Forestry Commission

FC Woodland Carbon Code: Carbon Assessment Protocol (v2.0)

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Acknowledgements

The authors would like to acknowledge the many forestry professionals past and present who have helped in the production of this new procedure.

Introduction

This document outlines the recommended procedures for undertaking a comprehensive carbon assessment of the living tree biomass, above- and below-ground, within an area of woodland. This version of the protocol does not therefore account for carbon in deadwood, whether standing or fallen, or deadwood in the below-ground components of the growing trees. It has been specifically written to be used in conjunction with the Forestry Commission's Woodland Carbon Code (Forestry Commission, 2010) which sets out a Project Design Standard for projects that aim to sequester carbon through woodland creation and to generate voluntary emission reductions for the purposes of demonstration or sale.

This document is organised into six main sections. Section 1 gives a general introduction to forest carbon monitoring, focussing in particular the choice of an assessment protocol which will be suitable for the scale of project envisaged. This introductory section is followed by sections relating to boundary definition, stratification, and detailed assessment methodologies designed for implementation in projects of varying scale and complexity.

Practitioners wishing to use this protocol to assess the amount of carbon in a forest carbon project are directed to Section 2 and the appropriate following Sections.

The assessment procedures outlined in Section 4, starting on page 26, have been developed from the well-established tariffing method (Hummel, 1955) advocated by the Forestry Commission since 1956 (Hamilton, 1975). The current publication is not just aimed at forestry professionals although it does assume some basic knowledge of forest measurement procedures as described in *Forest Mensuration: a Handbook for Practitioners* (Matthews and Mackie, 2006) and *Timber Measurement* (Mackie and Matthews, 2008). A brief introduction to basic measurements and conventions is presented in Appendix 1 on page 69 and a glossary of terms that may be less familiar to the reader is included on page 66. Terms included in the glossary are *italicised* the first time they appear within the text.

It is important to note that, although the Forestry Commission is moving towards adopting 4 centimetres as the standard minimum *dbh* which defines measurable trees established in biomass projects, the Forestry Commission's tariff system is constructed around a strict 7 centimetre minimum diameter. Because the protocols in this version of the carbon assessment protocol are reliant on the tariff system, the minimum diameter of a measurable *tree* is taken as 7 centimetres and smaller stems are defined as either *saplings* or *seedlings*.

The five main steps to performing a comprehensive carbon assessment on a woodland area are:

1. clearly defining the area to be assessed;
2. appropriately sub-dividing the area into strata;
3. deriving a tree stem volume estimate for each species or species group comprising the tree growing stock, possibly further subdivided by size-class;
4. estimating, for each stand of trees making up the growing stock, the allocation of biomass in different parts of the tree (*e.g.* roots and stump, main stem, branches and foliage);
5. converting the biomass estimates to their carbon equivalents.

The above steps are outlined in the sections Boundaries of the assessment, Stratification, Estimating the volume of the tree growing stock, Biomass allocation and Carbon conversion which respectively detail the relevant mensurational procedures and subsequent calculations required to implement a carbon assessment.

The biomass equations presented in Section 5 ('Biomass allocation') have been completely revised since the original (2012) version of the Carbon Assessment Protocol.

1. Project scale and choosing an appropriate protocol.

Significant progress has been achieved in the development of a methodology for a British forest inventory that could form the essential basis of a forest carbon monitoring, verifying and reporting framework for England, Scotland and Wales. The approach has been designed to enable countries and smaller regions to adopt enhanced sampling to derive compatible estimates of carbon stocks and stock changes for specified localities with greater precision than would be offered by the basic inventory, as required. It has also been possible to develop related approaches that could be applied to monitoring of forest carbon at smaller scales, for example covering a few trees in a small woodland or a discrete forest estate of a few thousand hectares. In addition, an approach involving application of forest carbon accounting models has been characterised, with applications primarily to the design and evaluation of carbon management projects prior to implementation. In total, five approaches have been identified:

1. **Model-based evaluation**
2. **Full survey**
3. **Plot-based survey**
4. **Two-stage survey**
5. **Sample-based inventory.**

This section of the Carbon Assessment Protocol presents an outline of these five approaches. With the exception of model-based evaluation, the discussion of each approach concentrates on describing the estimation of carbon in standing trees, however it is envisaged that carbon in debris, litter and soil could be estimated through natural extensions of the methods. The monitoring of carbon stocks and stock changes in harvested wood products through survey and inventory methods is beyond the scope of this report and is a subject for further work.

