	149.7	143.0	42.1	1276.0	42.4%
	Birch	77.7	75.8	67.4	47.4	28.3	15.9	12.5	3.7	328.7	10.9%
	Other	33.1	32.3	34.7	32.7	27.4	22.6	28.4	24.2	235.4	7.8%
	Total	254.9	389.4	535.8	555.9	478.3	352.2	339.3	101.9	3007.8	100.0%
2003	Scots pine	58.8	126.7	210.5	239.2	220.4	168.8	167.6	37.8	1229.6	38.5%
	Norway spruce	92.5	163.6	232.5	246.4	210.0	155.1	151.4	44.7	1296.2	40.6%
	Birch	86.3	84.5	75.1	53.1	33.9	18.0	16.8	4.2	371.9	11.6%
	Other	42.5	45.4	44.8	37.9	35.4	26.9	34.2	30.2	297.4	9.3%
	Total	280.1	420.2	562.9	576.6	499.7	368.8	370.0	116.9	3195.1	100.0%
2007	Scots pine	60.7	135.7	221.5	253.3	227.8	169.1	171.4	48.1	1287.5	38.9%
	Norway spruce	95.7	168.7	235.7	247.5	217.9	161.9	157.3	56.1	1340.8	40.5%
	Birch	94.7	97.8	87.6	62.2	37.9	21.3	20.1	6.9	428.5	12.9%
	Other	32.4	35.2	35.8	31.3	26.4	21.1	32.7	37.7	252.7	7.6%
	Total	283.5	437.4	580.6	594.3	510.0	373.4	381.5	148.8	3309.5	100.0%
Change 1998–2007	Scots pine	12.0%	12.7%	10.1%	10.5%	7.8%	3.1%	10.3%	50.8%	10.3%	
	Norway spruce	6.5%	4.8%	1.3%	0.4%	3.2%	8.1%	10.0%	33.3%	5.1%	
	Birch	21.9%	29.0%	30.0%	31.2%	33.9%	34.0%	60.8%	86.5%	30.4%	
	Other	−2.1%	9.0%	3.2%	−4.3%	−3.6%	−6.6%	15.1%	55.8%	7.3%	
	Total	11.2%	12.3%	8.4%	6.9%	6.6%	6.0%	12.4%	46.0%	10.0%	

Marklund (1987, 1988) pioneered the use of single-tree BiEqs for predicting the biomass of tree components, such as needles (not leaves), branches, bark, stem, stump and roots, of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pendula* and *Betula pubescens*, not stump and roots for birch). In deriving the BiEqs, the total fresh weight of each component per tree, and the fresh weight of samples from different components were measured in the field. The dry weight of each sample, defined as the constant weight at 105 °C, was measured in the laboratory and used for developing biomass equations per component. Trees were selected from 123 stands from different parts of Sweden, covering a wide variety of stand and site conditions. The resulting data were representative of Swedish forests at a national scale with the selected species constituting about 92% of the standing stem volume (SLU, 2010). Broad-leaved species constitute most of the remaining 8% and equations based on birch were applied for all broad-leaved species.

Marklund's (1988) below-ground BiEqs were developed to estimate biomass for forest fuels, and thus the total below-ground biomass is probably slightly underestimated by using the equations. To allow for all roots down to 2 mm diameter, BiEqs described by Petersson and Ståhl (2006) were applied. These equations were constructed by calibrating Marklund's data for sample trees, which included only the stump and coarse roots, against data for about 80 new trees that were inventoried in a similar way but with additional detailed information of small woody root fractions remaining in the ground (down to 2 mm root diameter). Petersson and Ståhl's (2006) trees were inventoried from six stands from the north, three stands from the middle and three stands from the southern part of Sweden. Sub-sampling of stump and roots and laboratory analyses were performed in a manner that tried to mimic the methodology used by Marklund (1988). Petersson and Ståhl's (2006) BiEqs were used to predict the biomass of stumps and roots for Scots pine and Norway spruce, but their BiEq for birch was based on only 14 birches and this was considered too small a sample to provide reliable results. Therefore, Petersson and Ståhl's (2006) Norway spruce below-ground biomass equations were applied to all broadleaved species. Above-ground referred to the biomass above stump height, which was assumed to be located at 1% of the tree height. The stem volume was defined as the volume of the stem including tip above stump height and bark, and it was estimated using Näslund's (1947) single tree volume equations based on 2390 Scots pines, 2425 Norway spruces and 1363 birches. As for the biomass equations, the data used in deriving the single tree volume equations corresponded to a wide variety of stand and site conditions and are representative of Swedish forests.

