SECTION 10

Survey methods for Kyoto Protocol monitoring and verification of UK forest carbon stocks

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Survey Methods for Kyoto Protocol Monitoring and Verification of UK Forest Carbon Stocks

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Summary

This report presents initial proposals for a methodology that may be used for the assessment of carbon stocks and stock changes relevant to forests and the wood chain in the UK over a five-year cycle, to sufficient accuracy and cost-efficiency. Firstly, consideration is given to the relative importance of carbon pools associated with forests and harvested wood products (HWP) in the UK. Existing networks, systems and methodologies relevant to the monitoring of carbon stocks in these pools are then reviewed and their suitability and accuracy evaluated. Based on this evaluation, a strategy is developed for the evolution of existing systems to meet requirements for reporting carbon stocks and stock changes. Opportunities for adding value to existing systems and monitoring networks through adaptation or extension are identified, including scope for integration and rationalisation. Emphasis is placed on a nested design in which national-scale surveys are used to provide input data to carbon stock/change models, while smaller numbers of research plots are measured more intensively to provide data for validation of models and verification of estimates. Monitoring of carbon stocks and stock changes in HWP is addressed separately and a methodology developed that is distinct from the proposed forest carbon monitoring system.

It is possible to adapt existing forest inventories and monitoring networks to provide verifiable estimates of forest carbon stocks by means of a transparent methodology. UK national estimates of carbon stocks and stock changes derived in this way should be accurate and precise, although precision may be poor for individual sites and stands. Further work on assessment of accuracy and precision needs to be carried out in parallel with implementation of the system. The success of the methodology hinges on the availability of an improved and validated forest carbon accounting model. Improvements also need to be made to yield models that underpin carbon accounting models.

A complementary system for monitoring carbon stocks and stock changes in HWP, both in use and disposed of in landfill, would need to be implemented almost from scratch. At this stage it is only possible to speculate about the main features of such a system and further development is necessary.

The marginal cost of implementing the forest carbon monitoring network is estimated at £1.5M. Certain marginal costs at the periphery of the project are not included in this estimate, notably additional research and development to improve yield models and integrate them into a carbon accounting model. The cost of implementing the HWP carbon monitoring system is unknown. The draft methodologies, both for forest and HWP carbon monitoring, are clearly at an early stage and further development, in collaboration with relevant experts, is needed before the designs of these systems can be finalised and implemented.

1. Introduction

The Kyoto Protocol (UNFCCC, 1998) contains a number of stipulations concerning the reporting by participating countries of net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities. The Protocol places restrictions on precisely what sources and sinks should be counted as part of a national greenhouse gas balance (notably in terms of any forestry activities initiated before 1990). However there is an implicit requirement for participating countries to develop the capability to periodically monitor and report carbon stocks and stock changes associated with national forests. In particular, countries are required to provide data to establish the level of national forest carbon stocks in 1990 and to enable an estimate to be made of changes in carbon stocks in subsequent years. More recently, discussions between participants about the scope of the Kyoto Protocol may result in this requirement being extended to the monitoring and reporting of carbon stocks and stock changes in HWP. The Protocol further stipulates that all such monitoring must be undertaken in a transparent and verifiable manner.

The purpose of this report is to present initial proposals for a methodology that may be used for the assessment of relevant carbon stocks and stock changes in the UK over a five-year cycle to sufficient accuracy and cost-efficiency. Firstly, consideration is given to the relative importance of carbon pools associated with forests and HWP in the UK. Existing networks, systems and methodologies relevant to the monitoring of carbon stocks in these pools are then reviewed and their suitability and accuracy evaluated. Based on this evaluation, a strategy is developed for the evolution of existing systems to meet requirements for reporting carbon stocks and stock changes. Opportunities for adding value to existing systems and monitoring networks through adaptation or extension are identified, including scope for integration and rationalisation. Emphasis is placed on a nested design in which national-scale surveys are used to provide input data to carbon stock/change models, while smaller numbers of research plots are measured more intensively to provide data for validation of models and verification of estimates. Monitoring of carbon stocks and stock changes in HWP is addressed separately and a methodology developed that is distinct from the proposed forest carbon monitoring system. The report concludes by presenting preliminary costs and levels of accuracy for elements of the proposed methodology. It should be stressed that the theoretical and practical development of a complete methodology represents a significant task. At this stage it is impossible to provide a description of a comprehensive system because many gaps in data and understanding remain. This report is therefore intended to present a review of current understanding, develop an initial proposal and present the underlying concepts that should be addressed during further development of the proposal.

1.1 Carbon pools associated with forests and HWP in the UK

The magnitude of the carbon stock of woodlands in the UK is large when compared to annual emissions at a national level (1536 MtC compared to 152 MtC yr^{-1}). However, as indicated in Figure 1, the majority of this carbon is associated with soils and harvested wood products, both in use and disposed of to landfill. In comparison, the stock associated with living biomass is small (134 MtC), and less than national emissions for the year 2000. It is thus clear that an assessment of the carbon stocks associated with the national woodland estate cannot be made on the basis of woodland inventory or forest growth and yield models alone. Soil inventories, in which forest soils are poorly represented in existing datasets (MLURI, NSRI and DANI) are essential for providing a robust estimate of woodland carbon stocks, while carbon associated with HWP also needs to be considered. It should be noted that there is large uncertainty associated with many of the values of carbon stock and stock change that are cited here, and other estimates are available. The estimates presented here are intended to give an indication of the relative magnitude of the different carbon stocks and stock changes, and no indication of confidence is given.

When carbon stock changes (as opposed to carbon stocks) associated with UK woodland and the wood chain are considered, the dominance of carbon in soils is less apparent. Soil carbon stock changes are estimated to be relatively low with high uncertainty. The uncertainty is a direct result of small stock changes being estimated to a very large carbon stock. Although the stock change associated with living biomass is significant and larger than that associated with soils, HWP in use and in landfill potentially make the largest contribution to the estimated carbon sink of the forestry/HWP system of the UK.

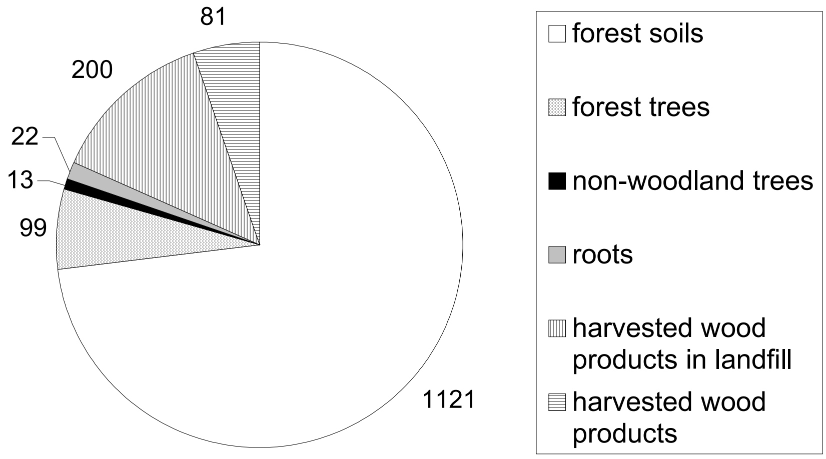


Figure 1: Carbon stocks (MtC) associated with UK woodland and HWP. Values for forest trees, non-woodland trees and roots (and stumps) are from Forestry Commission (2002). The value for carbon in forest soils was derived from individual country woodland areas (England, Wales, Scotland, Northern Ireland: Forestry Commission, 2002) together with their associated soil carbon densities (Milne, 2001). Carbon stocks associated with harvested wood products in use and in landfill are from Alexander (1997).

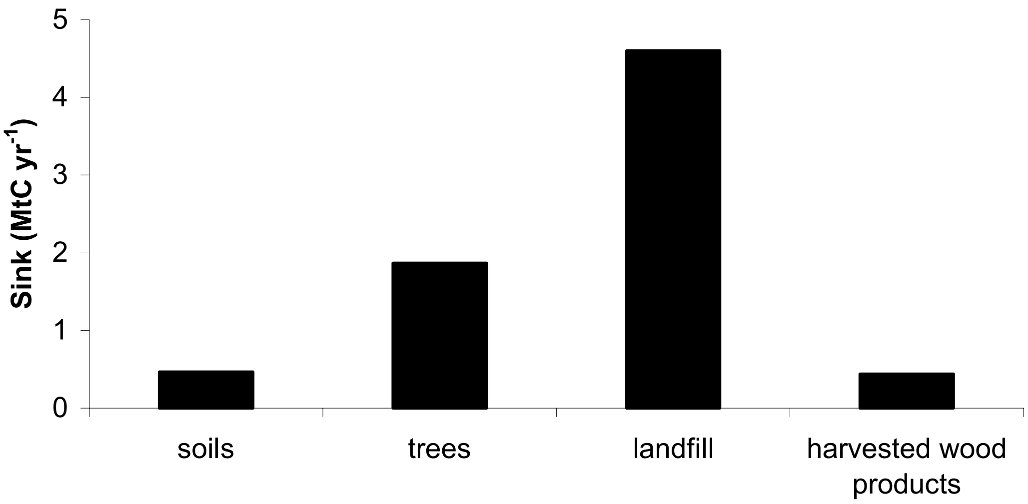


Figure 2: The carbon stock change associated with woodland and the wood chain in the UK. The sink associated with woodland soils is based on EU-wide estimates for 1995-2000 (De Vries *et al*., 2003) using the woodland area of the UK compared to that of the EU as a scaling factor. For broadleaf woodland alone, Milne *et al*., (2003) propose a value of 0.65 MtC for 2001. For both estimates, only the carbon stock change associated with existing woodland is included. The carbon stock change of forest soils associated with land use change represents a significant source (Milne *et al*., 2003) and is excluded from this assessment. Woody biomass carbon stock change is based on the output from CFLOW for 2001 (see Milne *et al*., 2003). The carbon stock changes associated with HWP in use and in landfill are from Alexander (1997).

The development of a national monitoring system for carbon stocks and stock changes associated with UK woodland must take into account the relative magnitude of the contributions from different pools, both current and potential. Different elements of the monitoring system may provide information applicable to only the stock or stock change inventories.

2. A review of existing UK forest monitoring networks and inventories

A number of forest monitoring networks and inventory systems already exist in the UK which could be incorporated into a UK carbon monitoring methodology:

- Long-term carbon flux network (CFN)
- Intensive forest health monitoring EU/ICP-Forests Level II network (L-II)
- Permanent mensuration sample plot network (PSP)
- UK woodland assurance scheme network (UKWAS)
- Forest condition monitoring EU/ICP-Forests Level I network (L-I)
- UK forest condition survey network (FCS)
- National inventory of woodlands and trees (NIWT)
- Forest Enterprise subcompartment database (SCDB)
- Survey of small woodlands and trees (SSWT)
- Land cover map 2000 (LCM2000).

Some of these networks and inventories already provide appropriate data at a suitable time resolution but others would require modification or additional measurements to be made. Details of each of these systems are given in the following review, including an assessment of each in terms of:

- Representation of forest stand types within the UK forest estate
- Spatial extensiveness
- Suitability of assessments for national carbon stock and stock-change inventories.

2.1 Carbon flux network (CFN)

Four long-term carbon flux monitoring sites have been established in woodland in the UK as follows.

<u>Straits Enclosure (Forest Research, Alice Holt):</u> 90 ha stand of GYC 6 oak planted during the 1930s on a surface water gley soil in Hampshire. The flux station was established in 1998, and has operated continually. The entire stand is due to be thinned in 2004-5.

<u>Harwood (University of Edinburgh):</u> Two flux systems were established in 2000 in a 4000 ha Sitka spruce forest in Northumberland of varying planting year and yield class on a peaty gley soil. One continuous system is sited in a 30-year old stand, with a second roving system used to assess carbon fluxes in a chronosequence investigating the effects of stand age on carbon balance.

<u>Griffin (University of Edinburgh):</u> Sitka spruce plantation (GYC 14) planted in 1981 on a peaty gley soil in Perthshire. The flux station was established in 1996 and has operated continuously apart from a break in 2002. The forest is currently being thinned.

<u>Pang catchment (CEH Wallingford):</u> Mixed broadleaf woodland dominated by oak situated in Berkshire. The flux station is currently being established as part of the NERC funded LOCAR project and has guaranteed funding for five years.

These four sites only represent two species – oak and Sitka spruce. As a result of their limited species and geographical coverage, their direct contribution to carbon inventory assessments is limited, although estimates of forest carbon exchange at a European scale have been made on the basis of data from the thirty flux sites associated with the EU FP5 CarboEuroflux research project (Martin *et al*., 1998). Their most valuable contribution is in providing data for the parameterisation and validation of stand level process models of carbon and water exchange. An example of data from one of these sites (Straits Enclosure) is shown in Figure 3 at a daily time step. Associated detailed ecophysiological measurements are undertaken at most sites including soil respiration, litter analysis, meteorology, leaf area, increment, individual tree allometry, rainfall interception and soil water chemistry analysis.