1.1. Description of approaches

1.1.1. Model-based evaluation

This approach is most suitable for application when a forest carbon management project is being proposed, designed and planned and an estimate of the amount of carbon sequestered (or magnitude of reduction in emissions) due the project is required prior to implementation as part of project evaluation. A model-based approach might also be relevant at a larger scale, for example when estimating the consequences for forest carbon stocks of significant changes in plans or policies for forest management at the estate and national scales.

Beyond project and policy evaluation, in principle models can be applied to the estimation and monitoring of actual forest carbon stocks, indeed they are often used for these purposes. However, it must be recognised the accuracy and precision of estimates derived in this way is likely to be low, with implications for the reporting of results and claiming of any carbon credits.

The application of the model-based approach involves defining the area of land relevant to the exercise (involving either existing forests or creation of new forests) and the breakdown of this land area into homogenous units (stands) in terms of:

- tree species composition (existing and/or intended)
- age classes/planting years of trees
- tree growth rates (yield classes)
- stand management regimes (existing and/or intended).

This information might be readily available from previous forest surveys, or may be based on assumptions. The characteristics are used to assign standard results from forest carbon accounting models to each stand, as illustrated in Figure 1.1.

Currently there are four main models that could be applied to this approach in Britain – the CEH C-FLOW model and the Forest Research CARBINE, CSORT and BSORT models. While currently BSORT is purely a model of biomass in standing trees, the C-FLOW model can also provide estimates of carbon in forest litter and soils as well as harvested wood products, while CARBINE can also estimate the potential reductions in emissions due to utilisation of harvested wood as a source of bioenergy and renewable material.

All existing forest carbon accounting models in use in Britain refer to the Forestry Commission’s yield tables (Edwards and Christie, 1981) for basic growth and yield predictions. The actual growing stock and therefore the carbon stock observed in an individual stand of trees may deviate significantly from model predictions, particularly those given in the underlying standard yield tables. For this reason, estimates of carbon stocks derived in this way are only precise for large collections (*i.e.* hundreds or more) of stands. Moreover, the Forestry Commission yield tables only represent a relatively limited set of management regimes which will not always be representative of actual stand management. When stand management departs systematically from the assumptions in the yield tables this could lead to biased estimates of forest carbon stocks and stock changes. The Forest Research CSORT model is being designed to work in conjunction with new dynamic models of forest growth and yield to enable the representation of a wider range of possible stand management regimes.

