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The costs of monitoring changes in forest soil carbon stocks

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The forest soil carbon sink is of potentially great monetary value under subsequent climate conventions, but the costs of reliable monitoring have never been analysed. Our study aimed at evaluating (1) costs and precision of varied sampling intensities at the plot level, (2) sample size, and (3) costs needed to detect a change in soil carbon at the national scale. Organic layer carbon measurements cost 520 euros per plot if 10 samples are analysed. At plot scale, the precision obtained with such sampling allows detection of a large change > 860 g C m^{-2}. At the national scale, two measurement rounds on a minimum of 3000 plots are needed to detect an expected change of 11 g C m^{-2} yr^{-1} in the organic layer of upland forest soils with a 10-year sampling interval. Measuring such a network once costs approximately 4 million euros, which is about 8% of the value of the annual CO_2 sequestration of 2.57×10^6 t CO_2 of upland forest soils in Finland.

Introduction

Monitoring changes in soil carbon stocks is a topical challenge due to the current requirements to report the carbon balance of forests under the Kyoto Protocol. Forests are included in the Protocol due to their potentially major effect on the atmospheric CO_2 concentration (UNFCCC 1997). The soil contains the major proportion of the forest carbon stock (the soil carbon stock represents over 60% of the total amount of carbon in upland boreal forests) and it also makes a considerable contribution to the forest carbon balance in individual countries (de Wit *et al.* 2006, Liski *et al.* 2006). Currently, changes in the carbon stock of forest soils have to be reported as a part of national greenhouse gas (GHG) reporting to the Climate Convention (UNFCCC 2001, IPCC 2003). Furthermore, carbon sequestration projects (specific clean development mechanism (CDM) and joint implementation (JI) projects) under the Kyoto Protocol need to verify stand scale changes in the vegetation and soil carbon stocks before the obtained carbon sinks are eligible in the carbon markets. In addition to reporting requirements under the international commitments, there are also scientific needs to monitor soil carbon in order to verify hypotheses on the feedbacks between soil processes and the atmosphere. The ability to detect changes in the soil carbon stocks by means of repeated measurements also forms a basis for testing the validity of soil carbon models that have applications ranging from ecosystem studies to nation-wide scenarios of the future GHG balance.

The soil carbon stock is large, and changes in boreal soils are expected to be small in relation to the size of the stock (Peltoniemi *et al*. 2004, Ståhl *et al*. 2004, Ågren *et al*. 2007). It is a challenging task to detect a small change in a large stock, especially in the case of forest soils where the regional between-site variation and spatial within-site variation are large (Conant *et al*. 2003, Yanai *et al*. 2003). Thus, only a few studies have been successful in reporting soil carbon changes at a number of sites in boreal forests on the basis of repeated sampling (e.g. Tamminen and Derome 2005), and only Sweden has a representative network of sample plots with repeated soil sampling where this could be attempted at a national scale (Ståhl *et al*. 2004). Since measuring soil carbon changes is a laborious and expensive undertaking, reporting the changes in the soil carbon stock is commonly based on soil carbon models (Peltoniemi *et al*. 2007).

According to model simulations, the current rate of soil carbon sequestration is estimated to be 11 g C m^{-2} yr^{-1} in Finland, 8 g C m^{-2} yr^{-1} in southeastern Norway, and 7.5 g C m^{-2} yr^{-1} in Sweden (de Wit *et al*. 2006, Liski *et al*. 2006, Ågren *et al*. 2007). In upland forest soils in Finland, the long-term (over 80 years) average annual soil carbon sequestration is reported to be 0.7×10^6 t C yr^{-1}, which is equivalent to 2.57×10^6 t CO_2 per year (Liski *et al*. 2006). The price of carbon allowances in the EU has varied from 12 to 25 euros per CO_2 tonne (http://www.climatecorp.com/pool.htm). Thus, assuming that the price of one CO_2 tonne is e.g. 20 euros, then the value of the soil carbon sink in Finland is 51 million euros per year. However, during the commitment period of the Kyoto Protocol, only a minor part (in Finland 0.6×10^6 t CO_2 per year) of the total carbon sink of forested land can be credited (UNFCCC 2001). The overall role of carbon sequestration by forest soil and vegetation will be under discussion during the negotiations of the subsequent commitment periods. However, verified carbon sinks resulting from the specific CDM and JI projects are eligible, and can be traded under the Kyoto Protocol already during the first commitment period (2008–2001).