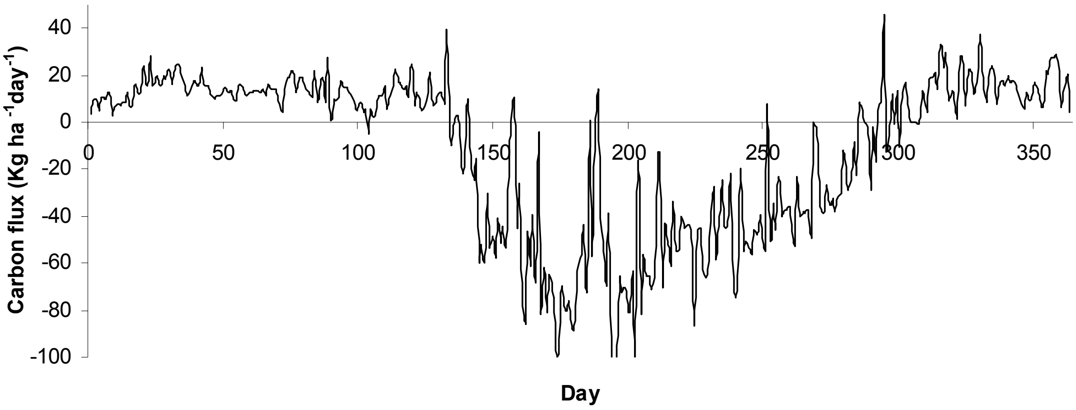


Figure 3: Carbon flux expressed on a ground area basis for lowland oak woodland at the Straits flux station in Hampshire for 2002.

Net ecosystem exchange is calculated by correlating the vertical component of windspeed with CO_2 and water vapour concentration fluctuations above the canopy. Fluxes are representative of areas of woodland of up to 100 ha, although the 'footprint' is highly dependent on windspeed. In isolation, flux measurements provide no information on the partitioning of carbon between wood, litter, soil and ground vegetation and do not account for carbon lost as dissolved or particulate organic carbon (DOC and POC) or removed as HWP. However, the programmes of intensive measurements outlined above enable stand level carbon budgets to be developed, which may be useful for validation of estimates from other assessment procedures or models.

2.2 Intensive Forest Health Monitoring – EU/ICP-Forests Level II (L-II)

The network for intensive monitoring on permanent observation plots was established in 1994. Currently there are approximately 900 plots across Europe, although the intensity of measurements varies from plot to plot. In the UK, ten sites were established in 1995 (oak, Sitka spruce and Scots pine: Durrant, 2000), with a further ten added in 2002 (beech and Norway spruce) to represent more species and regions within the UK (Figure 4).

Figure 4: Location of the twenty EU/ICP (Forests) L-II Intensive Forest Health Monitoring Plots in the UK.

Stand height, diameter and volume increment, foliar chemistry, soil chemistry, crown condition and ground vegetation are assessed at all sites, while litter, air quality, meteorology and soil water chemistry are assessed at a proportion of the sites. Key stand and site data for the 20 plot locations are provided in Table 1. The main assessments carried out in L-II plots are listed in Table 2. Not all assessments are carried out in all plots and the number of plots in which each assessment is made is also indicated in the table.

Deadwood and litter carbon stocks are not currently assessed, although new protocols are currently under review with the objective of developing the network to enable complete carbon stock and carbon stock change assessments to be made. In addition, the soil condition survey carried out under this network provides a framework for assessing soil carbon stocks across a wider network. Chemical analysis is undertaken for each soil horizon from a single representative pit, chosen from 30 profiles arranged on a systematic grid across the area of the plot. The results of chemical analysis for the representative pit can then be scaled by the mean depth of each horizon as revealed by the 30 point grid. Kirwan *et al*. (2003) have shown that between 25 and 36 pits are sufficient to capture the variability within a 0.3 ha plot typical of the L-II network. Soil carbon stocks estimated for the plots forming the UK L-II network are shown in Table 3.

A new regulation detailing forest monitoring in Europe is currently being negotiated in the European Parliament. It will cover the period 2003-4 to 2009-10 and follows the move of forest monitoring from DGVI (Agriculture) to DGXI (Environment). The new monitoring scheme has a wider remit than the old network, including the monitoring of biodiversity and carbon sequestration, possibly across the 16 × 16 km transnational grid in conjunction with the EU L-I Forest Condition Survey (see separate discussion below).

Table 1: Details of sites and stands comprising the twenty UK L-II Intensive Forest Condition Monitoring sites. The first ten sites in the list were established in 1995, and complete data-sets are available. The last ten were set up in 2002 and are subject to ongoing establishment and measurement programmes. Missing data indicates that establishment assessments are on-going or that records are not available.

Site	**Grid reference**	**Elevation (m)**	**Species**	**Planting year**	**Planting spacing (m)**	**GYC/ LYC**	**Basal area (m^2 ha^{-1})**
Alice Holt	SU790400	80	Oak	1935	-	6	22.0
Savernake	SU050880	107	Oak	1950	1.0 × 1.7	6/4	20.0
Grizedale	SD330910	115	Oak	1920	-	4/4	20.0
Thetford	TL950830	20	Scots pine	1967	1.7 × 1.8	12/10	36.6
Sherwood	SK160900	265	Scots pine	1952	1.0 × 1.2	12/9	39.3
Rannoch	NN600530	470	Scots pine	1965	1.4 x 2.0	8/9	32.8
Coalburn	NY690780	300	Sitka spruce	1974	1.8 x 2.2	18/18	47.1
Tummel	NN740610	400	Sitka spruce	1969	1.6 × 1.8	16/17	59.2
Loch Awe	NM960100	40	Sitka spruce	1971	2.0 x 2.4	24/24	55.0
Llyn Brianne	SN810480	450	Sitka spruce	1973	2.1 × 2.1	14/14	47.3
Canonteign	SX820820	200	Beech	1972	-	10/7	41.0
Bedgebury	TR170490	92	Beech	1950	-	8/9	29.0
Wangford	TL780810	50	Beech	1955	-	8/8	47.0
Wykeham	SE920880	220	Beech	1957	-	8	48.0
Kelty	NT120950	241	Beech	1958	-	6/4	37.0
Brechfa	SN480290	250	Beech	1952	2.2 × 2.2	6	49.8
Ardtornish	NM720500	73	Oak	1880	-	2	34.7
Culbin	NH990630	10	Scots pine	1962	-	12/12	43.0
Kiddens	SX860840	150	Norway spruce	1980	-	22/16	41.25
Clocaenog	SH980520	300	Norway spruce	1963	1.8 x 1.8	16/18	68.0

Table 2: Range of measurements made in UK L-II Intensive Forest Condition Monitoring plots. Detailed protocols for each measurement are given in EC (1998).

Measurement	**No. of plots**	**Frequency**
Increment	20	5 yearly
Crown condition	20	annually
Foliar chemistry	20	annually
Soil (chemistry & description)	20	10 yearly
Litterfall	13	2-8 weekly
Deposition	10	2 weekly
Air quality	17 (2)	1 month (30 minute)
Soil solution	10	2 weekly
Meteorology	6 (5)	daily (hourly)
Phenology	20	2-4 weekly
Ground vegetation	20	3 yearly

Table 3: Soil carbon stocks (to 1 m depth) for the original ten UK L-II Intensive Forest Health Monitoring Plots.

	Savernake	278		Coalburn	290		Loch Awe	124		Tummel	106		Rannoch	645
horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)
O	3	15.8	O	6	22.7	O	2	8.4	O	4	18.2	O	8	42.3
A	3	34.7	H	17	114.0	H	1.5	1.5	Ah1	30	36.0	H	25	450.1
E	19	61.2	Ah(g)	10	20.6	Ah	8	21.2	Ah2	6	4.9	E	7	28.5
2Btg	22	57.3	Eg	13	10.8	Eg	26	48.2	E	23	25.3	Bh	7	22.1
2BCtg	16	27.8	Bg	20	31.3	Bs	31	34.0	Bs	41	21.7	Bs	18	38.9
2Cgk	40	80.7	2BCg	57	91.1	BCg	15	10.8				Bhs2	28	34.8
												Bg	40	28.2
	Thetford	76		Llynbrianne	753		Grizedale	292		Sherwood	308		Alice Holt	157
horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)	horizon	depth	C (tC/ha)
O	2	10.8	O	6	27.7	O	4	26.0	O	3	14.0	O	3	6.5
Ah	13	32.2	H	13	399.9	H	2	31.0	H	2.5	40.9	Ah	7	13.3
Ah&Bw	11	12.1	A	15	87.2	Ah	6	28.6	AE&Ah	15.5	42.8	Eg	8	22.3
Bw	26	10.2	Bg	32	141.1	Bs	49	200.6	Bs	20	27.9	Btg	22	39.6
2BC	50	10.3	BC	53	97.3	Bc	5	6.3	BC	21.5	51.1	BCg	37	37.4
									2C	43	131.4	C(g)	26	38.5

2.3 Permanent Mensuration Sample Plot Network (PSP)

The first permanent mensuration sample plots were established before 1920, with the aim of providing data on which to base yield models for forest management and production forecasting such as those developed by Hummel, Christie and co-workers (Hummel and Christie, 1953; Bradley *et al.*, 1966; Hamilton and Christie, 1971; Edwards and Christie, 1981). On the whole PSPs have been established in single species, even-aged stands, and thus are not fully representative of all current forestry practice in the UK.

There are currently 509 active plots (Figure 5), representing primarily the major commercial species planted in the UK. Although the spatial distribution of the PSPs as shown in Figure 5 and 6 appears even and complete at first sight, this hides the clustering of a large number of plots at a smaller number of localities and site types. The representation within the network of tree species, age classes and planting spacing is shown in Figure 6.

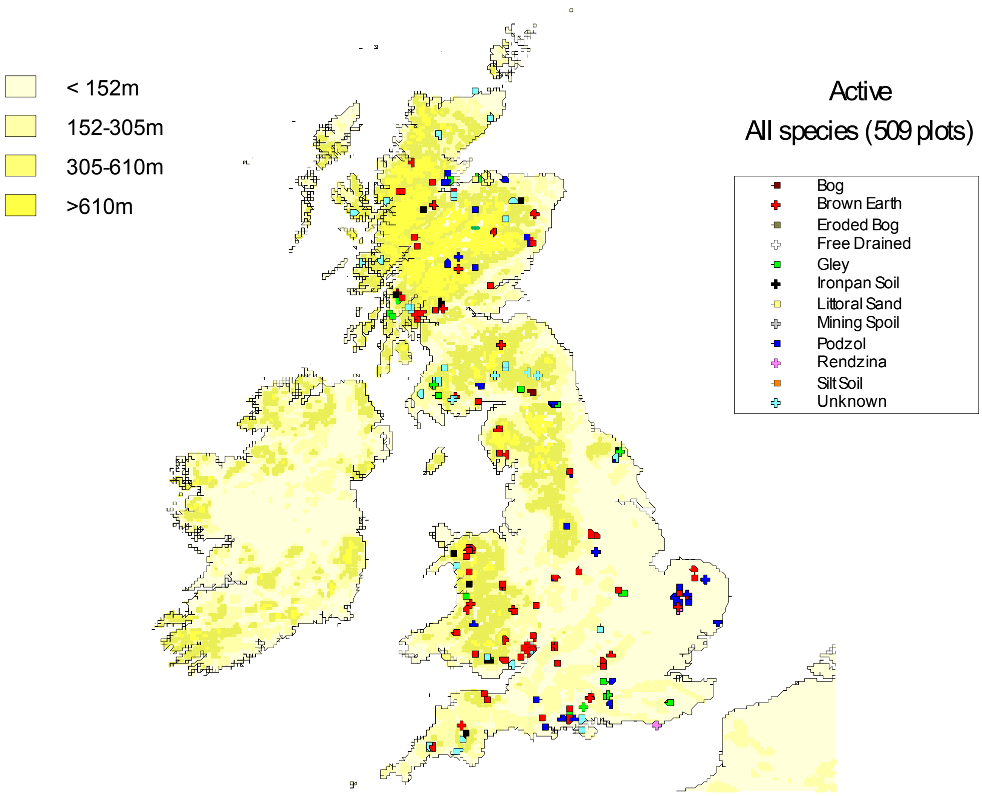
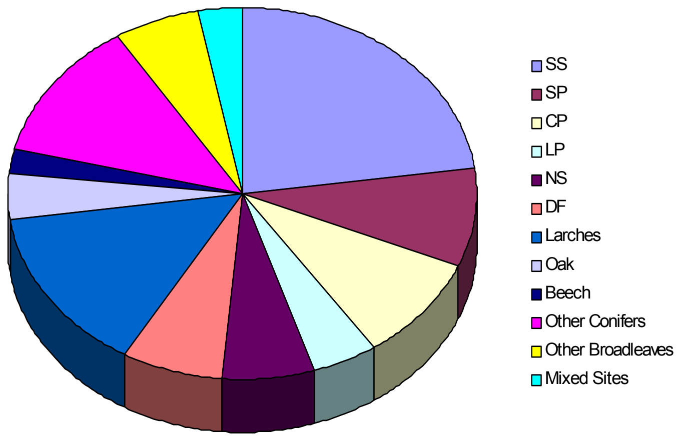
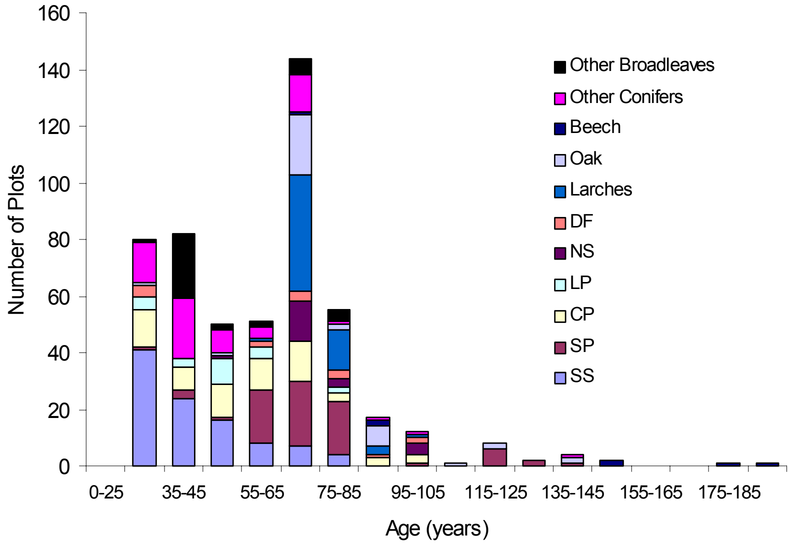