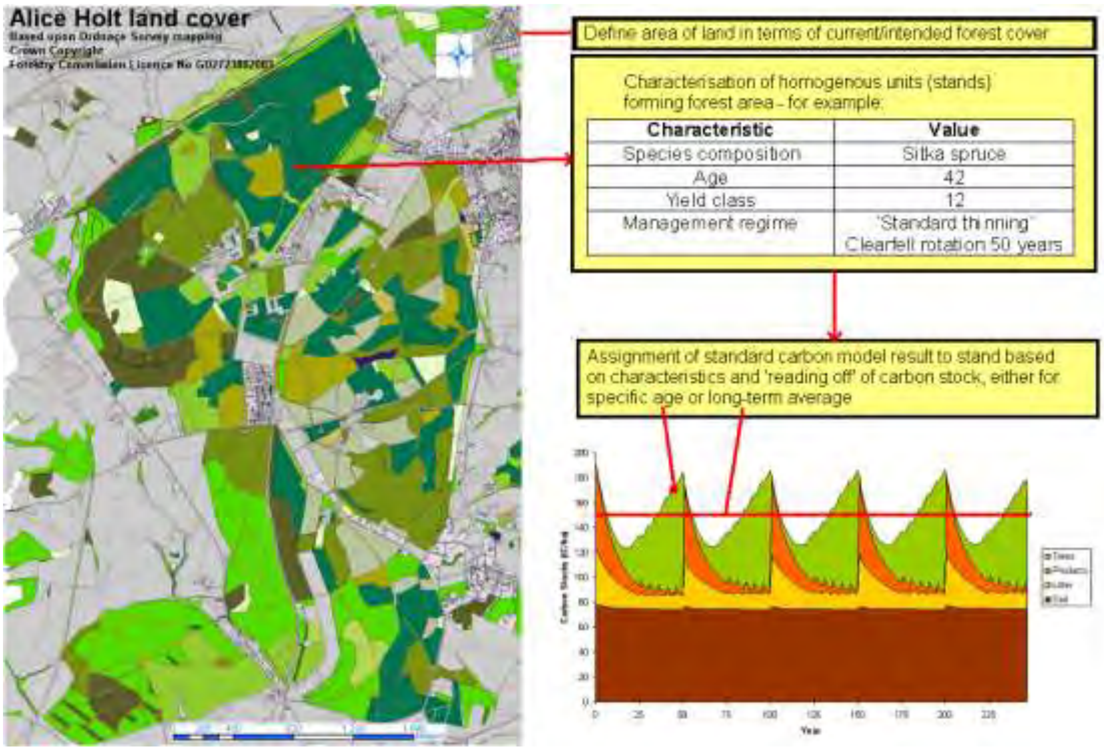

Figure 1.1 Illustration of basic principles of model-based evaluation applied to estimation of carbon stocks in an existing forest. The example standard result for forest carbon stocks is based on the CEH C-FLOW carbon accounting model (Dewar, 1990, 1991; Dewar and Cannell, 1992).

The issues of precision and, more importantly, accuracy in model-based estimates of forest carbon stocks could be addressed by carrying out a supporting survey of actual carbon stocks, which could be used to quality assure and, if necessary, adjust model estimates. However, reference to survey assessments suggests the case for adoption of one of the four survey- or inventory-based approaches described below.

The model-based approach is not considered further within this document, although specific models are applied in Sections 4 and 5 of the Carbon Assessment Protocol in order to derive realistic estimates of individual tree stem volume, crown and root biomass *etc.*

1.1.2. Full survey

This approach is most suitable for the estimation of carbon stocks and stock changes in very small woodlands, perhaps consisting of less than 3000 trees. This might occur when making an assessment in approximately 1 hectare of dense, young trees or in several tens of hectares of trees approaching 'parkland' spacing (beyond 10 metres).

The full survey approach is therefore most relevant to very small scale woodlands or forest carbon management forests. The approach draws on existing well-established forest mensuration techniques, particularly those employed in the periodic assessment of the growing stock in permanent forest sample plots. Permanent sample plots are used routinely for characterising the growth and yield of distinct areas of woodland as illustrated in Figure 1.2.

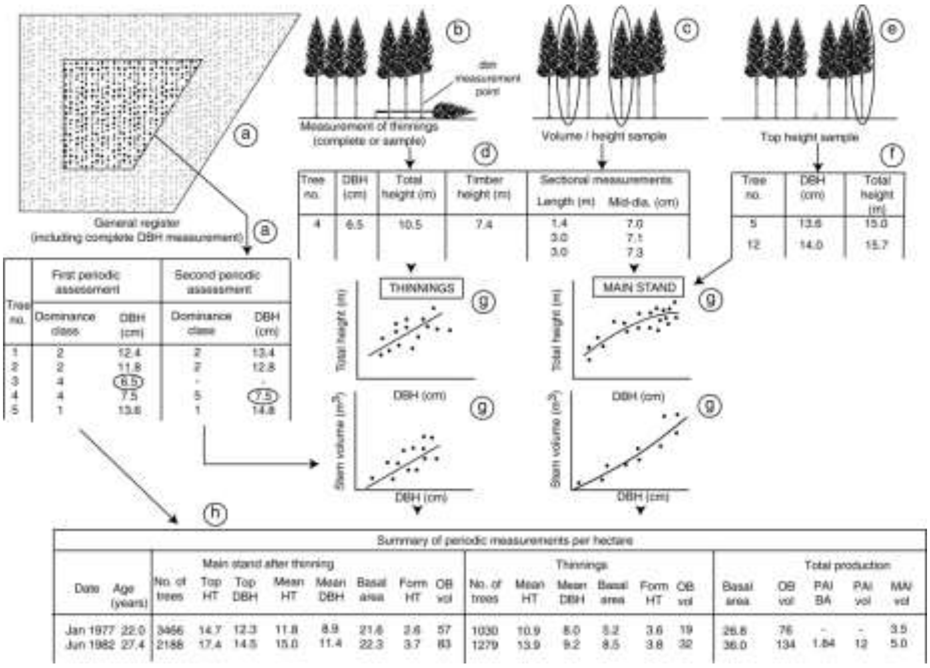

Figure 1.2 Illustration of periodic assessment of growing stock in a clearly delineated, discrete area of woodland. Labels (a)-(h) are discussed in the main text below.