For most sample trees, only tree species and stem diameter at breast height (dbh, 1.3 m above the imaged germination point) were used as independent variables in the regression equations. However, for a small proportion (basal area weighted) of sample trees, data are available for the height, age and crown height. Given measured variables of tree, stand and site, the function with the lowest root mean squared error (RMSE) were applied (Marklund, 1988; Petersson and Ståhl, 2006). Biomass or volume referred to the biomass or volume of living trees with a stem diameter at breast height larger than 99 mm (threshold for trees that are positioned on the sample plots). A conversion factor of 0.50 was used to convert biomass (dry weight) to carbon equivalents (C) (ton). A stoichiometric conversion factor of 3.67 (44/12) was used to convert C to carbon dioxide equivalents (CO_2).

Using the stock change method (IPCC, 2003), the change in the living biomass pool was estimated in two ways: (a) by directly applying biomass regression equations (Marklund, 1988; Petersson and Ståhl, 2006) to sample trees of the Swedish NFI, and (b) by applying stem volume regression equations (Näslund, 1947) to sample trees of the Swedish NFI and then multiplying the estimated total stem volume by BEFs to convert stem volume to whole tree biomass (Table 2).

To represent commonly used approaches, two different estimators were tested (for case a in Table 2): an estimator adapted for a paired sample approach (representing a design with permanent sample units) and an estimator for an independent sample approach (representing a design with temporary sample units). For both approaches, the test data were based on paired samples, and therefore the estimates of biomass should have been the same. However, in principle, estimates of variance should be smaller for the paired sample approach. The variance estimators are described in Appendix A.

To investigate the effect of different BEFs on estimates of biomass, individual BEFs were derived from estimates of biomass and volume, using standing stock data, for the years 1990 and 2005. To estimate the change in biomass stock, each BEF was multiplied by the change in stem volume using either the paired sample or independent sample approach (b in Table 2). The corresponding variance estimators were derived by Taylor series expansion (Appendix B).

The change in biomass between 1990 and 2005 $\Delta\hat{B}$, a in Table 2) was estimated directly from BiEqs for different tree fractions using the following ratio estimator (Thompson, 1992):

$$\Delta\hat{B}_i = \frac{A_i}{\hat{A}_{i_{T_2}}} \cdot \Delta\hat{B}_{i_{T_2-T_1}} = A_i \cdot \frac{\sum_{j=1}^{n_i} \Delta b_{ij}}{\sum_{j=1}^{n_i} a_{ij}} \tag{1}$$

where A_i is the official land and fresh water area of stratum or region i (http://www.lantmateriet.se; 2011-12-12), $\hat{A}_{i_{T_2}}$ is the estimated land area of stratum i in 2005, $\Delta\hat{B}_{i_{T_2-T_1}}$ is the estimated change in biomass from 1990 to 2005 based on paired samples, Δb_{ij} is the change in biomass per sample unit j and a_{ij} is the inventoried area for sample unit j. The change in biomass at a national scale, $\Delta\hat{B}$, is estimated by summing over all strata.

A similar estimator, where the biomasses were estimated using an independent sample approach, was also derived:

$$\hat{B}^*_{T_2} - \hat{B}^*_{T_1} = \frac{A_i}{\sum_{j=1}^{n_i} a_{ij}} \cdot \left[\sum_{j=1}^{n_i} b_{ij_{T_2}} - \sum_{j=1}^{n_i} b_{ij_{T_1}} \right] \tag{2}$$

where $\hat{B}_{T_1}$ and $\hat{B}_{T_2}$ are the estimated biomasses for 1990 and 2005, respectively. The variance of both estimators described by (1) and (2) was estimated by a standard variance estimator for a ratio estimator (Appendix A, Thompson, 1992).

In the alternative method, using stem volume regression equations, two BEFs were calculated as follows:

$$\widehat{BEF}_{T_1} = \frac{\hat{B}^*_{T_1}}{\hat{V}^*_{T_1}} = \frac{\frac{A}{\hat{A}_{T_1}} \cdot \hat{B}_{T_1}}{\frac{A}{\hat{A}_{T_1}} \cdot \hat{V}_{T_1}} = \frac{\hat{B}_{T_1}}{\hat{V}_{T_1}} \tag{3}$$

$$\widehat{BEF}_{T_2} = \frac{\hat{B}_{T_2}}{\hat{V}_{T_2}} \tag{4}$$

where $\hat{V}_{T_1}$ and $\hat{V}_{T_2}$ are the estimated stem volumes in 1990 and 2005, respectively. A is the measured land area and $\hat{A}_{T_1}$ is the estimated land area at 1990.