Figure 5: Location of the 509 currently active mensuration permanent sample plots.

(a)



(b)



(c)

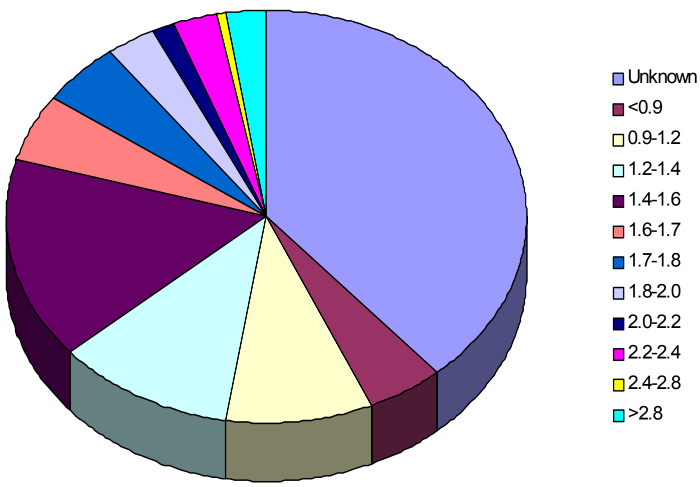


Figure 6: Representation within the network of 509 active permanent mensuration sample plots of (a) tree species, (b) age class and (c) planting spacing. Measurements made within the PSP network, typically every five years, are detailed in the following section.

Site assessments

- Soil type (on establishment)
- Ground vegetation (on establishment)

Assessments on all trees

- Status (alive/dead, canopy position)
- Stem quality class
- dbh

Assessments on samples of standing trees and thinnings

- Early height growth analysis (young stands on establishment)
- Total height
- Crown dimensions (depth of green crown, crown diameter, height to lowest live branch)
- Stem profile (3 m section diameter measurements)
- Stem volume to 7 cm top diameter over bark

The standard PSP measurement protocols (Hummel *et al*., 1959; Edwards, 1976) are purpose-designed to permit reliable stand-level estimates of tree stem volume and size-class distributions to be derived for standing trees and for any thinnings (Figure 7). Stem biomass is not assessed but could be obtained by applying standard values for the nominal specific gravity of wood (Lavers and Moore, 1983) to volume assessments. However, protocols for assessment of tree total and/or component biomass and soil carbon content could be developed and integrated with standard PSP procedures. Inclusion of such procedures would add significantly to the cost of periodic assessments. An alternative approach for biomass assessment might be to apply average allometric relationships to standard PSP data to obtain tree-level and stand-level estimates for roots, branches and foliage (Figure 8). Perhaps more importantly, PSP data has an explicit role in underpinning development of measurement systems and growth and yield models. This gives the PSP network a pivotal role as a link between stand-level inventory and survey assessments on the one hand and input data to models used for upscaling and forecasting on the other.

Recently the PSP network has been the subject of a significant strategic review (Matthews *et al*., 2003). The outcome is likely to be an assertive change of emphasis for the network, to primarily providing data for growth and yield model development, with any monitoring function being subsidiary and minor. Such a development would underline a role for PSPs in monitoring forest carbon stocks as one of support to the development of models used for upscaling and forecasting carbon stocks and stock changes, as well as validation of upscaled estimates and forecasts.

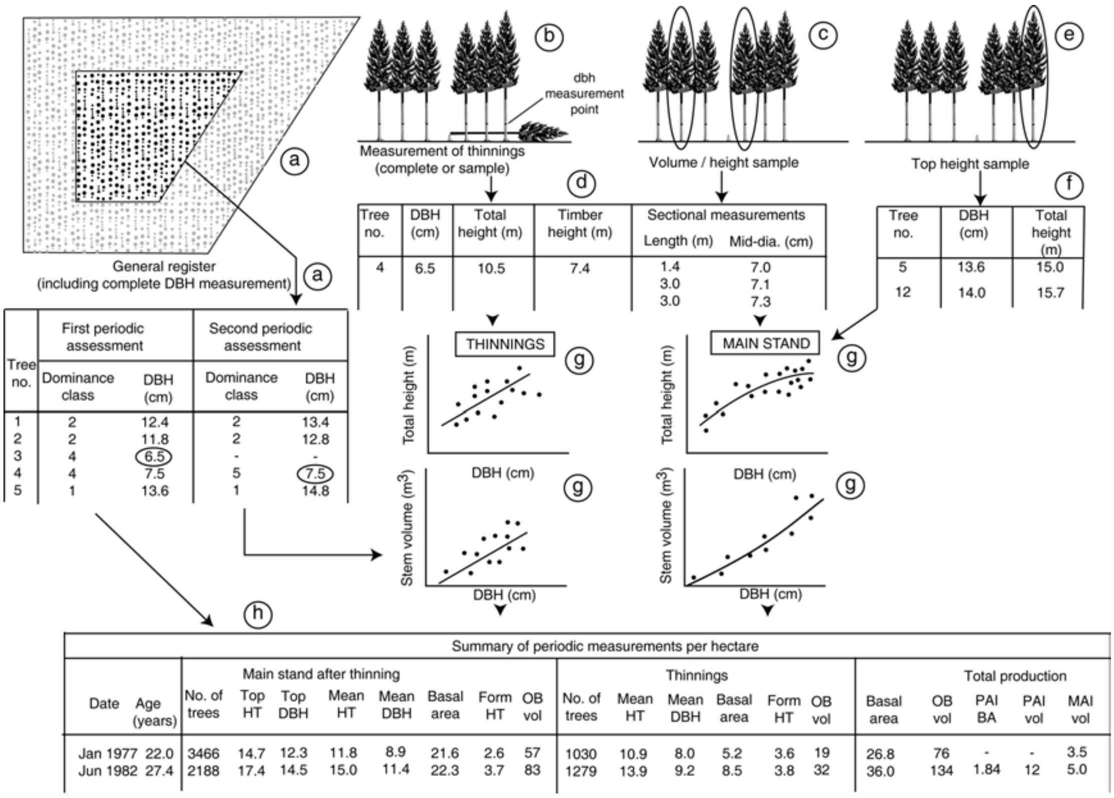


Figure 7: Schematic representation of the measurements associated with mensuration permanent sample plot assessments.

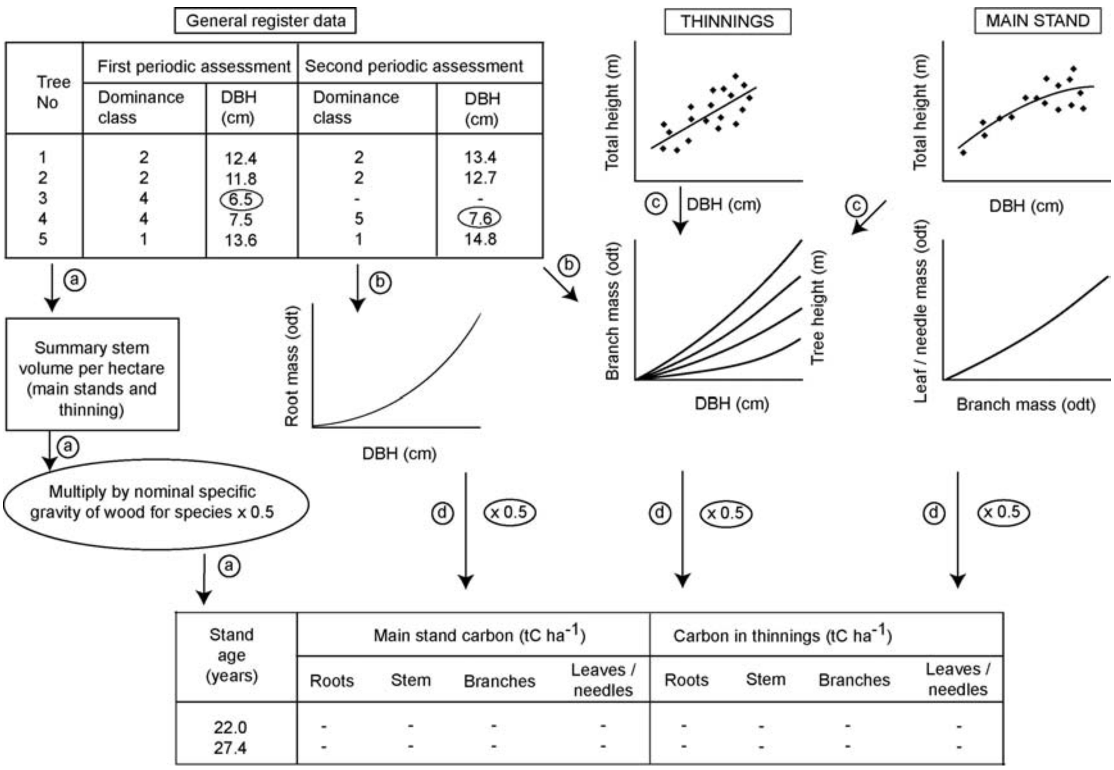


Figure 8: Schematic representation of how allometric relationships might be applied to mensuration permanent sample plot assessments to provide estimates of carbon stocks in tree biomass at a stand level.

2.4 UK Woodland Assurance Scheme

UKWAS plots have been or are in the process of being established using protocols similar to those for PSPs and in effect these plots constitute a component of the PSP network. However they are not formally integrated since their function is distinct and dissimilar to PSPs.

The objective of UKWAS plots is to provide data as part of monitoring of compliance with the principles and indicators specified in the UK standard for forest certification as administered by the Forestry Stewardship Council (UKWAS, 2000). For this purpose, plots are established on sites representative of stand conditions in a given locality and are managed according to standard local practice. In principle this makes them ideal for use in an inventory-based carbon stock monitoring system. In practice the cost of establishing enough plots to form a fully representative network capable of producing upscaled estimates would be prohibitive. Currently there are only 12 UKWAS plots (representing five species) in existence and these are limited to Scotland. At present there is no plan to extend the network to England and Wales.