The steps in the assessments involve (see labels in Figure 1.2):

a) Delineation of area containing trees to be assessed followed by a 'General register assessment', *i.e.* counting, measurement of dbh and classification (*e.g.* competitive status or position in canopy) of all trees in the area.
b) Marking of any trees being removed as thinnings and direct assessment of stem volume of all or a *sample* of them.
c) Assessment of total height (and possibly stem volume) of a sample of the standing trees after removal of any thinnings.
d) Tabulation of dbh, height and volume information for thinnings and standing trees.
e) Assessment of total height on a sample of dominant standing trees.
f) Tabulation of dbh and height information for dominant trees.
g) Analysis of correlations between tree height and stem volume to establish relationships with tree dbh.

h) Combining of General Register assessments with height and volume analyses to compute summary stand-level results for the stand (*e.g.* top height, mean dbh, overbark (OB) standing volume). The results for two periodic assessments, made in January 1977 and June 1982, are shown in this illustration.

Methods such as those employed in the measurement of permanent sample plots can extended quite simply to the periodic assessment of carbon stocks in clearly delineated, discrete areas of trees (Figure 1.3).

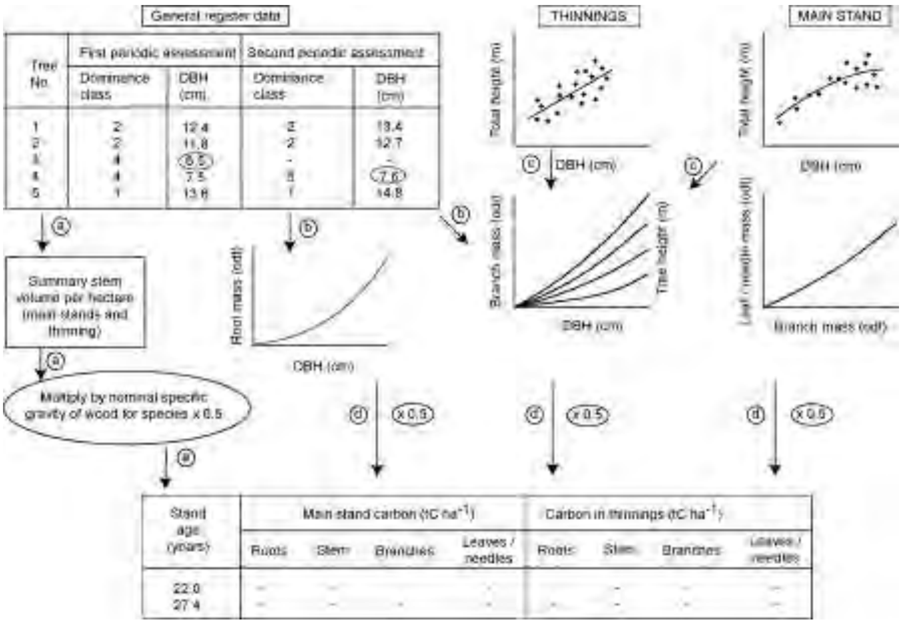

Figure 1.3 Illustration of periodic assessment of carbon stocks in a clearly delineated, discrete area of woodland. Labels (a)-(d) are discussed in the main text below.

Typically, the steps taken in such an approach would involve (see labels in Figure 1.3):

a) Preparation of General Register of trees followed by working up of summary results for stem volume per hectare in trees, as described in Figure 1.2. Stem biomass per hectare can be derived from an estimate of stem volume by multiplying the volume by a standard value for the nominal specific gravity for the wood (Lavers and Moore, 1983). Stem carbon per hectare can be derived in turn from stem biomass by assuming a carbon content for wood of 0.5 (Matthews, 1993).
b) Estimation of root, branches and foliage biomass of trees in the General Register through application of an appropriate allometric equation. Carbon in roots,

branches and foliage is then derived from the biomass estimate by assuming a carbon content for wood of 0.5 (Matthews, 1993).

c) If allometric equations for root, branches or foliage biomass involve terms in tree total height or stem volume then reference is made to appropriate relationships between these variables and tree dbh derived as part of standard mensuration assessments (Figure 1.2g).
d) Adding up results for tree root, branch and foliage carbon to obtain total root, branch and foliage carbon for all the trees (or per hectare, as required).

At this scale, when adopting this approach, there is the reassurance that every tree involved has been visited, counted and measured as part of the assessment. However, this does not guarantee a perfectly precise assessment. The calculations depend on a number of sequential assumptions, notably concerning interrelationships between tree dbh, height, stem volume and branch/root/foliage biomass. Estimation of stem carbon also depends on assumptions about wood density and all calculations involve reference to an assumed carbon content of biomass. Actual allometric relationships and conversion factors observed in particular stands of trees can exhibit systematic departures from predictions suggested by standard assumptions, therefore these need to be applied with care. There is a case for adopting a formal system for continuous periodic checking, quality assurance, updating and refinement of such standard relationships and assumptions.