The carbon sink of forest soils is, potentially, of considerable monetary value if the sinks are internationally accepted for creditation under a subsequent climate convention and if the validity of the soil carbon sinks can be confirmed. Potential methods for assessing forest soil carbon are currently being proposed, evaluated and implemented (e.g. IPCC 2003, de Wit *et al*. 2006, Liski *et al*. 2006, Ågren *et al*. 2007, Peltoniemi *et al*. 2007). In general, the methods are based on soil modelling, because soil carbon monitoring with repeated measurements is assumed to be too laborious and expensive. However, the costs of soil carbon monitoring on a representative, national-scale grid have so far not been reported. The efficiency of soil monitoring can be considerably improved through an advanced sampling design, i.e. selection of an appropriate sampling interval and stratified sampling, but their cost efficiency is not known. Cost analysis of potential sampling schemes forms the basis of evaluating the efficiency of national sampling designs in economic terms. In addition to evaluation of large-scale sampling schemes, cost analysis of stand-scale soil carbon monitoring is also needed, because monitoring data should be available to facilitate testing the validity of soil carbon models that are already applied in the national GHG inventories. Understanding the cost structure of stand-level monitoring is also needed for evaluating the economic feasibility of carbon sequestration projects such as CDM and JI projects under the Kyoto Protocol.

In this study, we evaluated the costs of different sampling intensities at the plot level, and the costs of measuring a reliable network of monitoring plots at the national scale. The specific questions addressed in this study were:

1. What is the relationship between sampling intensity and measurement costs in plot-scale soil carbon monitoring?
2. What is the number of sample plots needed at the national scale for the detection of a change in the soil carbon stock?
3. How are the monitoring costs of the required number of plots related to the potential monetary value of the detected soil carbon sink at the national scale?

The respective hypotheses set in this study were (i) that the economic feasibility of carbon sequestration projects in which stand-level monitoring of soil carbon is required are limited by the high monitoring costs, and (ii) that the costs of sampling-based monitoring of a nation-wide grid of sample plots are low in comparison with the potential monetary value of the forest soil carbon sink in Finland.

Material and methods

Cost estimation at the plot scale

A change in the soil carbon stock can be determined as the difference between the initial and subsequent measurements at the sampled sites. In this study we calculated the costs of remeasuring the soil carbon stock, i.e. the costs of one sampling round on a plot established and measured earlier. Thus, the total costs of the initial and the second measurement of a plot would be approximately twice the costs reported here (but corrections resulting from the development of methods and inflation should be taken into account).

Soil monitoring costs have a fixed and a variable components. At the plot scale, the variable component varies in direct proportion to the number of soil samples (n), while the fixed component is independent of n. The fixed component includes the costs of access to a sample plot and preparations for the soil sampling: direct personnel costs of driving and walking time (salaries), as well as the costs of transportation, daily allowances and accommodation. The variable component includes the costs (salaries and other costs) of soil sampling, sample preparation and laboratory analyses.

We compared different sampling intensities at the plot scale in terms of time required, total costs and accuracy of the obtained estimates.

At the plot scale, the time required for measuring soil carbon (m_{time}) in the organic layer was estimated as

$$m_{time} = (k_{time} + n \times t_{time}) \quad (1)$$

where k_{time} is a fixed time period per plot, and the variable component of time required, $n \times t_{time}$, was estimated as

$$n \times t_{time} = n(t_{fld} + t_{pre} + t_{pw} + t_{mst} + t_{C}) \quad (2)$$

where n is the number of samples per plot, t_{fld} is time used in sample auguring in the field, t_{pre} is time use for preparing and drying a sample, t_{pw} is time used for milling the samples, t_{mst} is time needed for moisture content determination, and t_{C} is time used for the carbon analysis of a soil sample. Time required for the different work phases was assessed during the resampling of 38 sample plots in the network of permanent sample plots of the Finnish National Forest Inventory. Times required are reported in Appendix. The average costs and time required for laboratory analysis at the Finnish Forest Research Institute (reported in Appendix) were applied in calculating the monitoring costs.