2.5 Forest Condition – EU/ICP-Forests Level I (L-I)

The L-I Forest Condition Survey is a Europe-wide assessment of spatial and temporal variation in forest condition using crown density or transparency as the principal indicator. Surveys of crown density have been carried out on an annual basis since 1986 at between 1700 plots (in 1988) and 6000 plots (in 2000) across Europe. Although strictly the L-I protocol does not require increment assessment, top height was recorded on establishment and dbh is routinely measured, alongside other measurements made as part of the UK national Forest Condition Survey (see section below). In principle, rough estimates of carbon stocks in tree biomass could be derived from such abbreviated assessments, using methodologies similar to abbreviated tariffing (Edwards, 1983), although they would be of relatively poor precision (around ±20%) and biased for individual sites. In addition, soil condition (carried out in 1994) and the nutritional status of the trees in terms of foliar chemistry (carried out in 1995) have been assessed on one occasion only. The soil condition survey involved descriptive and chemical analyses, but only for the top 20 cm (0-10 cm and 10-20 cm) which is insufficient for estimation of carbon stock and stock change. Despite these limitations, it has been possible to derive an estimate of the carbon sequestration rate of European forests based on this network, using stand age and soil type to derive stem wood increment from forest yield tables and an assumed ratio of total biomass to stem wood of 2.5 (De Vries *et al*., 2003). Soil carbon sequestration was estimated from soil C:N ratios and calculated retention times.

In the UK, there are approximately 90 L-I plots covering five tree species (oak, beech, Scots pine, Sitka spruce, Norway spruce) with the distribution as shown in Figure 9. The protocol requires a minimum plot size of 0.25 ha (although this is not always realised), with the crown density of 24 'internal' plot trees assessed across the four aspects (N, S, E, W, Figure 10). The plots have been established on a 16 × 16 km transnational grid across Europe, enabling pan-European assessments of forest condition to be made. A recent review indicates that potentially, the network could be enlarged from 90 to approximately 400 sites if plots were established within 500 m of the transnational grid intersections (Hendry, 2001). Data from other national networks are also submitted to the EU/ICP-Forests, generally based on a national grid varying in resolution from 1 x 1 km to 32 x 32 km. Special dispensation was given to the UK to continue using the FCS network (established in 1984 and based on a stratified random sample) for this purpose, as a result of the dispersed nature and heterogeneity of the UK forest estate.

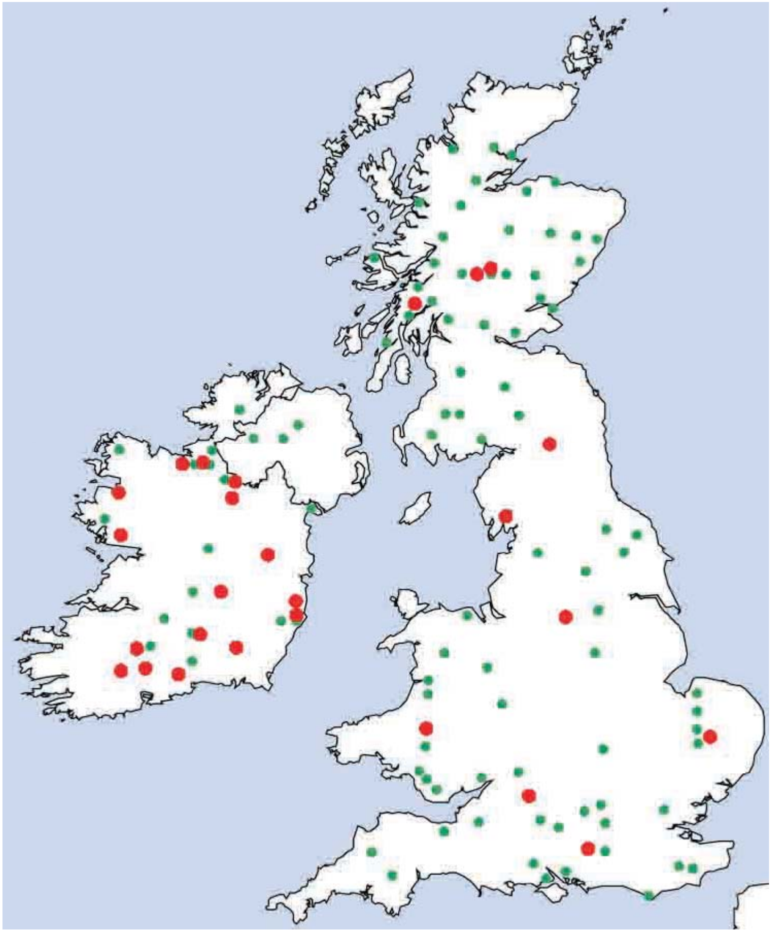


Figure 9: Location of the 90 L-I Forest Condition plots in the UK and Ireland. Those sites marked with large symbols are additionally L-II plots.

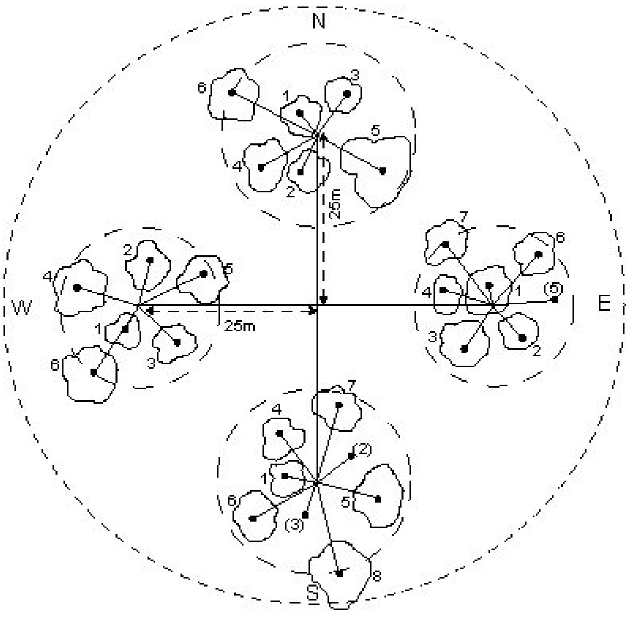


Figure 10: Typical layout of an EU L-I plot.

2.6 UK Forest Condition Survey (FCS)

The FCS was instigated in 1984 prior to the establishment of the L-I network and provides greater spatial representation and more detailed measurements than strictly required for the EU L-I network. As such, the L-I network forms a subset of the FCS network. The same five tree species are assessed (59 beech, 55 Norway spruce, 86 oak, 81 Scots pine, 66 Sitka spruce and 3 mixed broadleaf), with the distribution as shown in Figure 11 (Hendry *et al*., 2002), based on a stratified random sample (Binns *et al*., 1985).

In contrast to the plot-based layout and assessment protocol adopted in the L-I network, assessments are made on individual trees at the periphery of the forest stand (six trees for each of the four aspects), and thus there is no plot as such on which to express assessments at the stand level. On the other hand, more variables are measured in FCS than are strictly required under the EU L-I protocol as outlined above. The supplementary measurements include annual assessments of dbh and a single assessment of top height recorded on establishment, in principle enabling annual carbon stocks in biomass to be calculated at least at the individual tree level.

The full assessment protocol in FCS plots consists of:

Stand assessments on plot establishment

- Top height measured on establishment

Site assessments

- Soil type identified on establishment

Assessments on 4 × 6 = 24 peripheral trees

- dbh measured annually
- Crown condition (density) assessed annually
- Supplementary tree quality measures assessed on an annual basis
  - crown form/branch pattern
  - discoloration
  - degree of canopy closure
  - needle retention
  - mechanical damage
  - flowering
  - fruiting
  - insect and pathogen damage

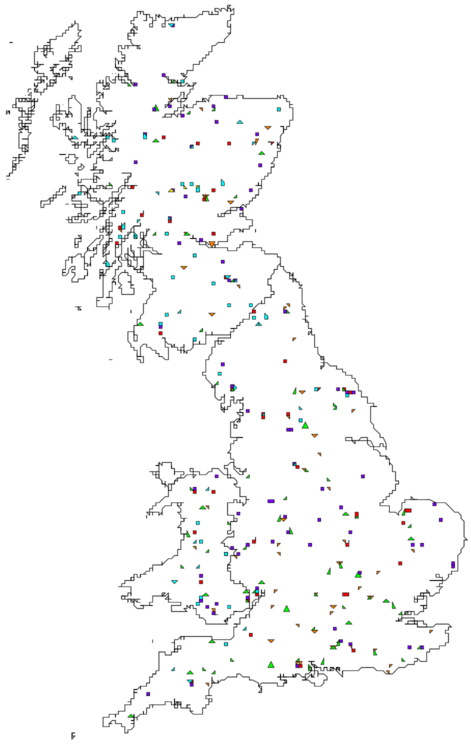


Figure 11: Location of the UK FCS plots in 2000. The network also includes all sites represented in the L-I and L-II networks.

2.7 National inventory of woodland and trees (NIWT)

This inventory, otherwise known as the Census of Woodland, is carried out every 10-15 years. The most recent survey (eg Forestry Commission, 2001) is based on a combination of analysis of the 1:25000 OS map and, primarily, interpretation of aerial photography. The NIWT considered woods of more than 2 ha area, although a separate survey of small woods and linear features was also conducted as part of the assessment, but in less detail (see separate section below). Ground-truthing of 1% of the national estate (in terms of forest area) was carried out by forest surveyors in a total of 40 897 sample squares. In the main, this sample was selected on a random basis but subject to stratification such that 1 in 5 woodlands of less than 100 ha, 2 in 5 woodlands of between 100 and 500 ha and all woodlands over 500 ha were included in the sample.

Adjustments to the sample grid were permitted where a woodland edge was found or serious problems were encountered in gaining access to the sample site. Summary information such as ownership and species mix was recorded for each 1 ha plot, and a more detailed structural survey was carried out in a 0.25 ha sub-plot. The full list of inventory data is shown in Table 4. Further details may be found in Gilbert (1999).

It is evident that the emphasis in NIWT is on qualitative rather than quantitative data. Nevertheless, the mensurational and structural assessments made in the 1% verification plots could be used in a similar manner to L-I and/or FCS plots to provide a broad scale validation of forecasts of forest carbon stocks derived from models. The additional cost of collecting data on soils in NIWT verification plots for use in verifying carbon stocks is likely to be prohibitive. An alternative application for NIWT data as input to models of carbon stocks and stock changes is discussed following a consideration of other relevant inventory systems below.

Table 4: Data collected in ground-truthing plots of the National Inventory of Woodland and Trees.

Stratum	Category	Options/comments (not exhaustive)
Meta-data	Owner status	Private, charity, FC, management company
	Woodland context	Forestry, farm, mixed
	Management	Timber, game, conservation, shelter, grazing, forest design, ornamental, unmanaged, agroforestry
Structure data	% cover	Upper & lower canopy, shrub, field, ground
	Standing deadwood	
	Number of trees	
	Abandoned timber	
	Fallen trees	7-20 cm, 20-50 cm, >50 cm
Element data	Woodland classification	Broadleaf, conifer, mixed, coppice, felled, SRC, windblow, unproductive
	Thinning frequency	Once, twice etc.
	Access	(For extraction)
	Dominant understorey (>2 m)	Species
	Regeneration	Vegetative, seedling, both
Crop data	Species	
	Species make-up	Pure, mixed, intruded
	Area	
	Stocking	
	Health	Crown dieback, general poor health, stem decay, windblow, animal damage, squirrel damage
	Timber potential	Normal, remedial, small only, unproductive
	Planting year	
	Top height	
	Mammal damage	Bark stripping, browsing

2.8 Survey of Small Woodland and Trees (SSWT)

The SSWT was carried out as part of NIWT but separately to the main survey, to assess the extent of woodland of less than 2 ha in area together with linear features (hedgerow trees and shelter belts), groups and individual trees. The country was stratified into coastal and non-coastal areas and a random sample of 1 km^2 squares representing 1% of the land area selected. For each selected grid square, 1:25 000 aerial photographs were used to identify features, with field data collected for two out of the 16 (250 x 250 m) squares in each 1 km^2 grid square. The only data recorded consisted of a broad classification of the woodland or individual trees in terms of type of woodland/tree feature and key species groups present. Application of SSWT data as input to models of carbon stocks and stock changes is discussed following consideration of other relevant inventory systems below.

2.9 Forest Enterprise subcompartment database (SCDB)

The subcompartment database provides stand-level information on the estate managed by Forest Enterprise across Great Britain, including area, species, year of planting, estimated productivity (GYC) and management prescription for the purposes of production forecasting and operational planning. The Forest Enterprise estate covers an area of 1053 thousand hectares of which 759 thousand hectares is productive high forest. This latter area constitutes approximately 30% of the estimated total area of woodland in Great Britain. Areas represented by the five species covered by the FCS, L-I and L-II networks, are summarised by General Yield Class in Table 5. The total area for the five species is 505 thousand hectares, approximately 20% of the estimated total area of woodland in Britain.