The annual change in biomass from 1990 to 2005 was estimated based on paired samples as follows:

$$\widehat{BEF}_{T_2} \cdot \Delta\hat{V} = \frac{\hat{B}_{T_2}}{\hat{V}_{T_2}} \cdot \frac{A}{\hat{A}_{T_2}} \cdot \Delta\hat{V}_{T_2-T_1} \tag{5}$$

where $\Delta\hat{V}_{T_2-T_1}$ is the estimated change in volume between 1990 and 2005. The corresponding equations based on independent samples are

$$\widehat{BEF}_{T_1} \cdot [\hat{V}^*_{T_2} - \hat{V}^*_{T_1}] = \frac{A}{\hat{A}_{T_2}} \cdot \hat{B}_{T_1} \cdot \left[\frac{\hat{V}_{T_2}}{\hat{V}_{T_1}} - 1 \right] \tag{6}$$

$$\widehat{BEF}_{T_2} \cdot [\hat{V}^*_{T_2} - \hat{V}^*_{T_1}] = \frac{A}{\hat{A}_{T_2}} \cdot \hat{B}_{T_2} \cdot \left[1 - \frac{\hat{V}_{T_1}}{\hat{V}_{T_2}} \right] \tag{7}$$

It should be noted that the BiEqs and BEFs were derived at a national scale, whereas the estimates apply at a regional scale. Estimates at a national scale can be calculated by summing over all strata (31 strata in the whole of Sweden). The variances of the estimators described by (5)–(7) were estimated by Taylor series expansion (Appendix B).

3. Results

Biomass, stem volume and their changes with time were estimated using different estimators combined with the stock change approach (Table 3). BEFs derived using estimates of the standing stocks in 1990 and 2005 were found to be of the same order of magnitude (1.40 and 1.36 ton CO_2/m^3, respectively) (Tables 3 and 5). However, the BEF for the change in stock between 1990 and 2005 was lower (420/402 = 1.05 ton CO_2/m^3). Estimates of change in biomass stocks between 1990 and 2005 based on BEFs combined with estimates of stem volume were about 30% higher than those based on biomass equations. As expected, the paired sample method resulted in lower estimated sample variances than the independent sample method (Table 4). The BEFs were not constant over time (Table 5).

4. Discussion

4.1. Biased estimators and ways to reduce this bias

Assuming that separate biomass equations for different tree fractions can allow for these fractions developing in different ways, Table 3 indicates that estimates based on combining BEFs and stem volume overestimate the net change of living biomass in Sweden. This is probably because BEFs derived using estimates of standing stock do not represent the true relation between change in biomass and change in volume. Even though the true population is unknown due to sampling effects, this study indicates a large potential bias is introduced when BEFs based on the standing stock are used. This bias may be particularly large in the case of Sweden because the net change is the difference between large values for gross growth and gross harvest (equivalent to 170 vs. 129 M ton CO_2 per year). This corresponds to a stem volume growth of about 124 M m^3 per year (2006; The Swedish NFI) and a stem volume harvest of about 94 M m^3 per year (2006; Swedish Forest Agency, 2009). During the period studied, the average BEF based on the standing stock was estimated to be 1.38 (whole tree ton CO_2-equivalents/m^3 stem wood), whereas the average BEF for change in stock was estimated to be 1.15 (data for a few selected years are shown in Table 5). Norway spruce and Scots pine are also the dominant species in Finland, and according to the Finnish NFI, the BEFs for these species are 1.48 and 1.28 ton CO_2/m^3, respectively. Although the estimates based on BEFs derived for change in stock are probably unbiased, they varied substantially over time, which is likely due to a combination of sampling errors and real changes in BEFs over time. Therefore, in the absence of BiEqs, we would neither recommend the use of BEFs derived from stock estimates nor BEFs based on changes in stock. Instead, the use of age-dependent BEFs, or similar models described in Section 1, may help eliminate or reduce the risk of bias. However, the application of such models often requires comprehensive underlying data normally obtained from NFIs, which can be problematic. Forestry has made an important contribution to the Swedish economy for many years, which is why the Swedish NFI was started in 1923. The importance of forestry differs among countries and if it is not a key-category, the IPCC (2003) accepts a higher uncertainty (Tier 1) for reported carbon stock changes.