The costs of measuring carbon (m_{cost}) in the organic layer of a plot were estimated as

$$m_{cost} = (k_{cost} + n \times w_{cost}) \quad (3)$$

where k_{cost} is fixed costs, and the variable costs, $n \times w_{cost}$, were estimated as

$$n \times w_{cost} = n(w_{fld} + w_{pre} + w_{pw} + w_{mst} + w_{C}) \quad (4)$$

where w_{fld} is the costs of sample auguring in the field, w_{pre} is the costs of preparing and drying a sample, w_{pw} is the costs of milling, w_{mst} is the costs of determining the moisture content, and w_{C} is the costs carbon analysis of a soil sample.

The costs resulting from measuring the mineral soil layers were estimated as

$$b_{cost} = l \times n(v_{fld} + v_{pre} + v_{pw} + v_{mst} + v_{org}) \quad (5)$$

where l is the number of mineral soil layers to be sampled, n is the number of soil samples per layer, v_{fld} is the costs of sample auguring in the field, v_{pre} is the costs of the preparation and drying of a sample, v_{pw} is the costs of sieving, v_{mst} is the costs of determining the moisture content, and v_{org} is the costs of determination of the organic matter content.

In addition to estimating the costs with a variable number of soil samples per plot, we also calculated the costs of pooled sampling in which 20 sub-samples were taken from the organic layer and 20 sub-samples from each of the three mineral soil layers (to a depth of 40 cm), and then pooled by layer before laboratory analysis in which only one sample per layer per plot was analysed.

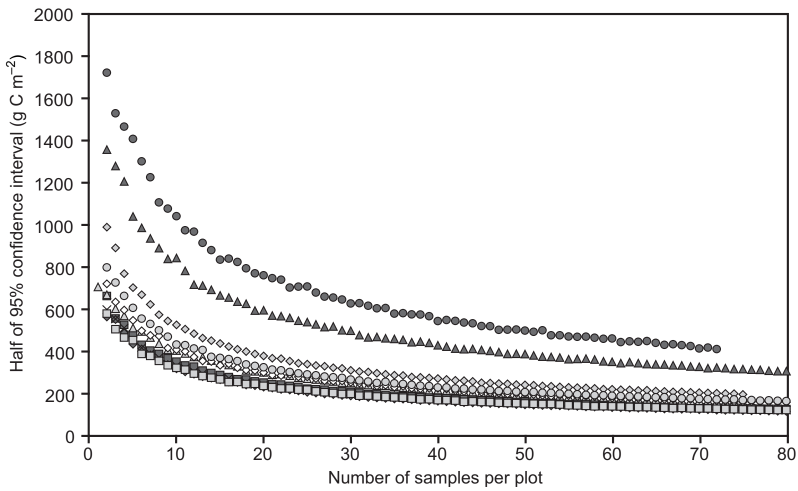

Fig. 1. 95% confidence intervals (g C m^{-2}) of the carbon stock in the organic layer according to sample size (n per plot) for five intensively sampled Norway spruce plots (shown by light grey and open symbols) and five Scots pine plots (shown by × and dark grey symbols) (according to P. Muukkonen unpubl. data).

The gain in the accuracy of the plot mean C stock was assessed as a function of the measurement costs. In this cost analysis, we used as source data the relationship between the accuracy of the estimated mean and the number of samples per plot (Fig. 1) for the 10 intensively sampled plots (5 Scots pine stands and 5 Norway spruce stands that represented intermediate age classes). In their study focussing on the within-site spatial variation of the carbon stock, a total of 73–116 organic layer samples were taken with a soil corer (∅ 58 mm) at each study site, and the sampling points were located on a grid with distances ranging from 0.10 m to several meters to allow analysis of the spatial autocorrelation (Muukkonen *et al*. 2009).

Number of plots needed for detection of a change at the national scale

The number of plots needed for detection of a change in the soil carbon stock was estimated using the equation:

$$n = (t \times s/E)^2 \quad (6)$$

where n is the number of sample plots required, t is a value taken from Student's t distribution table for a given number of degrees of freedom and desired confidence interval, s is the estimated standard deviation of the measured values, and E is the desired half of the confidence interval (Avery and Burkhart 1994, Smith 2001). The desired confidence interval of a carbon stock estimate should allow detection of the expected change in the soil carbon stock. We assumed that the average rate of change is 11 g C m^{-2} yr^{-1}, as has been predicted by models (Liski *et al*. 2006). Thus, the desired half of the confidence interval of the carbon stock estimate (E) is 27.5 g C m^{-2} with a sampling interval of 5 years, increasing to 137 g C m^{-2} with extension of the sampling interval to 25 years (assuming that the carbon change increases linearly over time).