The abbreviated nature of SCDB data might appear to be limiting; however the explicit link to models used in production forecasting for the Forest Enterprise estate may provide a framework onto which models for estimating carbon stocks and stock changes could be mounted. The partial coverage of the UK forest estate would still need to be addressed either by extending the SCDB system, development of a parallel system to handle non-Forest Enterprise woodlands or through some form of extrapolation of forecasts for Forest Enterprise woodlands to the rest of the estate. These points are discussed further following consideration of other relevant inventory systems below.

Table 5: Areas of productive high forest represented in the SCDB by general yield class (GYC) for the five species covered by L-I, L-II and FCS. Data are also available for other species.

GYC $m^3\ ha^{-1}\ yr^{-1}$	**Area represented in SCDB (ha)**				
	Beech	**Oak**	**Sitka spruce**	**Norway spruce**	**Scots pine**
0	1914	3975	9741	459	3798
2	1533	3340	2740	297	1736
4	1304	7900	2228	280	2422
6	5276	4213	9300	1446	11488
8	4874	374	22102	2607	23362
10	602	39	41795	5069	16450
12	18	8	88146	6414	8304
14	6	21	82497	5482	2770
16	5	4	58800	3766	105
18	0		30587	2261	1
20	3	1	14436	1043	1
22		0	4950	340	
24			2503	8	
26			64		
28			1		
30			1		

2.10 Landcover map 2000 (LCM2000)

LCM2000 is a map of land cover in the UK derived from the Great Britain and Northern Ireland Countryside surveys (Haines-Young *et al*., 2000). These were based on analysis of satellite imagery and detailed ground-truthing of 500 (1 km^2) sample squares across all land-use classes. The pixel size of the satellite images was 0.0125 ha, in theory giving considerably greater spatial detail than NIWT. LCM2000 and NIWT are not completely compatible (Figure 12), and in a recent analysis (Hall *et al*., 2003), only 1.8 Mha of the 2.75 and 2.34 Mha total woodland areas (from LCM2000 and NIWT, respectively) was consistently represented. Differences in interpretation between the two datasets explain some of this discrepancy. For example, satellite imagery can map heather as woodland, while young trees or felled areas due for restocking will not be registered in satellite imagery, but will be included in NIWT on the basis of the SCDB (FC land) and grant aid (non-FC land) records. Differences in the spatial resolution of NIWT and LCM2000 also contribute to the discrepancies. For example, woodlands of less than 2 ha (a total of 120 000 ha) are not included in NIWT but are mapped in LCM2000.

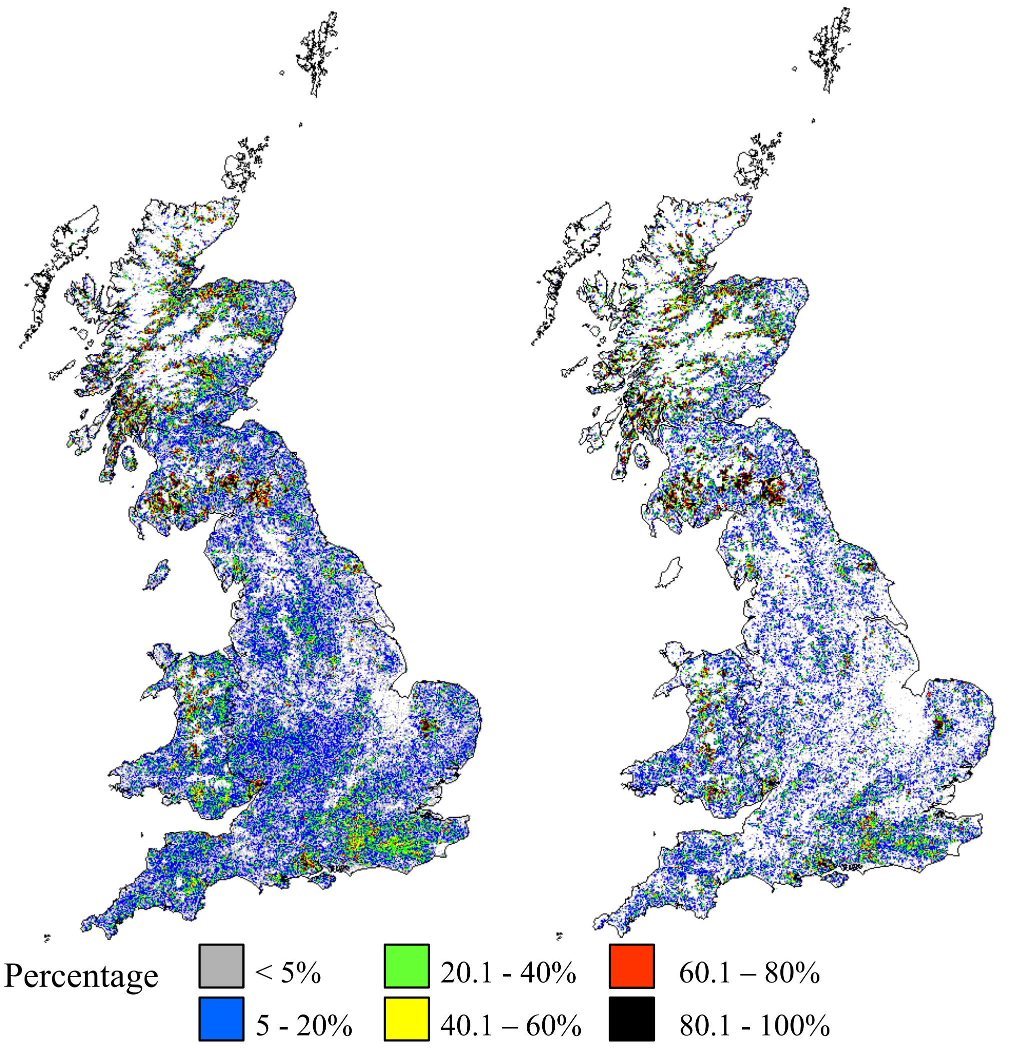


Figure 12: Comparison of woodland areas from LCM2000 (left) and NIWT (right). The different colours represent the % cover of woodland in each 1 km^2 grid square.

LCM2000 is essentially a map of land cover and does not include inventory assessments for areas identified as consisting of forest. As a consequence, extending LCM2000 to include surveys providing input data to models for estimation of forest carbon stocks and stock changes would be a major exercise. Its inclusion is thus solely for the purpose of land-use classification and ensuring compatibility between woodland and non-woodland carbon inventories.

3. Adapting UK forest monitoring networks and inventories for estimating carbon stocks and stock changes

Any cost-effective system for estimating forest carbon stocks and stock changes will at some level rely on models. Since direct monitoring of the entire UK forest estate would be impractical, carbon accounting models or statistical estimates are likely to be used for spatial and possibly temporal interpolation and/or extrapolation of carbon stock estimates. In contrast, verification is carried out through direct monitoring of a sample of sites. The suitability of the monitoring networks and inventory systems reviewed above for application within such a framework for monitoring and reporting carbon stocks and stock changes is evaluated in Table 6. The evaluation is presented in terms of the following criteria:

- Comprehensive/representative – the extent to which the network/inventory covers the UK forest estate, or constitutes a representative sample.
- Relevant – whether data collected in the network/inventory can be used to estimate or infer carbon stocks and stock changes.
- Accurate and/or precise – the accuracy and precision that might be expected in carbon stock and stock change estimates derived from data *currently* collected.
- Adaptable and/or extendable – the potential for adaptation and/or extension of the network/inventory to address carbon monitoring objectives, either to achieve greater comprehensiveness or to improve quality of data on which to base estimates of carbon stocks and stock changes.

Additional discussion is presented below, with particular consideration given to the scope for developing and adapting existing networks to support monitoring of carbon stocks and stock changes.

3.1 Monitoring networks

Table 7 further summarises the key information on monitoring networks detailed in Table 6, specifically number of plots, species represented, assessments relevant to monitoring carbon stocks and potential error. In addition, Table 7 provides indicative costs of establishment and periodic measurements based on Forest Research experience. Periodic assessment costs are based on an assumed 5-year measurement cycle. Where networks require assessments to be made more frequently these have been accumulated for a 5-year period. Estimates of costs are for all measurements made within a given network protocol, and not only those relevant to the monitoring of carbon stocks or carbon stock change. The costs can therefore not be used directly in all instances to provide a budget for the establishment and development of a carbon inventory network.

Table 6: Overview of existing forest monitoring networks and inventories with particular regard to their application to monitoring of forest carbon stocks and stock changes.

Network/ survey	Comprehensive and/or representative?	Relevant?	Accurate and/or precise?	Adaptable and/or extendable?
CFN	Four sites and two species only. Not always representative of local management.	Data can be used to develop stand-level carbon budgets. However supporting analyses are needed to decompose net flux results into contributions due to different carbon pools. DOC, POC and removals in the form of HWP not accounted for.	In principle very accurate and precise for the particular stands being assessed but further validation of key assumptions in the methodology would be appropriate. Impossible to scale up to regional or national estimates from small number of sites in network.	Assessments could be extended to account for DOC, POC and removals due to HWP. Too expensive to extend network to permit upscaling of estimates to regional or national level with sufficient accuracy and precision. Could provide partial or complete validation of more extensive estimates derived from an alternative methodology.
L-II	Ten to twenty sites and five species only. Not always representative of local management.	Data can be used to provide periodic estimates of carbon stocks and stock changes in standing trees and soil. Protocols for the assessment of carbon stocks/changes in dead wood and litter are being developed.	In principle very accurate and precise for the particular stands being assessed with estimates of carbon stocks estimates likely to be within ±5 %. However no formal analysis of accuracy and precision of relevant assessment protocols has been undertaken. Impossible to scale up to regional or national estimates from small number of sites in network.	Methodology would require only limited adaptation/extension to provide estimates of carbon stocks for all relevant carbon pools. However cost of extending network to represent UK forests and provide regional or national estimates likely to be prohibitive.
PSP	509 sites, 44 species and a range of management regimes. However, plot holding is designed to meet specific requirements for the development and calibration of yield models. As such it is currently not a priority for the network to be representative of UK forests. Includes UKWAS plots as informal component of network. Covers GB only but DARDNI maintain PSP network in Northern Ireland.	Data can be used to provide periodic estimates of carbon stocks and stock changes in stem wood of standing trees and due to removals in the form of HWP.	In principle very accurate and precise for the particular stands being assessed with estimates of stem wood carbon stocks likely to be within ±5 %. However no formal analysis of accuracy and precision of relevant assessment protocols has been undertaken. Scaling up to regional and national estimates of carbon stocks/changes would be problematic because network is not designed for this purpose.	Allometric relationships could be used in conjunction with PSP data to provide estimates of total carbon in standing trees and removed as HWP. L-II type assessments could be incorporated into PSP protocols to provide estimates of carbon stocks/changes in other pools but this could add significantly to costs. Future development of the PSP network would need to be carried out with extreme care if the twin objectives of support for development of yield models and monitoring of carbon stocks/changes were to be achieved.
UKWAS	12 sites across Scotland and 3 species only, forming informal component of PSP network. Management representative of regimes in general practice for regions of the Scotland in which plots are located.	Data can be used to provide periodic estimates of carbon stocks and stock changes in stem wood of standing trees and due to removals in the form of HWP.	In principle very accurate and precise for the particular stands being assessed with estimates of stem wood carbon stocks likely to be within ±5 %. However no formal analysis of accuracy and precision of relevant assessment protocols has been undertaken. Impossible to scale up to regional or national estimates from small number of sites in network.	Allometric relationships could be used in conjunction with UKWAS plot data to provide estimates of total carbon in standing trees and removed as HWP. L-II type assessments could be incorporated into PSP protocols to provide estimates of carbon stocks/changes in other pools but this could add significantly to costs. Expansion of network to represent forest types and management regimes across all UK regions and to permit upscaling of carbon stock/change estimates to regional/national level could form the basis of a statistically robust national forest carbon monitoring network. However the number of plots required would be high and costs likely to be prohibitive.
FCS	350 sites including L-I locations but also extending to represent spatial and compositional heterogeneity of UK forests. 5 species only, representative primarily of high forest. Includes L-I plots as formal component of network. Management representative of local regimes.	Data inadequate for estimation of carbon stocks or stock changes.	Data inadequate for estimation of carbon stocks or stock changes.	Improvement of mensurational assessment protocols, application of stem volume functions and allometric relationships, inclusion of soil carbon assessments to L-II standard and introduction of formal plot-based design would permit estimation of carbon stocks and stock changes but would add significantly to cost if high accuracy and precision were required.