Assessment Method E, fully explained in Section 4.2, is just one variant of a full survey as described above.

1.1.3. Plot-based survey

This approach is most suitable for the estimation of carbon stocks and stock changes in small forest estates or localities, typically involving less than 100 distinct stands of trees of arbitrary area.

The application of the approach involves defining the area of land relevant to the exercise and the breakdown of this land area into homogenous stands. Survey sample plots are put into each stand at random locations and basic mensuration assessments are made, typically (Figure 1.4):

- All trees are counted and classified for species and possibly characteristics such as competitive status and canopy position.

- A *systematic sample*[1] of the trees in the plot are measured for dbh. (In many situations all trees in the plot will be measured.)
- A smaller systematic sample of the trees in the plot are measured for total height and possibly other variables (*e.g.* total height, crown width and depth, diameter at different points on the stem).

Other variables may also be measured within the sample plots, such as dead wood, young regenerating trees and even soil characteristics.

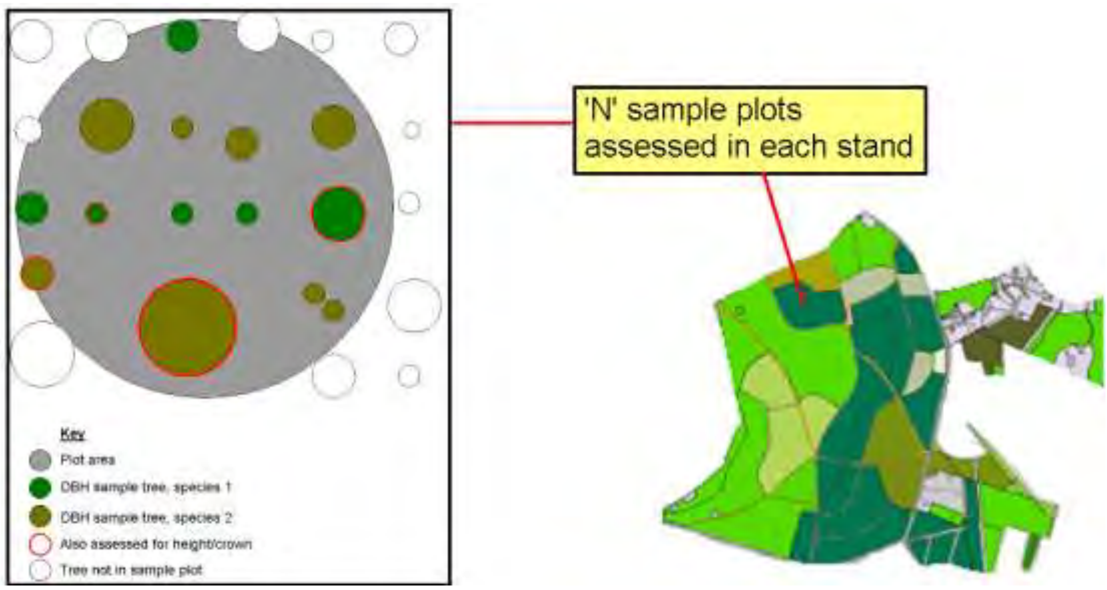

Figure 1.4 Illustration of basic principles of a plot-based survey for estimation of carbon stocks in a small forest estate. An example of assessments taken in a circular-shaped plot is shown.

The numbers of plots required and their shape and area will be determined by the statistical details of the survey being undertaken, including the required level of precision of the carbon stock results. The Forestry Commission has published standard procedures for mensuration assessments in stands (Matthews and Mackie, 2006; Mackie and Matthews, 2008), including recommendations for numbers of plots required for stands of different areas, selection of plot shape (circular or rectangular) and plot area, the latter generally depending on the density of the trees being measured. However, survey details may vary from these recommendations depending on specific objectives.

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[1] In a systematic sample, the sampling units (sample trees) are selected such that they are evenly distributed (for example at the intersections of a grid) within the boundary of the area being assessed (in this case, the sample plot).

The processing and analysis of the survey sample plot measurements on trees typically involves:

- Computation of basic mensurational results for each stand (numbers of trees, *basal area*, *quadratic mean dbh*, stem volume, *top height* and/or mean height).
- Estimation of tree and stand biomass (by component, *e.g.* root, stem, branch, foliage) through reference to standard allometric relationships with respect to tree dbh, height *etc.*
- Estimation of tree and stand carbon from biomass by reference to standard values for carbon content (typically 0.5 – see Matthews, 1993).