Since the regionally representative mean soil carbon stock and its standard deviation have not yet been measured, we assumed a standard deviation of 1000 g C m^{-2}, which is the value reported for the mean carbon stock of the uppermost soil layers (Peltoniemi *et al*. 2004). In addition, we applied values of 1250 and 1500 g C m^{-2} for the standard deviation in order to determine the sensitivity of the results to this assumption.

Costs of monitoring a network of plots

At the monitoring network level, the costs vary in direct proportion to the number of sampled plots and sampling frequency, while the fixed costs consist of the establishment costs of monitoring, such as training the field personnel, setting up a database, purchasing field equipment, analysing data, etc. The fixed costs of monitoring a network of plots are not assessed in this study,

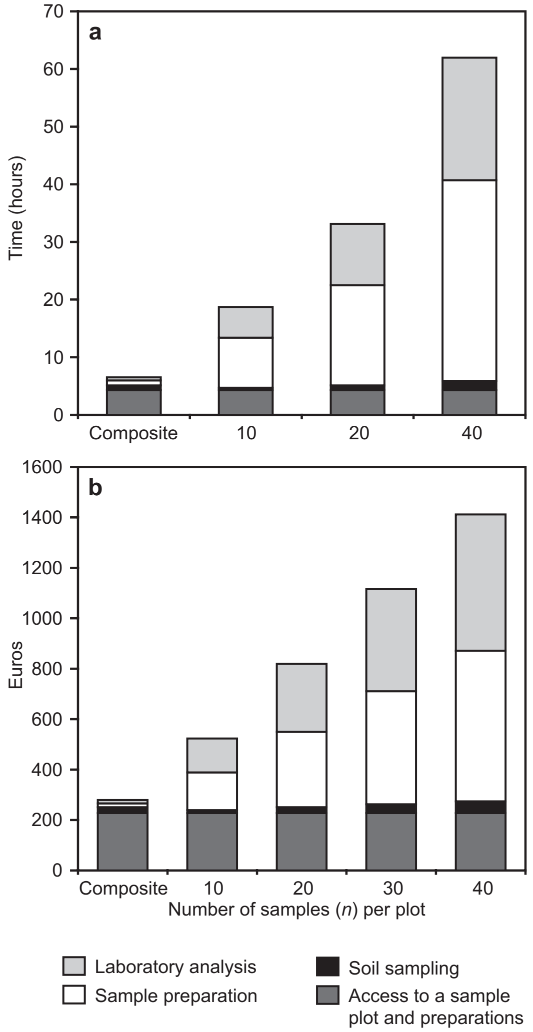

Fig. 2. Resources in (**a**) time and (**b**) euros needed for sampling the organic layer on one plot with different sampling designs (number of samples per plot varied from one composite sample to 40 separate sub-samples).

because they cannot be generalized to other countries and organizations.

The monitoring costs of the network of sample plots (M) was estimated as

$$M = N(m_{cost} + b_{cost}) \quad (5)$$

where N is the total number of plots in a monitoring network, m_{cost} is the cost of measuring carbon in the organic layer of a plot (including fixed costs (k_{cost}), and variable costs ($n \times w_{tot}$), b_{cost} is the cost of measuring carbon in three mineral soil layers (to a depth of 40 cm) on a plot. The measurement costs of the organic layer were estimated with the assumptions of both 10 and 20 soil samples per plot, and the costs of three mineral soil layers (b_{cost}) were estimated with the assumption of both 10 and 20 soil samples per plot from each of three mineral soil layers. In addition, we estimated the costs with pooled (composite) sampling where plot-wise samples were pooled before the laboratory analyses, and only one sample per layer per plot was analysed, i.e. $n = 1$ in Eqs. 4 and 5.