Network/ survey	Comprehensive and/or representative?	Relevant?	Accurate and/or precise?	Adaptable and/or extendable?
L-I	90 sites based on 16 km x 16 km European transnational grid. 5 species only, representative primarily of high forest. Management representative of local regimes. Plots also form key component of FCS network.	Data can be used to develop crude estimates of tree stem carbon stocks and stock changes.	Estimates of tree stem carbon likely to be within ±30 % for an individual site although this could be improved if supplementary measurements were taken. Estimates will be biased for an individual site but unbiased when estimates are aggregated over many sites.	Including mensurational assessments in protocols, application of stem volume functions and allometric relationships, extension of soil carbon assessments to L-II standard and refinement of plot area definitions would permit periodic estimation of carbon stocks and stock changes. Abbreviated nature of any cost-conscious mensurational and soil assessments that may be introduced, coupled with relatively small plot areas, is likely to limit precision to within ±20 %. Reliance on generic stem volume functions and allometric relationships, and restricted numbers of soil assessments likely to result in estimates being biased for individual sites but unbiased when aggregated across sites. This has implications for network design and extensiveness if applied to estimation of carbon stocks/changes.
NIWT	Stratified random plots covering 1 % of woodland area for ground truthing survey based on analysis of aerial photographs. More than 40 000 plots provide a network representative of management, objective, soil type and productivity at a local level.	The large number of plots and good representivity of the network would enable good estimates of carbon stocks to be made, but only when used as input to appropriate models. The data could also be used as input to a detailed woodland change matrix approach, similar to that currently used at a UK level for all land use classes.	Many of the data are qualitative, with a large uncertainty associated with any quantitative measures. However, because of the large number of plots and the collection of important descriptive 'meta-data', NIWT would be able to narrow the uncertainty associated with existing land use change estimates of carbon stock change.	The most important shortcoming of the data-set is the lack of soils information. This could be corrected by reference to soil maps, although the existing national coverage may not have sufficient resolution. Future surveys could include soil information. NIWT represents a largely untapped resource and further analysis will reveal its potential.
SSWT	Stratified (coastal and non-coastal) sample of 1% of land area. For each 1 km^2 sample square, features were identified from aerial photographs, the sample square sub-divided into 16, with 2 selected for field data collection. Data were collected on the area of small woodland (<2 ha), linear features and individual trees.	The data are only suitable for improving estimates of woodland cover (small woodlands), and could also be used as basic input (number of trees) for estimating the carbon stock of non-woodland trees.	No information is available on tree size, stocking density etc. and thus uncertainty is large, and dependent on the error associated with estimates of mean tree size and associated data required for scaling.	When the survey is repeated (2004-09), a measure of tree size would make the data-set more useable.
SCDB	Crop information for all woodland (and non-woodland) blocks managed by Forest Enterprise. The database is therefore comprehensive, but may not be fully representative if management objectives differ significantly between FE and privately managed woodland.	In conjunction with appropriate forest yield/growth models the SCDB can provide a robust estimate for above-ground carbon stocks associated with the FE managed estate (production high forest), making up 25% of the UK forest estate. No information is available on deadwood, litter or soils.	The complete coverage of the FE estate together with the long history of development of production forecast models would make robust estimates of carbon stocks achievable. Changing management practice may, however, increase the uncertainty associated with these estimates, while management objectives other than timber production are also likely to result in stocks and stock changes being overestimated.	A small proportion of forest soil maps have been digitised, and this is ongoing process with the ultimate aim of covering the FE estate. These data could usefully be incorporated with the SCDB. The most valuable adaptation of this data-set would be to further extend it to the private sector.
LCM2000	A broad classification of land use based on satellite imagery which can only distinguish between conifer and broadleaf woodland.	LCM2000 would need to be integral in any carbon inventory to maintain compatibility with other (non-woodland) national data-sets. However, no information on carbon stocks, stocks change or individual crops is given at a local level.	Estimates of woodland cover from NIWT and LCM2000 do differ, resulting from interpretation, scaling and technological differences.	Further exploration of the differences between LCM2000 and NIWT would be a valuable process during the establishment of a national carbon monitoring network

Table 7: Summary of key attributes of the existing monitoring networks

Network	No of plots/ species	stock change	tree biomass	stem biomass	litter/ soil	max error	Cost per plot establish ment	Cost per plot periodic measure ment	notes
CFN	4/2	✓	(✓)	(✓)	(✓)	±5%	£50k	£200k	(a,b)
L-II	20/5	✓	✓	✓	✓	±5%	£4k	£75k	(a,c,d)
PSP/UKWAS	509/44			✓		±5%	£3K	£1.5k	(a,c,d)
L-I	90/5			✓	(✓)	±30%	£0.5k	£0.15k	(a,e)
FCS	350/5			✓		±40%	£0.5k	£0.15k	(a,f,g)

a. Costs greater than £1000 are rounded to the nearest £500; costs less than £1000 are rounded to the nearest £50.
b. Methodology does not account for carbon losses as POC or DOC, or removal as HWP.
c. Maximum error in PSP dbh assessment (stand level) estimated at ±0.2 cm; error in conversion of tree dbh assessments to plot stem biomass estimated at ±5% based on Hummel *et al*. (1959) and Jeffers (1955).
d. Net flux can be estimated from periodic carbon stock change. Methodology for assessment of deadwood and litter is under development and not yet implemented.
e. Error estimates based on Edwards (1983) and supplementary analysis of plot level errors in regression equations of standing volume on top height and basal area per hectare. Note that biomass assessments are only made possible in the L-I network because of the additional mensurational assessments made as part of the (national) FCS protocol.
f. Tree-level estimates only; plot-level estimates are not possible because no formal plot is established.
g. Error estimate based on (f) adjusted to account for application of equation based on stand top height at the tree level.

Intensive network

High cost prevents the extension on an intensive network to a sufficient number of sites to verify national-level or district-level estimates of carbon stocks and stock changes. However, these are the only types of network which provide complete measurements for all relevant forest carbon pools. These measurements could be used to validate estimates of carbon stocks derived from carbon accounting modules or more coarse-scale monitoring networks, and as such, the contribution made by intensive networks is essential. The CFN is an elegant approach to monitoring of the net carbon flux of forests but does have a number of limitations. Firstly, the time-step at which flux assessments have been made is much finer than required for a five-year reporting period. Fine scale assessments are routinely integrated, requiring the implementation of statistically-based gap-filling procedures to replace missing data. The gap-filling procedure should be independent of any process-based model which might itself be calibrated using the flux data. There are also issues associated with data storage and quality assurance for the CFN approach as discussed by Aubinet *et al*. (2000). Protocols would need to be developed to adjust raw CFN measurements to account for loss of carbon through DOC and POC as well as through removal of biomass as HWP. The most logical way to achieve this would seem to be through further integration of the CFN with the L-II network. The L-II network is already well placed to take on the role identified for an intensive network in validating models and coarse-scale estimates. However, inclusion of flux-tower measurements at some suitable sites would provide valuable verification of assessments made using the L-II protocols on the basis of a completely independent measurement procedure. Site selection requirements for flux towers are exacting, including an approximately homogenous 500 m fetch in relatively simple terrain. These requirements would severely limit an expansion of the CFN within the current L-II network.

Intermediate network

The principal role of a network such as that formed by PSPs and UKWAS plots is probably in the calibration and validation of forest carbon accounting models and underlying growth models. This role will be especially important if carbon accounting models (or benchmark estimates derived from them) are to represent the diversity of stand conditions in the UK, particularly in terms of management regime. The emphasis should be placed on improving and verifying representation in carbon accounting models of tree and stand biomass / carbon dynamics in response to alternative silvicultural prescriptions. The presumption is that soil carbon stocks, while influenced by management of above-ground biomass, do not vary greatly in response to management interventions, except in extreme cases such as afforestation of previously bare ground or long-term denuding or complete removal of forest cover. Accordingly, protocols for the periodic assessment of litter and soil carbon at a relatively low precision may need to introduced, particularly since information on the carbon content of forest soils is poor at the national level. The strategic development of the PSP network (Matthews *et al*., 2003) with less emphasis on monitoring and priority given to providing data for model development underlines the role for an intermediate network as one of support for model calibration and validation. However, there may be a secondary application for estimates obtained from an intermediate network in verifying more coarse-scale carbon stock estimates derived from models from an extensive network. Any assessments of litter and soil carbon made in an intermediate network, albeit with limited precision, would be particularly important for this type of application. It is likely that at least a proportion of the existing EU L-I sites would be upgraded and incorporated within the intermediate network. Furthermore, a sub-set of the intermediate network might be selected to provide more detailed information of the soil/litter carbon pools and act as benchmark sites for validating the extensive network.

Extensive network

Compared to intensive and intermediate networks, extensive networks such as FCS and L-I are weak in terms of the completeness and precision of the assessments for estimation of carbon stocks. However, their strength lies in their potential to cover a representative range of sites, tree species and management regimes. High cost would prevent complete assessments of carbon stocks being made, even with limited precision, but the extensive network would permit the broad-scale verification of national and district estimates of carbon stocks derived from carbon accounting models. For reasons elaborated in the discussion of the intermediate network, emphasis in extensive plots would be on assessment of forest biomass with only limited consideration of litter and soil carbon, possibly through collection of input data for a litter / soil carbon model such as one based on RothC (Falloon and Smith, this report), or by using soil type as a surrogate for carbon stocks based on measurements in the intermediate network. The verification process would consist of a plot-by-plot comparison of estimates made by the carbon accounting model with assessments from the extensive network. Inherent in this application would be a network fully representative of the UK forest estate and probably based upon an extension of the 16 x 16 km transnational grid. Alternatively or additionally, depending on the configuration of the network, it may be possible to compare upscaled estimates at national or district level derived independently using the carbon accounting model and statistical analysis/synthesis of estimates made in the extensive network. The FCS and L-I networks and the NIWT ground-truthing plot network would require careful adaptation and harmonisation of protocols in order to provide robust estimates of carbon stocks. In the case of the FCS network, a plot-based assessment protocol would need to be incorporated, perhaps taking a modified L-I plot design as a minimum specification. The 0.25 ha assessment area used for structural assessments in NIWT ground-truth plots would be ideal, but introduction of even abbreviated mensurational assessments for all trees in a plot of this area in all situations would be prohibitively costly. As with the FCS network, one solution might be to include a modified L-I plot within the 0.25 ha area. In general, if a unified plot design could be adopted across FCS, L-I and NIWT ground-truth plots, either based on the L-I system or otherwise, then the extensive carbon monitoring network could be formed from the combination of these three networks or from appropriate sub-sets of plots in each network. In any event, a unified protocol for assessment of mensurational (and other) variables to support carbon stock assessment would need to be developed. This could be based on assessments of tree dbh and either tree or stand height, depending on stand structure and density following protocols similar in principle to abbreviated tariffing as described by Edwards (1983).

The precision of abbreviated mensuration procedures has been estimated to be within ±20% (Edwards, 1983). Analyses carried out as part of this review suggest that stand-scale allometric relationships used as part of these procedures are subject to bias, effectively inflating uncertainty to ±30% or more. However, scope exists to improve on or refine existing procedures and underlying allometric relationships. Research could be carried out to support the revision of relevant procedures as part of their adaptation to biomass estimation. Improved allometric relationships could also be derived, eliminating bias and ensuring that precision is within ±20% (see Figure 13). It should also be noted that although estimates of standing stem carbon are uncertain in young crops, the uncertainty falls as the expected standing carbon stock increases. This reflects the small proportion of stem biomass compared to total biomass and uncertainty in allometric relationships at early stages of development.

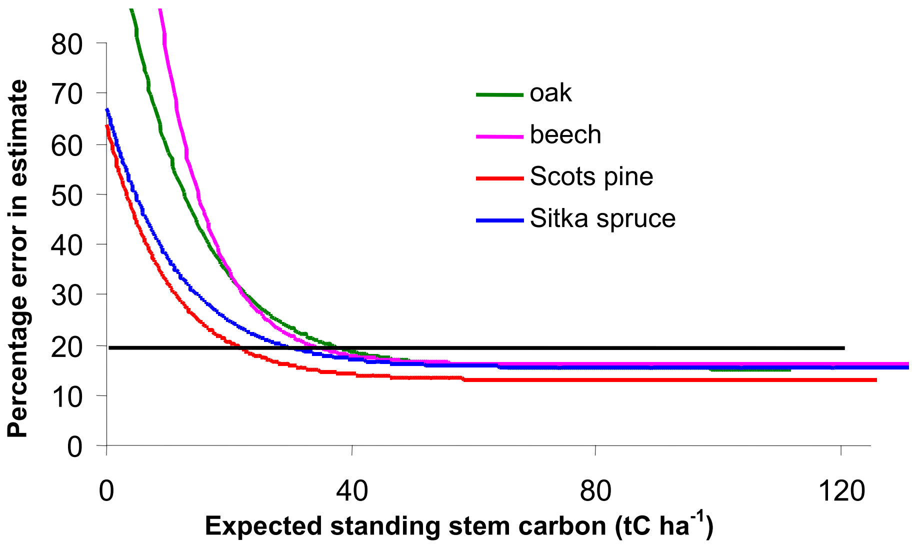


Figure 13: Relationship between percentage error in the estimate and expected standing stem carbon for four species, as estimated using stand-level form-height / top-height equations. The horizontal line shows the percentage error in estimates based on more intensive, single tree functions, which may be applied in stands of low density and volume.