Our evaluation of the consequences of using BEFs relies on the assumption that biomass functions result in good (close to unbiased) results. This assumption rests on the ability of biomass functions to adapt to different conditions (through the measured independent variables) in a manner that BEFs cannot do. Although BEFs are assumed to be constants our results show that they vary substantially over time, and we think that this is an important

Table 2
Overview of principal biomass estimators, sample design and principal variance estimators. The biomass estimators (a and b) are explained in the text and the variance estimators in Appendixes A and B. Every estimate was evaluated for area-based sampling. BEFs were derived at a national scale, whereas all estimates were calculated per stratum (31 strata or regions in the whole of Sweden).

	Biomass estimator	Sample design	Variance estimator
a	$\Delta\hat{B}$	Paired samples	$Var(\hat{B}^*_{T_1}) + Var(\hat{B}^*_{T_2}) - Cov(\hat{B}^*_{T_1}, \hat{B}^*_{T_2})$
	$\hat{B}^*_{T_2} - \hat{B}^*_{T_1}$	Independent samples	$Var(\hat{B}^*_{T_1}) + Var(\hat{B}^*_{T_2})$
b	$\widehat{BEF}_{T_2} \cdot \Delta\hat{V}$	Paired samples	$Var[\widehat{BEF}_{T_2} \cdot \Delta\hat{V}]$
	$\widehat{BEF}_{T_1} \cdot [\hat{V}^*_{T_2} - \hat{V}^*_{T_1}]$	Independent samples	$Var[\widehat{BEF}_{T_1} \cdot (\hat{V}^*_{T_2} - \hat{V}^*_{T_1})]$
	$\widehat{BEF}_{T_2} \cdot [\hat{V}^*_{T_2} - \hat{V}^*_{T_1}]$	Independent samples	$Var[\widehat{BEF}_{T_2} \cdot (\hat{V}^*_{T_2} - \hat{V}^*_{T_1})]$

Table 5
Inconsistency in BEFs for standing stock and change in stock, for managed land in Sweden (whole tree tons of CO_2-equivalents per cubic meter stem volume).

Biomass estimator (ton CO_2/m^3)	Biomass expansion factor
$\widehat{BEF}_{1990}$	1.40
$\widehat{BEF}_{1995}$	1.39
$\widehat{BEF}_{2000}$	1.38
$\widehat{BEF}_{2005}$	1.35
$\widehat{BEF}_{1995-1990}$	1.22
$\widehat{BEF}_{2000-1995}$	1.08
$\widehat{BEF}_{2005-2000}$	0.85

message to people and countries involved in greenhouse gas reporting based on NFI-type data.

4.2. Comparing approaches

Although not studied here, the default method might be an alternative approach to the stock change method (IPCC, 2003). When using the default method, changes in biomass for the living biomass pool may be estimated by applying BEFs to growth and drain. We argue that the risk of bias is probably higher when using the default method and will now try to discuss why: The Swedish NFI provides estimates of stem volume and growth based on bore cores extracted from sample trees (on temporary sample plots). To obtain acceptable accuracy, the estimated growth is based on the last five fully developed annual year rings combined with average data for 5 years. This means that the growth for recent years has to be extrapolated. The drain is probably underestimated as it is difficult in the field to judge whether the harvest occurred within the last year, and a proportion of stumps are usually unidentified; however, we have tried to eliminate this underestimation by calibration from stock changes on permanent plots. Alternatively, harvests may be estimated indirectly from consumption or production statistics of harvested wood products. For both growth and drain we expect a large potential bias when converting volume to biomass. This bias may be reduced if separate BEFs are derived for growth and harvest. One advantage of using harvest statistics is the data is reasonably up to date but disadvantages include (i) both legal and illegal export/import need to be considered, (ii) the proportion of pulp that is biomass has to be known, (iii) the data does not account for natural mortality and (iv) harvest cannot be correlated with land use (harvest should be reported and recorded for several KP-activities). Thus, it is likely that the risk of systematic errors is higher using the default rather than the stock change method. The stock change method combined with data from a NFI typically does not have the disadvantages described above (i–iv), and the same methodology can be applied for all carbon pools (above-ground and below-ground biomass, litter, dead wood and soil organic carbon). Moreover, the stock change method for a permanent sample design minimizes the risk of double counting and makes it straightforward to gauge the accuracy of estimates.