Results

Measuring costs of soil carbon changes at the plot scale

The costs of measuring carbon in the organic layer increased from 280 euros to 820 euros per plot when the number of soil samples analysed increased from one pooled sample to 20 individually analysed samples (Fig. 2b). These costs included both fixed costs (e.g. transportation and preparations of the sampling) and variable costs of the measuring. The fixed costs that are not dependent on either the sample size or the number of sampled layers was 230 euros per plot (Fig. 2b). In addition to measurements on the organic layer, measuring also the carbon stock in three mineral soil layers costs 140 euros when only one pooled sample per layer is analysed, but 1700 euros if 20 samples per plot are analysed separately. With pooled sampling the total required for measuring carbon in the organic and mineral soil layers was 15.4 hours per plot (3.2 for transporting the field personnel, 1.1 hours for finding the plot and making preparations, 2.2 hours for organic layer sampling and analysis, and 8.9 hours for the sampling and analysis of 3 mineral soil layers down to a depth of 0.5 m; *see* Appendix). Increasing the number of samples per plot, especially, affected the time required for sample preparation (drying and milling the samples), which accounted for 52% of the time required and 36% of the total costs of measuring carbon in the organic layer when 20 samples were taken per plot (Fig. 2).

The total costs of measuring carbon in the organic layer were 47 euros per soil sample, of which 70% were personnel costs (Fig. 3). The most time-consuming part of the work was sample preparation for the laboratory analysis; drying and milling accounted for 44% of the personnel costs per sample. The overall cost breakdown for the mineral soil samples was similar, although the time required for each mineral soil layer was assumed to be twice the time used for organic layer sampling.

The total costs of measuring the soil carbon stock in the organic layer increased approximately from 520 to 1100 euros with an increase in the number of samples per plot from 10 to 30. However, the gain achieved with the increased sampling costs was improved precision of the estimate, e.g. in one of the Norway Spruce stands the width of the 95% confidence intervals of the mean estimate of the carbon stock in the organic layer decreased by 160 g C m^{-2} (from 430 to 270 g C m^{-2}) with a 500 euro increase in costs per plot (Fig. 4). Thus, at the plot level, a change of 860 g C m^{-2} in the carbon stock in the organic layer can be measured (a detectable change has to be larger than two times the width of the confidence interval) by repeated sampling with costs of 500 euros per plot, while the costs of detecting a smaller change of 540 g C m^{-2} are doubled (Fig. 4).

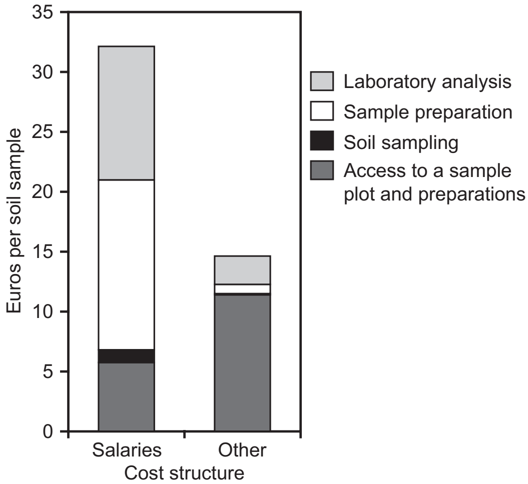

Fig. 3. Salaries and other costs of the sampling and analysis of one soil sample.

Soil carbon monitoring at the national scale

The approximate estimate for the minimum number of sample plots required to detect a change in the forest soil carbon stock in Finland is 3000 plots with a sampling interval of 10 years (Fig. 5). This sampling intensity allows detection of an expected change of 110 g C m^{-2} per 10 year if the standard deviation of the measured carbon stock is smaller than 1500 g C m^{-2}. If the sampling interval is extended to 15 years, then a minimum of 1200 plots need to be measured

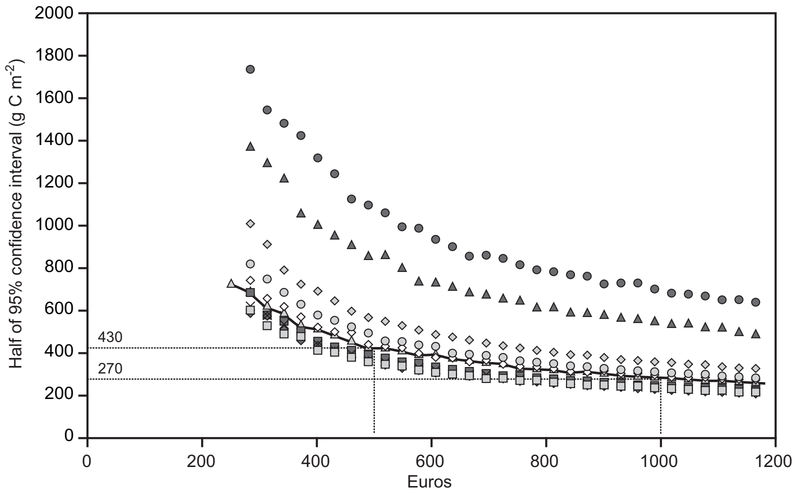

Fig. 4. Precision (g C m^{-2}) of the organic layer carbon stock estimate of a plot according to the measurement costs on five Scots pine plots (× and dark grey symbols) and on five Norway spruce plots (light grey and open symbols).