3.2 Inventories

Individual stands comprising UK forests are highly heterogeneous, and therefore any system for monitoring carbon stocks and stock changes will require a minimum set of inventory information for the UK forest estate:

- A GIS-based map defining forest areas at the stand level across the UK.
- Basic data on properties of individual stands, specifically:
  - soil type
  - tree species composition
  - productivity (eg GYC)
  - age class structure
  - prescribed management.

None of the four key inventory systems currently available (NIWT, SSWT, SCDB and LCM2000) are ideally suited to providing such information but it may be possible to carry out suitable adaptations and extensions.

Forest cover map (FCM)

An essential first step in developing a system that could support carbon stock estimation would appear to be to reconcile the discrepancies in the representation of woodland areas and types in the four inventories to develop a unified forest cover map. The resultant, harmonised approach to forest cover mapping and the underlying methodology would then need to be applied consistently across the UK. This may require significant additional field surveys or may simply involve re-analysis and reconciliation of existing records, depending on the details of the approach adopted.

Basic inventory data

Having obtained a consistent FCM, basic data on stand properties as specified above would need to be ascribed to individual stands. For stands managed by Forest Enterprise, this information could be transferred directly from the SCDB, provided that the harmonised FCM represented stands in a consistent way to the SCDB. If this was not the case, a set of rules would need to be devised for translating SCDB records into FCM records. It may be possible to develop a parallel approach for forests managed by the Northern Ireland Forest Service.

An entirely different and probably more elaborate protocol would need to be developed to derive basic stand data for the remainder of the UK forest estate. The rudiments of such a protocol may be found in the system currently adopted for the production forecast of private woodlands carried out by the Forestry Commission. Private sector management companies provide the Forestry Commission with broad-brush data on areas, species composition, age class structure and management regimes practised in their stands. Normally it is not possible to relate data to specific stands. The Forestry Commission applies a set of assumptions about the average productivity of stands of different species in different regions of Britain and these can be used in combination with the private sector stand data to run a 'first order' production forecast. It is not clear whether this relatively coarse-resolution data is sufficient to provide accurate forecasts of carbon stocks to an acceptable level of precision and, equally importantly, in accord with the principles of transparency and verifiability stated in the Kyoto Protocol. One way of investigating this might be to carry out a sensitivity analysis based on forecasts for the Forest Enterprise estate using basic input data for all stands or equivalent coarse-resolution data and assumptions as applied to private-sector woodlands.

The extent of basic data required for individual stands in the UK depends on the details of the carbon accounting system adopted. For example, quite simplistic data on tree species composition and prescribed management may be sufficient if a methodology such as that proposed by Kirschbaum *et al*. (2001) was adopted, although more complete data would be required to support any verification exercise. Ideally, stand-level data described above would be available and attributable for all stands in the UK as a minimum data-set. Any survey that is carried out to obtain such a data-set may be able to take advantage of remote-sensing technologies currently under development. For example, if data on species composition and age class structure only were to become available for individual stands, then remote-sensing techniques based on aerial photographs and assessments might be used to infer stand height and density, from which parameters representing stand productivity and management regime could be derived. The potential of such approaches seems worthy of review and evaluation.

4. Surveys and inventories relevant to HWP carbon stocks

The prime and arguably only source of information on UK carbon stocks and dynamics in the UK is Alexander (1997). Sources of data relevant to the assessment of HWP carbon stocks, either by direct inventory or as input to models, were exhaustively reviewed and defendable, conservative estimates of carbon stocks in different wood product categories and landfill were derived. A key result, showing the development of carbon stocks in wood products in primary and secondary use in the

UK over the period 1965 to 2000 is presented in Figure 14. The total carbon stock in viable HWP in the year 2000 is estimated as between 80 and 90 MtC, of which approximately 65% is accounted for by carbon in structural timber in domestic and commercial buildings (with the estimate for commercial buildings believed to be particularly conservative). If carbon in non-structural timber (eg internal door frames, furniture, card and paper) in domestic and commercial buildings is included, the proportion of the total viable HWP carbon stock accounted for rises to 85%, and if stocks in fencing are also included, over 90% is accounted for. These results suggest that monitoring of this sub-set of HWP categories in primary and secondary use should account for at least 90% of viable HWP carbon stocks.

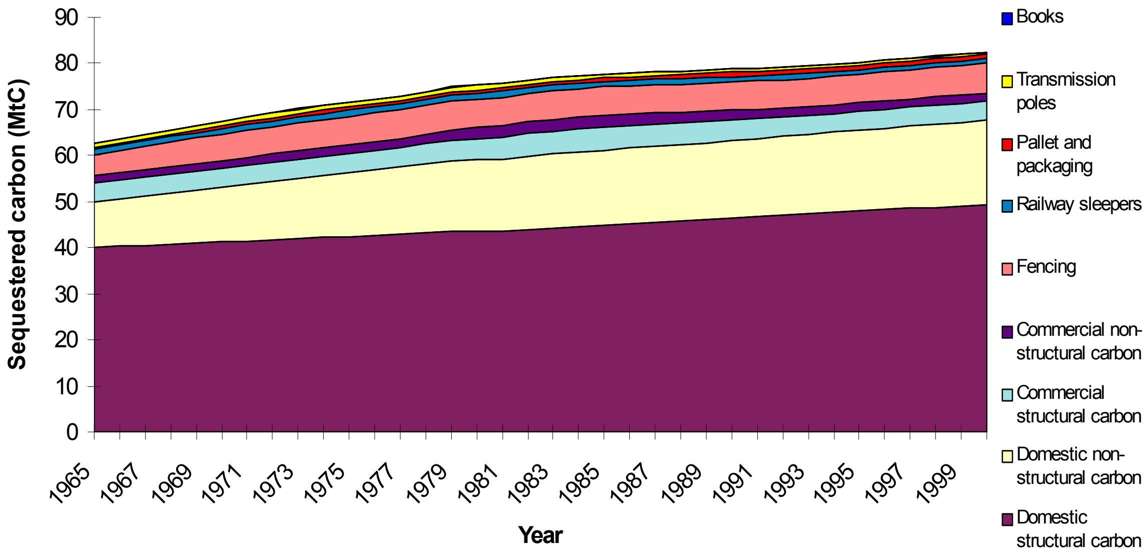


Figure 14: Estimated carbon stocks in wood products in primary and secondary use in the UK over the period 1965 to 2000 showing the contributions made by different types of product. Carbon stocks in wood products disposed of to landfill are not included. Note that currently, approximately 90% of the harvested wood making up UK wood products is imported from outside the UK. Redrawn from Alexander (1997).

Estimates of carbon stocks in HWP in landfill are much more uncertain than for viable HWP, and have been estimated for the year 2000 by Alexander at 216 MtC. In contrast to forests themselves, monitoring networks and inventories for assessment of HWP carbon stocks are few and limited. The most relevant and useful data sources were identified by Alexander as:

For estimation of carbon in structural timber

- GB/England housing and construction statistics (DoE, 1979; 1982; 1993; 1995a), including data on number of buildings by floor area.
- England House Condition Survey (DoE, 1986; 1991), including data on age structure of buildings.
- England/Wales commercial and industrial construction statistics (DoE, 1977; 1981; 1985; 1995b), including data on numbers of buildings by floor area.

- Commercial data on quantities of structural timber incorporated into buildings by end-use type, size (floor area) and year of construction (G. Kellet, Barratt Homes Newcastle Ltd.; N. Priday, Border Oak Design Ltd.; G. Matthews, consultant materials scientist – personal communications).
- UK timber consumption statistics (FAO, 2003; Whiteman, 1991).
- Surveys of timber consumption in end-product form (Whiteman, 1991; True, 1974; Elliot, 1985).
- Estimates of average service life of wood used as fencing (Clarke and Boswell, 1976).

For estimation of carbon in HWP in landfill

- Surveys of quantities of waste being disposed to of landfill (DoE, 1992; 1997; CIPFA, 1996; MEL Research, 1995), including data on the proportion of waste made up by HWP.

These various surveys, inventories and data sources were difficult to integrate and the estimates developed by Alexander often relied on one-off assessments for a single year; for example, the distribution of buildings in terms of year of construction is only available for the year 1986 and is limited to England (DoE, 1986). It also proved necessary to rely on commercial data which, although reliable and in principle available, may be difficult to obtain. The classification of timber consumption statistics in terms of 'raw' wood product types (eg roundwood and sawlogs), rather than in terms of end-use categories also frustrated the analysis, particularly for estimation of carbon stocks in fencing. Most seriously, no data were available for estimating carbon stocks in non-structural HWP in domestic and commercial buildings – representing at least 20% of total viable HWP carbon stocks. However, Alexander was able to develop and apply a methodology for surveying this category of wood product.

5. Adaptation of HWP surveys and inventories for estimating carbon stocks and stock changes

Given the potential and irregular nature of existing surveys and inventories, it is difficult to suggest ways in which they can easily be extended to monitor HWP carbon stocks. In effect, survey and inventory procedures will need to be instigated from scratch, although elements of methodology from previous studies may be adopted. The two main elements of interest would appear to be:

- Inventories of domestic and commercial buildings, by building type, floor area and year of construction.
- The survey method of Alexander (1997) used for estimation of carbon stocks in non-structural HWP in buildings.

6. Development of forest and HWP carbon monitoring methodologies

Based on the above review and evaluation of monitoring networks, surveys and inventories, a draft methodology has been developed for the periodic estimation of carbon stocks and stock changes in forests and HWP in the UK, and if needed, for country/district-based estimates. For monitoring of forest carbon stocks, the methodology draws heavily on concepts and resources from existing inventories and monitoring networks. For HWP, the methodology proposed below would require instigation (or more regular and comprehensive implementation) of surveys in the domestic and commercial sectors.

6.1 Forest carbon monitoring

The proposed monitoring system is based on four nested methodologies or 'modules'. as outlined in Table 8, with a schematic diagram of the relationships between the individual modules given in Figure 15. The first of these (Module A) is an inventory-based approach supported by a forest carbon accounting model that generates district-level and national-level estimates of carbon stocks in forest biomass, litter and soil. The other three modules (B-D) supply data and assessments for the verification of estimates generated by module A, or to support development, calibration and validation of the carbon accounting model.

Module A

This consists of a GIS-based forest cover map (FCM) based on a unification of NIWT, SSWT, SCDB and LCM2000. The FCM shows the location and area of individual forest stands across the UK. Minimal data would be recorded against each individual stand and used as input to a carbon accounting model. The data are likely to include:

- soil type
- species composition
- productivity (yield class and/or stand height and density)
- age class structure
- management prescription.

These data might be collected by ground survey, assessed using remote-sensing techniques or assigned on the basis of default assumptions made for districts or grid-squares of the UK. For some stands, it may be possible to transfer data directly from existing systems such as SCDB. The specification of the carbon accounting model is assumed to be based on a combination of upgraded and validated components of CARBINE, CFLOW and ROTHC models. It should be noted that this is not the only option for Module A. The detailed specification for the module and underlying model depend strongly on the requirements implicit in national and international agreements on approaches to forest carbon accounting. For example, if the accounting methodology of Kirschbaum *et al*. (2001) was to be accepted internationally and adopted in the UK, then the 'carbon accounting model' might consist of simple benchmark values of long term carbon stocks associated with particular combinations of site, (possibly) species and management regime. These benchmark estimates may be derived in turn from simulation results for different scenarios obtained using a unified and upgraded version of CARBINE, CFLOW and ROTHC, but this more complex model would not need to be integrated into this module of the forest carbon monitoring system. On the other hand, if 'real time' carbon accounting was to be adopted, then a dynamic carbon accounting model such as a combined CARBINE/CFLOW/ROTHC system would need to be integrated directly into Module A.