Plot-based surveys usually conform to well-established statistical designs, consequently the calculation of results and estimation of uncertainties is straightforward. However, although quite measurement-intensive, as with full surveys the calculations depend on assumptions about interrelationships between tree dbh, height, stem volume and branch/root/foliage biomass as well as biomass carbon content. There is a case for adopting a formal system for continuous periodic checking, quality assurance, updating and refinement of such standard relationships and assumptions.

Assessment Methods A to D, fully explained in Section 4.1 below, are practical applications of the plot-based methodology described above. Each of Methods A-D is applicable in different situations; the choice of the appropriate method is guided by the decision tree illustrated in Figure 4.1.

1.1.4. Two-stage survey

This approach is most suitable for the estimation of carbon stocks and stock changes in moderately sized forest estates or localities, typically consisting of collection of stands with a total area of up to 5000 hectares.

The aim of two-stage sampling is to achieve comprehensiveness by making abbreviated assessments in all stands, while also achieving acceptable accuracy and precision by making plot-based assessments in a sample of stands. The plot-based assessments are used in the analysis of survey data to quality-assure and 'calibrate' the more comprehensive abbreviated assessments.

The application of the approach involves defining the area of land relevant to the exercise and the breakdown of this land area into homogenous stands.

Assessments in all stands

In each stand, abbreviated (generally stand-level) assessments are made which may include some or all of:

- Total canopy occupancy of trees in stand.
- Relative canopy occupancy of different tree species.
- Numbers of trees per hectare by species (qualitative visual assessment).
- Basal area per hectare by species (qualitative visual assessment or possibly relascope sweep – see Matthews and Mackie, 2006; Mackie and Matthews, 2008).
- Stand quadratic mean dbh by species (qualitative visual assessment, possibly supported by measurement of a nominated 'mean tree').
- Stand top and/or mean height by species (qualitative visual assessment, possibly supported by hypsometer measurement of a nominated point in canopy).

These assessments might be taken at a series of points in the stand, at one specific point or during a 'walk through', as appropriate and as defined for a particular procedure to achieve specified objectives.

Assessments in a sample of stands

In a specified sample of stands (perhaps 100 stands selected at random), plot-based assessments are carried out according to the principles described for a plot-based survey.

The processing and analysis of the survey measurements on trees typically involves steps as already described for a plot-based survey. The results for conventional mensurational variables such as mean dbh and top height are used to quality-assure and, if necessary, calibrate the abbreviated results for all stands (see example in Figure 1.5 on page 15). These quality-assured assessments can then be worked up for all subcompartments into estimates of tree and stand biomass in a similar manner to plot-based measurements by reference to standard allometric relationships and ultimately estimates of carbon stocks can be estimated.

As with plot-based surveys, there is a case for adopting a formal system for continuous periodic checking, quality assurance, updating and refinement of such standard relationships and assumptions used in calculation of survey results.

Two-stage surveys are not considered further in the current Carbon Assessment Protocol.

1.1.5. Sample-based inventory

This approach is most suitable for the estimation of carbon stocks and stock changes in very large forest estates or expanses of woodland, typically consisting of collection of stands with a total area of many thousands or even millions of hectares. This includes situations encountered involving the forests for an entire country or significant region, and is therefore applicable to national inventories.

The inventory approaches employed in different countries display many similarities, although there are often significant differences in the details. The essential features include:

- A statistically based survey of a sample of the total area of forest.
- Assessment of the species composition, age structure, productive potential, growing stock and other features of interest in the sample area(s), depending on the objectives of the inventory.
- Analysis of the results for the sample area(s) to estimate the species composition, age structure, productive potential, growing stock and other features of interest in the entire forest area, with known uncertainty.

The description presented below concentrates on the methodology currently under development for the latest National Forest Inventory (NFI) in Britain.