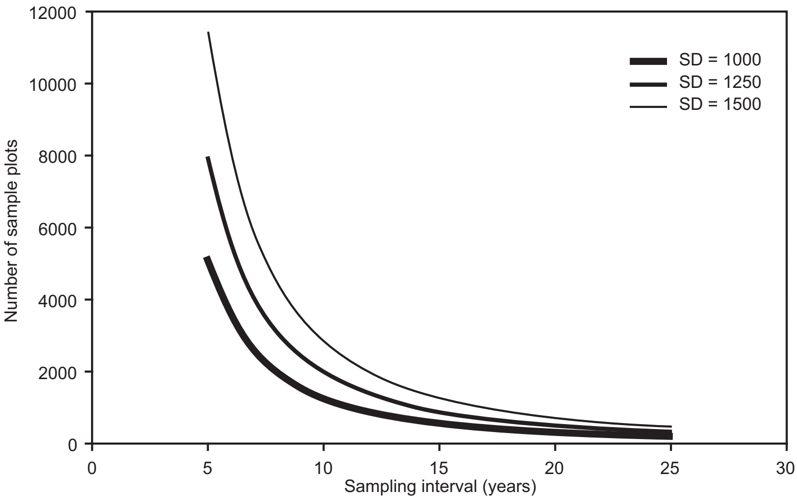

Fig. 5. Sample size required with different sampling intervals calculated on the basis of the assumption that the change to be detected is 11 g C m^{-2} per year. Standard deviation (SD) of carbon stock measurements was assumed to be 1000 g C m^{-2} (Peltoniemi *et al.* 2004). Larger values (1250 and 1500 g C m^{-2}) were applied to show the sensitivity of the results to this assumption.

to detect a change under the assumption that the rate of change and trend are constant.

The total costs of carbon measurements in a network of 3000 plots were estimated to be approximately 1.5 million euros if only pooled samples are taken (Table 1). With 10 organic layer samples per plot, and 10 samples from each of the three mineral soil layers, the total costs were 4 million euros. Since the change can only be estimated on the basis of two consecutive measurements of a network of plots, the costs of measuring the change can be approximated to be more than double this figure.

Discussion

Monitoring costs at the plot scale

At the plot scale, detection of a change in the soil carbon stock presupposes repeated intensive sampling that provides the information required for estimating the within-site variation in the soil carbon stock. Measuring the within-site variation is a laborious undertaking; in the case of 20 organic layer samples per plot, sample preparation and laboratory analysis accounted for 85% of the total time required for measuring a plot and the total costs were 3-fold those in pooled sampling. According to our results, measuring the carbon in the organic layer costs 1100 euros per plot if 30 samples per plot are analysed. At plot scale, the precision obtained with such a sampling protocol is low allowing detection of a change that is larger than 540 g C m^{-2} (equivalent to 20 t CO_2 per ha). In a chronosequence study, the average increase in the organic layer was 47 g C m^{-2} during a 10-year period (Peltoniemi *et al*. 2004). Thus, a change in the carbon stock in the organic layer at plot scale is difficult to detected. Due to a lower rate of change and high spatial variation very high number of samples per plot is needed. Therefore, at plot or stand scale soil is expensive to monitor in comparison with the monetary value of sequestrated carbon. The economic feasibility of the carbon sequestration projects may be based on the large carbon sink of the vegetation, but such projects also have to monitor (potentially negative) changes in the soil carbon stock and account for the soil monitoring costs.

The differences in the cost structures between sampling intensities are not very sensitive to the applied unit costs. Since the unit costs for salaries, transportation and other costs are case specific, and depend on the local conditions (e.g. distance between sampled sites and research centre where the staff is based and laboratory analyses carried out, accommodation options in the study area, average income level), the costs calculated in our study cannot be directly generalised without checking the validity of these unit costs in other conditions. The applied unit costs are reported in detail in the appendices in order to allow full evaluation and comparison with the unit costs of the target region.