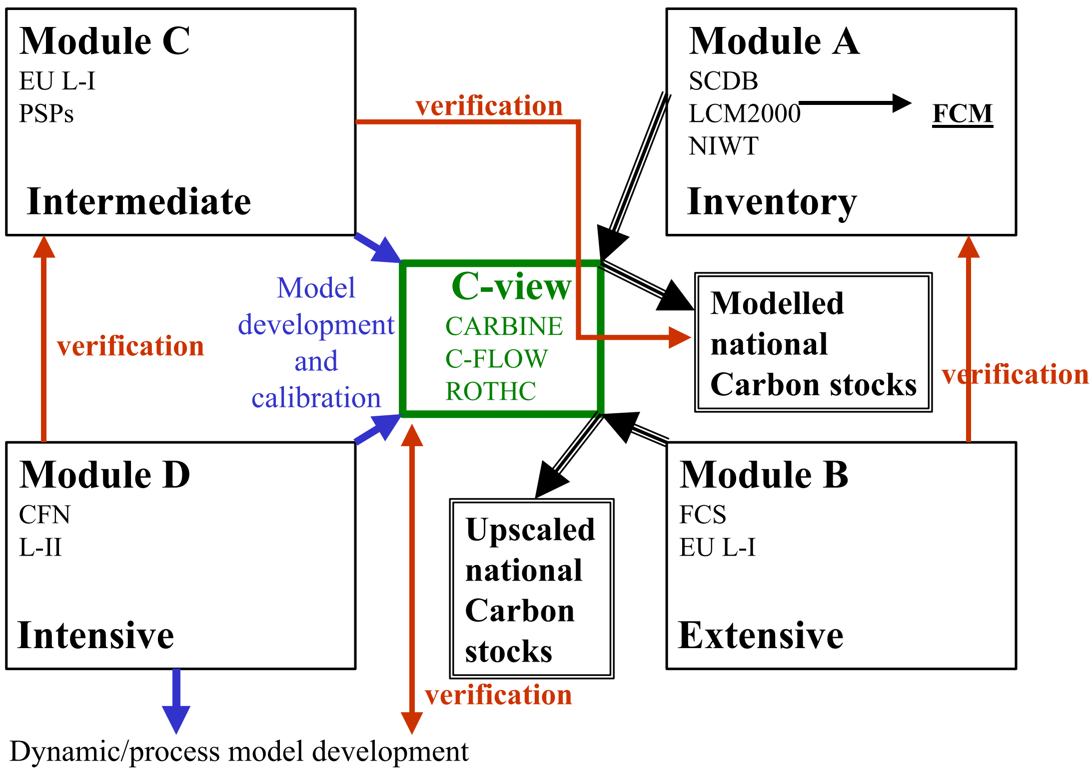


Figure 15: Schematic representation of a proposed forest carbon monitoring network.

Module B

This module consists of an extensive forest monitoring network as described earlier in this report. The main function of the module is to provide broad-scale verification of national and district estimates of carbon stocks derived from carbon accounting models. It would be based on a representative grid, possibly an extension of the 16 x 16 km transnational grid with plot information collected at a relatively low level of precision. Because of the representative nature of the network, it would have the potential for providing estimates of carbon stocks and stock changes totally independent of those generated in Module A.

Module C

This module consists of an intermediate forest monitoring network as described earlier in this report. The main function of the module is to provide data for improving and verifying representation in models of tree and stand biomass / carbon dynamics in response to alternative silvicultural prescriptions. There may be a secondary application for estimates obtained from this network in verifying more coarse-scale carbon stock estimates derived from models from an extensive network (see Module B). Module C would primarily be based upon an adapted PSP network, but also with the incorporation of a number of EU L-I plots.

Module D

This module consists of an intensive forest monitoring network as described earlier in this report. The main function of the module is to provide data for validating estimates

of carbon stocks derived from carbon accounting modules or more coarse-scale monitoring networks. Module D would be based on a combination of CFN and L-II plots. An additional role would in aiding the development of dynamic/process models of forest growth which could be used for future projections of carbon stock change taking predictions of environmental change into account.

Precision and costs of forest carbon monitoring

An overview of the four modules comprising the draft forest carbon monitoring system is presented in Table 8. This includes a brief description of the purpose of each module (A-D), its structure, assessments taken and also estimates of precision along with indicative costs based on entries in Table 7. Marginal costs take account of potential for integrating the proposed system into existing monitoring networks, also as indicated in Table 8. The total marginal cost of implementing the forest carbon monitoring system is estimated at £1.5 M.

6.2 HWP carbon monitoring

The monitoring system proposed here is based on the results of Alexander (1997), which indicated that 75% of the contribution of viable HWP to carbon stocks is made by the two HWP categories of

- structural timber in buildings
- non-structural wood in buildings

with the remainder being made up by a mix of minor products, but notably fencing. HWP disposed of to landfill also make a separate, potentially highly significant contribution to carbon stocks. Accordingly, a monitoring system is proposed consisting of four modules (E-H), one for each category of HWP indicated above.

Module E

This module is concerned with the estimation of carbon stocks in structural wood in buildings. It consists of a complete inventory of domestic and commercial buildings in the UK in terms of :

- building type (domestic or category of commercial, possibly type of construction)
- floor area (or approximation to building size)
- year of construction.

A carbon stock would be attributed to each building based on these data. This inventory would need to be repeated every five years. Alternatively, if a comprehensive survey could be carried out initially, it might be possible to use data on demolitions and new construction to carry out periodic updating of a base inventory. Validation could be provided by repeating the comprehensive survey and updating the base survey, but over a cycle longer than five years. Independent research would be needed to verify estimates of quantities of structural wood in buildings of different types, sizes and periods of construction.

Table 8: Description of the four modules associated with the forest carbon monitoring network. *Forest Research Ecosystem Database.

Module	Sampling design and intensity	Siting within stand	Plot/assessment layout	Assessment protocols	Application	Cost and accuracy/precision	Comments
A	Complete representation of forest stands down to a threshold minimum area.	Sampling at random locations through stand, but with stratification according to CS2000, NIWT and FE SCDB methodologies.	Point sampling based on nominal 0.01 ha plots?	According to updated CS2000/NIWT methodology, harmonised with existing FE SCDB strategic and tactical survey procedures (also subject to revision).	Input data to GIS and database, coupled to unified CFLOW/CARBINE/ROTHC model for estimation of carbon stocks. Possible re-survey of a sample of plots.	Cost not yet quantified but high. Marginal costs for partial re-survey might be ~£400k. Accuracy and precision unknown but could be quantified. Scope exists to adapt inventories and models to improve precision.	Potential applications for remote sensing to provide estimates of area, top height and stocking.
B	Stratified sample of forest stands by site, climate, species, age class and management including 16 km x 16 km grid. Around 500 sites.	Centre of stand.	Based on EU Level I N, S, E, W plots within 25 m radius of centre sited within nominal 0.25 ha plot. Individual plots take area 0.01 ha – collapses to full 0.25 ha plot when stocking is below specified threshold.	Forest condition (EU Level I), soil type, species, planting year top height, stocking, tree dbh, nominal or actual management history and future management.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation for Module A.	Establishment cost £180k which could be spread over several years. Cost of periodic surveys £90k. Marginal cost depends on future priority given to existing Forest Condition Survey. Worst case scenario is £150k (establishment) and £75k (periodic survey).	Potential to succeed Forest Condition Survey. Potential to evolve into integrated EU Level I, Forest Condition Survey and mensuration permanent sample plot network.
C	Based on forest stands including a proportion at 16 km x 16 km locations. Around 100 sites.	Within uniform area, accessible but avoiding forest edges.	Based on mensuration permanent sample plot design with area 0.1 to 0.15 ha with marked boundaries and tree numbers.	Full permanent mensuration sample plot procedure, forest condition (Level I). Including: • Biomass – sample plot procedure + allometric bolt-ons (BSORT) • Understorey – methodology based on literature review • Coarse woody debris – Level II methodology, under development • Ground vegetation – could be done as part of litter but questionable value • Litter – rough and ready assessment carried out as part of Level II soil survey. – needs to be evolved • Soil – Level II methodology down to 1 m.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation in Modules A and B.	Establishment cost £400k which could be spread over several years. Cost of periodic surveys £220k. Marginal cost depends on scope for integration with mensuration permanent sample plot network and is estimated at £200k (establishment) and £100k (periodic surveys).	
D	Based on forest stands in principal tree species. Around 20 sites. CFN sites also included to provide additional level of data capture for model development.	Within uniform area, accessible but avoiding forest edges.	Based on EU Level II plot design (0.3 ha) containing mensuration permanent sample plot (0.1 to 0.15 ha) with marked boundaries and tree numbers.	As Module C plus assessments of climate, litter dynamics and DOC. To include sites containing flux towers.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation in Levels A and B. Also support to development, calibration and validation of process-based models of carbon dynamics.	Total cost £510k per year. Marginal cost depends on level of commitment to EU Level II network and is estimated at £110k per year.	Equivalent to EU Level II and CFN.

Module F

This module is concerned with the estimation of carbon stocks in non-structural wood in buildings. A survey approach similar to that adopted by Alexander (1997) would be adopted, but could be simplified by developing a classification system for key elements of this pool. For example, default assumptions could be permitted for quantities of wood in standard items such as work-tops, chairs and door-frames. The survey would need to be repeated every five years. The only practical way of carrying out this survey would appear to be through engaging voluntary assistance in providing survey data from the general public and commercial enterprises, perhaps as part of an educational programme on environmental issues.

Module G

This module deals with estimation of the component of carbon stocks in viable HWP due to fencing and other minor product categories. Two alternative options are possible. The first option is to divide the country into grid squares, perhaps of 1 km x 1 km resolution. A random sub-sample of these squares would be selected, stratified according to land-use with emphasis on urban, sub-urban and agricultural areas. A survey would be carried out in each grid square to identify key linear features associated with minor HWP categories, specifically fence lines, power transmission lines using wooden transmission poles and railway lines with wooden sleepers. The length of each feature within the grid square would be recorded and standard values used to convert these assessments to equivalent carbon stocks. Some of these product categories might be regarded as so minor that they could be ignored. The SSWT would provide invaluable experience for a survey of this type. The alternative option is to model stocks of carbon in these minor HWP categories using validated estimates of consumption and product service lives. This approach could be justified by the relatively small contribution made to HWP carbon stocks.

Module H

Module H is concerned with the estimation of carbon stocks in HWP disposed of to landfill. Although this carbon stock and its associated stock change may be one of the most important in the UK forest and wood chain system, at this stage the details of the assessment protocols for this module are the most speculative. An option for the methodology is based on a 100% survey of the landfill sites in the UK. For each site, an initial assessment is made of the volume occupied by the landfill material and then at five-yearly intervals, of the increment of this volume. The proportion of the volume made up of HWP is estimated from appropriate waste statistics, landfill site records or default values for individual localities of the UK. This volume is converted to an equivalent carbon stock using standard assumptions about moisture content and density for appropriate HWP categories. Emissions of greenhouse gases from each landfill site would have to be monitored, modelled or assigned a value based on estimates attributable to the decay of HWP. However, it should be noted that HWP is regarded as one of the most recalcitrant fractions of landfill material and, as such, is believed to make a relatively small contribution to greenhouse gas emissions resulting from decay processes.

Precision and cost of HWP monitoring system.

The precision of estimates derived using an approach such as adopted in Module E has been estimated at within ±10%. For Modules F-H, precision is highly dependent on the details of implementation and cannot be estimated at this stage. Costs of implementing this proposed HWP carbon monitoring network are unknown.

7. Conclusions

It is possible to adapt existing forest inventories and monitoring networks to provide verifiable estimates of forest carbon stocks by means of a transparent methodology. UK national estimates of carbon stocks and stock changes derived in this way should be accurate and precise, although precision may be poor for individual sites and stands. Further work on assessment of accuracy and precision need to be carried out in parallel with implementation of the system. The success of the methodology hinges on the availability of an improved and validated forest carbon accounting model. This would need to be based on a combination of existing models, notably CARBINE, CFLOW and ROTHC in conjunction with significant improvements in known areas of weakness. Improvements also need to be made to yield models that underpin carbon accounting models; in particular, flexible and dynamic models are needed to better represent the diversity of silvicultural systems in the UK.

A complementary system for monitoring carbon stocks and stock changes in HWP, both in use and disposed of to landfill, would need to be implemented almost from scratch. At this stage it is only possible to speculate about the main features of such a system and further development is necessary.

The marginal cost of implementing the forest carbon monitoring network is estimated at £1.5M. Certain marginal costs at the periphery of the project are not included in this estimate, notably additional research and development to improve yield models and integrate them into a carbon accounting model. The cost of implementing the HWP carbon monitoring system is unknown.

The above draft methodologies, both for forest and HWP carbon monitoring, are clearly at an early stage and further development, in collaboration with relevant experts, is needed before the designs of these systems can be finalised and implemented. Finally, it should be noted that this report has been concerned with the theoretical and practical aspects of designing a forest carbon monitoring system without considering adjustments, constraints or omissions that may be imposed as part of an internationally-negotiated framework for reporting carbon stocks and stock changes. In general the draft systems have been designed to accommodate any modifications that may be necessary to comply with such national or international protocols.

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