4.3. A design for the future

We expected that the use of paired samples (permanent design) would be the most efficient method for estimating changes. This was verified by our results; the sample standard error when an independent sample design was used to mimic a NFI based on temporary sample plots was about twice that for a paired sample de-

Table 3
The estimated stock and change in stock of stem volume and biomass (CO_2 equivalents), for all land in Sweden; $B\hat{E}F^*_{1990} = 3650/2600 = 1.40$ (ton whole tree biomass in CO_2-equivalents per cubic meter stem volume) and $BEF^*_{2005} = 4070/3002 = 1.36$ (ton CO_2/m^3). $\Delta\hat{V}$ and $\Delta\hat{B}$ are derived according to Formula (1) and $\widehat{BEF}_{T_i}, \hat{V}^*_{T_i}$, and $\hat{B}^*_{T_i}$ according to Formula (3).

		Stock		Stock	Change in stock	
		1990		2005		2005–1990
Stem volume (M m^3)	2600	$\hat{V}^*_{1990}$	3002	$\hat{V}^*_{2005}$	402	$\Delta\hat{V}$
Tree biomass (CO_2 M ton)	3650	$\widehat{BEF}_{1990} \times \hat{V}^*_{1990}$	4214	$\widehat{BEF}_{1990} \times \hat{V}^*_{2005}$	564	$\widehat{BEF}_{1990} \times \Delta\hat{V}$
Tree biomass (CO_2 M ton)	3525	$\widehat{BEF}_{2005} \times \hat{V}^*_{1990}$	4070	$\widehat{BEF}_{2005} \times \hat{V}^*_{2005}$	545	$\widehat{BEF}_{2005} \times \Delta\hat{V}$
Tree biomass (CO_2 M ton)	3650	$\hat{B}^*_{1990}$	4070	$\hat{B}^*_{2005}$	420	$\Delta\hat{B}$

Table 4
Estimates of whole tree biomass (CO_2 equivalents) and corresponding estimate of accuracy for different estimators and sample designs.

	Biomass estimator	Formula	Sample design	Change in stock 2005–1990, CO_2 (M ton)	Standard error, CO_2 (M ton)
a	$\Delta\hat{B}$	(1)	Paired samples	420	26.7
	$\hat{B}^*_{2005} \times \hat{B}^*_{1990}$	(2)	Independent samples	420	66.0
b	$\widehat{BEF}_{2005} \times \Delta\hat{V}$	(4) and (5)	Paired samples	545	27.9
	$\widehat{BEF}_{2005} \times [\hat{V}^*_{2005} - \hat{V}^*_{1990}]$	(4) and (7)	Independent samples	545	68.3

sign. A lower sample error was also expected for estimates based on BiEqs compared to BEFs combined with volume. Again, the results supported this, but the differences seemed to be largely dependent on design rather than estimator. For all estimates, it should also be borne in mind that the influence of potentially incorrectly specified models was not considered.

It is evident that an increasing number of countries are using permanent design in their NFIs (Tomppo et al., 2010). Data inventoried by the NFIs are also frequently used as a basis when reporting changes in the carbon pool of living biomass under the UNFCCC/KP. We concur with this use and believe it is important to derive national representative biomass equations for individual species/groups of species.

5. Conclusion

This study supports the hypothesis that there is a risk of bias when estimating changes in living biomass using BEFs derived from standing stock data. BEFs derived for change in stock may be unbiased but vary substantially over time, which is undesirable. For countries with no representative biomass equations, age-dependent BEFs may be suitable alternatives.

The highest accuracy was obtained when estimating changes in living biomass using individual tree representative biomass equations per tree fraction. The equations were applied to a permanent sample based approach combined with the stock change method. Many countries have adopted the same or similar approach when reporting under the UNFCCC/KP and underlying data are normally obtained from a NFI.

Acknowledgement

The authors thank the MISTRA FutureForests program for part-funding this work.