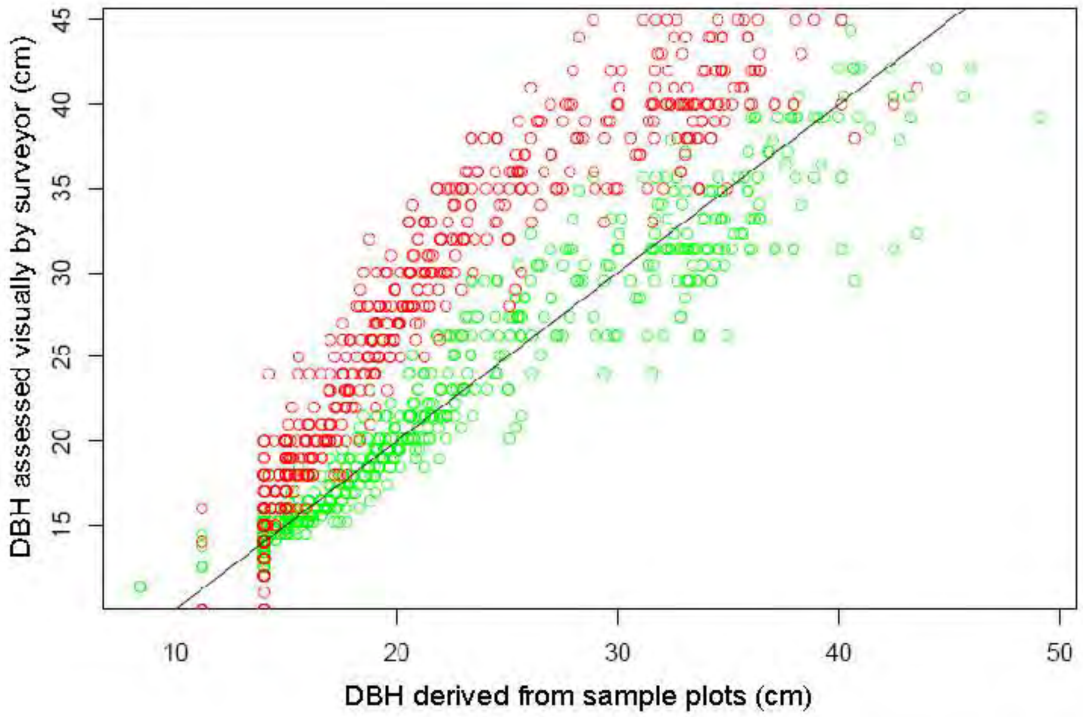


Figure 1.5 Illustration of how sample plot-based results can be used to quality-assure and calibrate abbreviated (often visual) stand-level assessments of mensurational variables, taking the example of mean dbh. The visual assessments made by a surveyor are shown plotted against observations derived from sample plots. Before calibration (red circles), the bias in the surveyor's assessments is apparent. The green circles show the adjusted assessments following calibration. Graph provided by Prof. Hubert Hasenauer, University of Natural Resources and Applied Life Sciences, Vienna.

Selection of sample areas

The approach to sampling forest areas has been designed to enable countries and smaller regions to adopt enhanced sampling to derive compatible estimates of carbon stocks and stock changes for specified localities with greater precision than would be offered by the basic inventory for England, Scotland or Wales, as required.

Currently, the proposed basic inventory sampling scheme in each country involves (Figure 1.6):

- Digital mapping, through interpretation of aerial photographs, of all forest areas with an area of at least 0.5 hectare in advance of selection of sample areas.
- Superposition of an 8 km x 8 km grid onto map. Identification of a 1 hectare square in the southwest corner of each of these grid squares. If the 1 hectare

square contains at least 0.05 ha of woodland, then the square is included as part of a systematic sample of forest areas.

- Identification of a further sample of 1 hectare squares containing woodland by random selection. (Squares containing partial areas of woodland are selected with less frequency than squares formed completely of woodland – rules are defined to determine these relative frequencies.)

The total number of 1 hectare sample squares is selected to achieve target levels of precision in the results for variables of interest at the appropriate national or regional scale. Currently, the NFI sampling scheme aims to cover approximately 1% of the total forest area in England, Scotland and Wales.

The NFI sampling scheme is an effective compromise between efficient statistical design and a requirement for flexibility in inventory objectives. The adoption of a primarily random sampling scheme for location of 1 hectare squares makes it possible to very easily enhance the basic level of sampling in particular areas of woodland in small regions or localities within the countries, in order to address the requirements of local stakeholders for more detailed or precise inventory information.