Monitoring costs at the national scale compared to the potential value of the soil carbon sink

At the regional and national scale, the change in the soil carbon stock can be assessed on the basis of a representative network of sample plots. However, there is relatively little information available about the minimum sample size required for assessing changes in soil properties. We roughly estimated that repeated measurements on a minimum of 3000 sample plots are needed to detect an expected change of 11 g C m^{-2} yr^{-1} in the organic layer of upland forest soils in Finland with a sampling interval of 10 years. The average annual increase in the Fennoscandian soil carbon stock is predicted to be 7.5–11 g C m^{-2} yr^{-1} (de Wit *et al*. 2006, Liski *et al*. 2006, Ågren *et al*. 2007). This predicted change refers to the sum of changes in both the organic and mineral soil layers, but we assume that the major part of the change will take place in the organic layer, because the annual input of plant detritus into the soil primarily takes place at and near the soil surface. In addition, due to the fact that the residence time of carbon in the soil increases with depth, the greatest changes are most likely to occur in the organic layer (Gaudinski *et al*. 2000). If the rate of change in the organic layer is only one half of the expected value of 11 g C m^{-2} yr^{-1}, then the required sample size for detection of a change is approximately 12 000 plots. Also detection of a change in the mineral soil layers needs a large number of plots due to the lower rate of change and the larger variance of the mean carbon stock estimate (Peltoniemi *et al*. 2004).

We calculated that measuring the carbon stock on 3000 sample plots costs approximately 4 million euros, which is about 8% of the value of the annual CO_2 sequestration of upland forest soils in Finland (2.57×10^6 t CO_2 yr^{-1}, Liski *et al*. 2006), assuming that a sink will be credited with the current CO_2 tonne prices of the EU carbon allowances (20 euros per CO_2 tonne). Our cost estimates of measuring soil carbon included the costs of field work to the laboratory analyses, but not the time and resources needed for data analysis and reporting. Since the costs of 4 million euros are for one measurement round, the costs for a repeated measurement could be approximately 8 million euros and the actual monitoring costs with a sampling interval of 10 years would be about 2% of the value of the soil carbon sink over the 10-year period.

According to the Kyoto Protocol, only a small proportion of the forest carbon sinks in the majority of the signatory countries are allowed to be credited (UNFCCC 1997, Pohjola *et al*. 2003), but future commitments may give a large role and/or responsibilities to the forest sector. If forests will also be included in the subsequent agreement, it is clearly in the interest of all those countries with large forest resources to know their actual carbon sequestration potential and to be able to report their carbon stock changes, thus gaining monetary value. In the case that soils are assumed to have a minor role in carbon sequestration, countries still have to verify that their soils are not carbon sources when they

Table 1. Soil carbon measurement costs (euros) for one sample plot and for a network of 3000 plots.

	Costs per measured plot					Grand total (3000 plots)
	Fixed	Variable costs per layer			Total	
		Organic layer	Mineral soil layer	Number of mineral soil layers		
Pooled[a]	230	50	70	3	490	1500000
10 samples	230	290	280	3	1360	4000000
20 samples	230	590	560	3	2500	7500000

[a] 20 sub-samples were taken from the organic layer and 20 sub-samples from each mineral soil layer, and pooled by layer before laboratory analysis.

are gaining carbon credits from the vegetation carbon sink. Currently, only Japan and Canada are gaining credits from a major part of their forest carbon sinks (UNFCCC 2001, Pohjola *et al*. 2003), and they are already in the process of developing an advanced national GHG inventory for the forest sector (e.g. http://carbon.cfs.nrcan.gc.ca/cbm/index_e.html).

Our results indicate that monitoring costs will greatly increase if the sampling interval is shorter than 10 years. Many countries have recently established soil monitoring networks (e.g., Coomes *et al*. 2002, Ståhl *et al*. 2004), and this will enable them to reduce costs by using a longer sampling interval in the monitoring if a change estimate is needed for the period that follows the commitment period of the Kyoto Protocol. Since forest carbon sequestration in the CDM and JI projects already have a monetary value, the soil carbon sink of the forested area in the signatory countries is also likely to have a corresponding value in the future, and it will therefore be necessary to estimate the costs of soil carbon monitoring on both the project/stand and national scales. According to IPCC guidance (2003, 2006), model-based approaches can be used in national GHG inventories for estimating the change in soil carbon, but a set of monitoring sites that allow repeated measurements of soil carbon over time are, in all cases, needed to evaluate and validate the results of the models.