Appendix A

Variance estimators for the ratio estimator (Formula (1)):

$$\Delta\hat{B} = A \cdot \frac{\Delta\hat{B}_{T_2-T_1}}{\hat{A}_{T_2}}$$

The ratio estimator was calculated at a regional scale:

$$\Delta\hat{B}_i = A_i \cdot \frac{\sum_{j=1}^{n_i} \Delta b_{ij}}{\sum_{j=1}^{n_i} a_{ij}} = A_i \cdot R_i$$

where $\Delta\hat{B}_i$ is the ratio estimated change in biomass for region i, A_i is the measured area of region i in 2005, Δb_{ij} is the change in biomass for region i and sample unit j between 1900 and 2005, a_{ij} is the estimated area for region i and sample unit j in 2005, and n_i is the number of sampling units (cluster of sampling plots) within region i. The estimated variance at a regional scale was calculated as follows:

$$\widehat{Var}(\Delta\hat{B}_i) \approx \frac{A_i^2}{\left(\sum_{j=1}^{n_i} a_{ij}\right)^2} \cdot n_i \cdot S^2_{\Delta b_{ij} - R_i \cdot a_{ij}}$$

where $S^2_{\Delta b_{ij} - R_i \cdot a_{ij}}$ is the square of the standard deviation based on $\Delta b_{ij} - R_i \cdot a_{ij}$. Each region constituted a stratum and the estimated variance for all strata (i.e., whole of Sweden) was calculated as follows:

$$\widehat{Var}(\Delta\hat{B}) = \sum_{i=1}^{N} \widehat{Var}(\Delta\hat{B}_i)$$

where N is the number of strata (counties in Sweden).

Variance estimators for the ratio estimator (Formula (2)):

$$\hat{B}_{T_2} - \hat{B}_{T_1} = \frac{A_i}{\sum_{j=1}^{n_i} a_{ij}} \cdot \left[\sum_{j=1}^{n_i} \Delta b_{ij_{T_2}} - \sum_{j=1}^{n_i} \Delta b_{ij_{T_1}}\right]$$

The formula was separated into

$$\hat{B}_{T_2} = \frac{A_i}{\sum_{j=1}^{n_i} a_{ij}} \cdot \sum_{j=1}^{n_i} \Delta b_{ij_{T_2}} \quad \text{and} \quad \hat{B}_{T_1} = \frac{A_i}{\sum_{j=1}^{n_i} a_{ij}} \cdot \sum_{j=1}^{n_i} \Delta b_{ij_{T_1}}$$

$\widehat{Var}(\hat{B}_{T_2})$ and $\widehat{Var}(\hat{B}_{T_1})$ were calculated separately. A similar procedure was used to evaluate $\widehat{Var}(\Delta\hat{B})$:

$$\widehat{Var}(\hat{B}_{T_2} - \hat{B}_{T_1}) = \widehat{Var}(\hat{B}_{T_1}) + \widehat{Var}(\hat{B}_{T_2})$$

Estimates of variances were made per stratum and summed over all strata to obtain values at a national scale.

Appendix B

Variance estimators for Formulae (5)–(7) by Taylor series expansion:

According to Formula (5):

$$\Delta\hat{B} = \widehat{BEF}_{T_2} \cdot \Delta\hat{V} = \frac{\hat{B}_{T_2}}{\hat{V}_{T_2}} \cdot \frac{A}{\hat{A}_{T_2}} \cdot \Delta\hat{V}_{T_2-T_1}$$

However, in practice BEFs are not applied to the same sample units that they are derived from. Therefore, to obtain a general formula we assume that the BEF was derived at T_3:

$$\Delta\hat{B} = \frac{\hat{B}_{T_3}}{\hat{V}_{T_3}} \cdot \frac{A}{\hat{A}_{T_2}} \cdot \Delta\hat{V}_{T_2-T_1}$$

$$\hat{u} = \frac{1}{A} \cdot \Delta\hat{B} = \frac{\hat{B}_{T_3}}{\hat{V}_{T_3}} \cdot \frac{\Delta\hat{V}_{T_2-T_1}}{\hat{A}_{T_2}} = B^*_{T_3} \cdot \Delta V^*_{T_2-T_1}$$

where $B^*_{T_3} = \frac{\hat{B}_{T_3}}{\hat{V}_{T_3}}$ and $\Delta V^*_{T_2-T_1} = \frac{\Delta\hat{V}_{T_2-T_1}}{\hat{A}_{T_2}}$.