The efficiency of soil carbon monitoring can be improved and costs reduced by lengthening the sampling interval, as demonstrated by this study. Furthermore, stratification is often used to improve the efficiency of sampling (e.g. Cochran 1977). In stratified sampling, similar sites are grouped into the same strata. It has been estimated that, by grouping similar sites (in terms of model-predicted change in the soil carbon stock) into the same stratum, and optimally allocating samples to these strata (according to the size and variance of the strata), the number of plots that needs to be measured can be decreased by 25% without a reduction in the precision of the estimates (Peltoniemi *et al*. 2007). Thus, model-based stratification could decrease the monitoring costs by 25% from 4 to 3 million euros. The gain provided by stratification is, however, sensitive to uncertainties in the predicted changes (e.g. those resulting from future thinning activities) and precision of the measurements. In general, optimal allocation of the sampling effort to different strata and the use of sample sizes needed for detecting a change in different age classes, are key questions to be addressed in future studies on improving the efficiency and reliability of soil carbon monitoring.

The costs can also be reduced by pooled sampling, which has been a common practice in the earlier soil surveys. However, the use of pooled samples (one sample analysed per layer per plot) means that information on the within-site variation is lost and it is difficult to determine when the difference between two measurement rounds of a plot is significant. Despite these drawbacks, the method is efficient in regional and national soil surveys aimed at assessing the change in the mean carbon stock. We calculated that the monitoring costs are reduced to less than one third by the use of pooled sampling, which means that the costs of measuring once a representative network of 3000 sample plots (1.5 million euros) is only 0.3% of the potential value of the soil carbon sink of the 10-year period, assuming that carbon sinks are internationally agreed to be credited equally with emission reductions. Since detection of a change requires repeated measurements, double costs have to be accounted if initial measurements are not already available. We conclude that current climate policy has developed a clear incentive to develop reliable national soil carbon monitoring systems and, through early establishment of a representative network of monitoring plots, future costs can be decreased as a result of reasonable sampling interval

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Appendix. Fixed and variable costs of measuring soil carbon on a plot as applied in this study. The estimates of time required and costs of the field and laboratory work are based on the average time required and costs of sampling and laboratory analysis at Finnish Forest Research Institute.

Table A1. Applied personnel costs per working time.

Salaries	1000 €/month	€/day	€/hour
Laboratory technician	3.04	151.8	21.0
Forest engineer	3.90	193.4	26.7
Research assistant	2.36	118.1	16.3

Table A2. Fixed costs per plot (assuming that 2 plots per day are sampled by a 2-person crew).

	Time required (hours)	Number of persons	Fixed personnel costs per plot (€) (calculated with salary of a forest engineer)
Crew transportation	1.5	2	80.0
Walking time to a plot	0.1	2	5.3
Finding the plot	0.25	2	13.3
Preparations for soil sampling	0.3	2	16.0
			Other costs per plot (€)
Transportation (100 km per day á 0.42 €/km)			42
Daily allowance (2-person crew)			31
Crew accommodation			40
Total fixed costs per plot			227.7

Table A3. Variable costs per sample.

	Time required per sample (hours)	Salaries €/h	Salaries €/sample	Other costs €/sample	Total €/sample
Organic layer					
Soil sampling	0.04	26.67	1.07	0.10	1.17
Drying	0.15	16.30	2.36	0.20	2.56
Powdering	0.73	16.30	11.81	0.57	12.38
Measuring the moisture	0.24	20.94	5.06	0.46	5.52
CHN analyses with LECO device	0.29	20.94	6.07	1.77	7.84
Total	1.44		26.38	3.10	29.48
Mineral soil layers					
Soil sampling	0.08	26.67	2.13	0.10	2.23
Drying	0.15	16.30	2.36	0.20	2.56
Powdering	0.73	16.30	11.81	0.30	12.11
Measuring the moisture	0.24	20.94	5.06	0.48	5.54
Analyses of org. matter	0.24	20.94	5.06	0.48	5.54
Total	1.43		26.43	1.56	27.99