Using Taylor series expansion (Kendall and Stuart, 1977):

$$\widehat{Var}(\hat{u}) \approx \widehat{Var}(B^*_{T_3}) \cdot (\Delta V^*_{T_2-T_1})^2 + \widehat{Var}(\Delta V^*_{T_2-T_1}) \cdot (B^*_{T_3})^2 + 2 \cdot B^*_{T_3} \cdot \Delta V^*_{T_2-T_1} \cdot \widehat{Cov}(B^*_{T_3}, \Delta V^*_{T_2-T_1})$$

If the sample units at T_3 are independent of those at T_2 and T_1 (i.e., if the *BEF* is derived from one sample and applied to another sample), then

$$Cov(B^*_{T_3}, \Delta V^*_{T_2-T_1}) = 0$$

If $T_3 = T_2$ and permanent sample units are used (dependence, Formula (5)) then

$$V^*_{T_2} = \frac{\hat{V}_{T_2}}{\hat{A}_{T_2}} \quad \text{and} \quad V^*_{T_1} = \frac{\hat{V}_{T_1}}{\hat{A}_{T_2}}$$

$$\Delta V^*_{T_2-T_1} = \frac{\hat{V}_{T_2} - \hat{V}_{T_1}}{\hat{A}_{T_2}} = \frac{\hat{V}_{T_2}}{\hat{A}_{T_2}} - \frac{\hat{V}_{T_1}}{\hat{A}_{T_2}} = V^*_{T_2} - V^*_{T_1}$$

$$\widehat{Var}(\Delta\hat{V}^*_{T_2-T_1}) = \widehat{Var}(V^*_{T_2}) + \widehat{Var}(V^*_{T_1}) - 2 \cdot \widehat{Cov}(V^*_{T_2}, V^*_{T_1})$$

$$Cov(V^*_{T_2}, V^*_{T_1}) = E(\hat{V}_{T_1}) \cdot Cov\left(\frac{\hat{V}_{T_2}}{\hat{A}_{T_2}}, \frac{1}{\hat{A}_{T_2}}\right); \hat{E}(\hat{V}_{T_1}) = V^*_{T_1} \quad \text{and}$$

$$\widehat{Cov}\left(\frac{\hat{V}_{T_2}}{\hat{A}_{T_2}}, \frac{1}{\hat{A}_{T_2}}\right) = \frac{1}{(A_{T_2})^2} \cdot n \cdot S^2_{V^*_{T_2}, \frac{1}{\hat{A}_{T_2}}}$$

$$\widehat{Cov}(B^*_{T_2}, \Delta V^*_{T_2-T_1}) = \widehat{Cov}(B^*_{T_2}, V^*_{T_2}) - \widehat{Cov}(B^*_{T_2}, V^*_{T_1})$$

$$\widehat{Cov}(B^*_{T_2}, V^*_{T_2}) = \frac{n}{\hat{V}_{T_2} \cdot \hat{A}_{T_2}} \cdot S^2_{B^*_{T_2}, V^*_{T_2}}$$

If $T_3 = T_2$ and temporary sample units are used (independence, Formulae (6) and (7)) then

$$Cov(V^*_{T_2}, V^*_{T_1}) \approx Cov(B^*_{T_2}, V^*_{T_1}) \approx 0$$

estimates of variances ($\overset{\wedge}{Var}(\hat{u})$) for both the permanent and temporary sample approaches were made per stratum and summed over all strata to obtain values at a national scale. This is a simplification since the BEFs were derived at a national scale.

References

Albaugh, T.J., Bergh, J., Lundmark, T., Nilsson, U., Stape, J.L., Allen, H.L., Linder, S., 2009. Do biological expansion factors adequately estimate stand-scale aboveground component biomass for Norway spruce? For. Ecol. Manage. 258, 2628–2637.

Albrektson, A., Valinger, E., 1985. Relations between trees height and diameter, productivity and allocation of growth in a Scots pine sample tree material. In: Crop physiology of Forest Trees, Proceeding of an International Conference. University of Helsinki, Department of Plant Breeding, pp. 95–105.

Axelsson, A.L., Ståhl, G., Söderberg, U., Petersson, H., Fridman, J., Lundström, A., 2010. Development of Sweden's National Forest Inventory. In: Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., (Eds.), National Forest Inventories – Pathways for Common Reporting. USA, pp. 541–553.

FAO, 2004. Global Forest Resources Assessment Update 2005 – Terms and Definitions. Food and Agriculture Organization of the United Nations, Forestry Department, Forest Resource Assessment Programme. Working Paper 83/E, Rome, 2004.

Fang, J.Y., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292, 2320–2322.

Guo, Z., Fang, J., Pan, Y., Birdsey, R., 2010. Inventory-based estimates of forest biomass carbon stocks in China: a comparison of three methods. For. Ecol. Manage. 259, 1225–1231.

IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change. IPCC/OECD/IEA, Paris, France.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC/OECD/IEA/IGES, Hayama, Japan.

Jalkanen, A., Mäkipää, R., Ståhl, G., Lehtonen, A., Petersson, H., 2005. Estimation of the biomass stock of trees in Sweden: comparison of biomass equations and age-dependent biomass expansion factors. Ann. For. Sci. 62, 1–10.

Kendall, M.G., Stuart, A., 1977. The Advanced Theory of Statistics, fourth ed. vol. 1, Griffin, London, 1977.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEF) for Scots pine, Norway spruce and birch according to stand age for boreal forests. For. Ecol. Manage. 188, 211–224.

Lehtonen, A., Cienciala, E., Tatarinov, F., Mäkipää, R., 2007. Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic. Ann. For. Sci. 64, 133–140.

Levy, P.E., Hale, S.E., Nicoll, B.C., 2004. Biomass expansion factors and root:shoot ratios for coniferous tree species in Great Britain. Forestry 77, 421–430.

Löwe, H., Seufert, G., Raes, F., 2000. Comparison of methods used within Member States for estimating CO_2 emissions and sinks according to UNFCCC and EU Monitoring Mechanism: forest and other wooded land. Biotechnol. Agron. Soc. 4, 315–319.

Marklund, L.G., 1987. Biomass functions for Norway spruce (*Picea abies* (L.) *Karst.*) in Sweden. Swed. Univ. of Agric. Sciences, Dep. of For. Surv., Report, 43, p. 127.

Marklund, L.G., 1988. Biomass functions for pine, spruce and birch in Sweden. Swed. Univ. of Agric. Sciences, Dep. of For. Surv., Report, 45, p. 73 (In Swedish with English summary).

Näslund, M., 1947. Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i södra Sverige samt i hela landet. Meddelande från Statens Skogsförsöksanstalt, vol. 36, p. 3 (in Swedish).

Pajtík, J., Konopka, B., Lukac, M., 2011. Individual biomass factors for beech, oak and pine in Slovakia: a comparative study in young naturally regenerated stands. Trees 25, 277–288.

Petersson, H., Ståhl, G., 2006. Functions for below-ground biomass of *Pinus sylvestris*, *Picea abies*, *Betula pendula* and *B. pubescens* in Sweden. Scand. J. For. Res. 21, 84–93.

Ranneby, B., Cruse, T., Hägglund, B., Jonasson, H., Swärd, J., 1987. Designing a new national forest survey for Sweden. Studia Forestalia Suecica 177, 29.

Satoo, T., Madgwick, H.A.I., 1982. Forest Biomass. Forestry Sciences. Martinus Nijhoff/Dr. W. Junk, The Hague, p. 152.

Schroeder, P., Brown, S., Mo, J., Birdsey, R., Cieszewski, C., 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. For. Sci. 43, 424–434.

SLU, 2001. Forestry statistics 2001, Official Statistics of Sweden, Swedish University of Agricultural Sciences, Umeå, Sweden, p. 104 (in Swedish).

SLU, 2006. Forestry statistics 2006, Official Statistics of Sweden, Swedish University of Agricultural Sciences, Umeå, Sweden, p. 114 (in Swedish).

SLU, 2010. Forestry statistics 2010, Official Statistics of Sweden, Swedish University of Agricultural Sciences, Umeå, Sweden, p. 100 (in Swedish).

Somogyi, Z., Cienciala, E., Mäkipää, R., Muukkonen, P., Lehtonen, A., Weiss, P., 2007. Indirect methods of large-scale forest biomass estimation. Eur. J. For. Res. 126, 197–207.

Swedish Environmental Protection Agency, 2006. Sweden's National Inventory Report 2007-Submitted under the United Nations Framework Convention on Climate Change. The Swedish Environmental Protection Agency, Bromma, Sweden, p. 281.

Swedish Forest Agency, 2009. Swedish Statistical Yearbook of Forestry. Official Statistics of Sweden (in Swedish).

Thompson, S.K., 1992. Sampling. Wiley Series in Probability and Mathematical Statistics, USA, p. 343.

Tobin, B., Nieuwenhuis, M., 2007. Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. Eur. J. For. Res. 126, 189–196.

Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E., 2010. National Forest Inventories – Pathways for Common Reporting. USA, p. 612.

United Nations, 1998. Report of the conference of the parties on its third session, held at Kyoto from 1 to 11 December 1997. UNFCCC, FCCC/CP/1997/7/Add.1, p. 60.