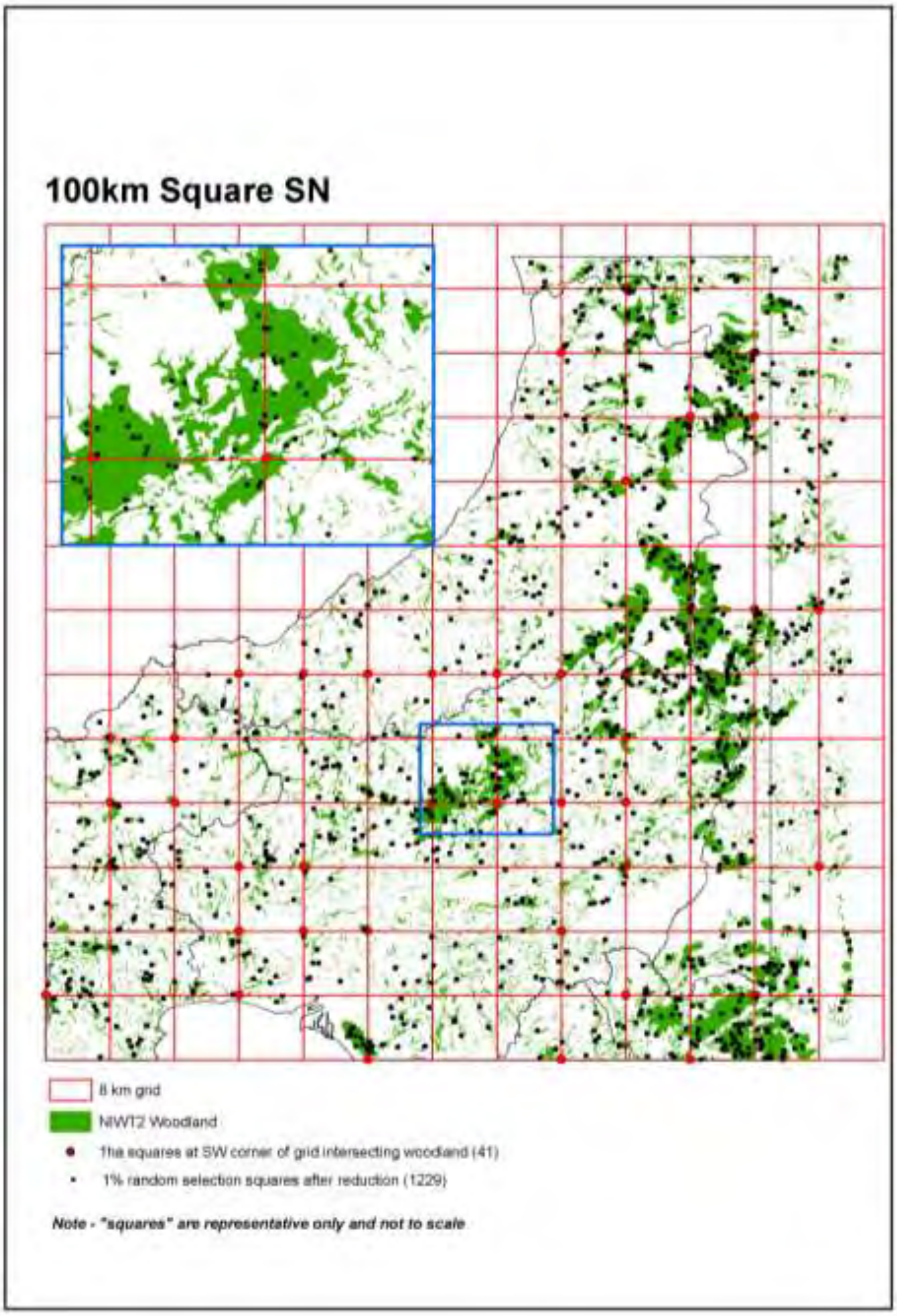


Figure 1.6 The basic forest area sampling scheme for NFI, illustrated for a 100 km x 100 km region covering part of south-west Wales. The forest area map is shown, as are the locations of 1 hectare sample squares coincident with 8 km x 8 km basic sampling grid. Also shown are randomly located 1 hectare sample squares representing approximately 1% of the forest area in the region.

Survey of sample areas.

Currently, the proposed survey assessments in each 1 hectare sample square are based on the general surveying principles described earlier, including an element of two-stage sampling (Figure 1.7):

- The area within the 1 hectare square is broken down into homogenous stands (with a minimum total woodland area of 0.05 ha) and areas not containing woodland. (In many situations, the 1 ha square will consist of a single section of woodland.)
- Abbreviated (generally stand-level) assessments are made in each stand within the square.
- Plot-based assessments are made in one stand within the square, selected with probability proportional to the area of the stand falling within the square.

The abbreviated stand-level and plot-based assessments made in the square are similar to those described earlier for two-stage sampling. The main purpose of the abbreviated assessments is to determine the species composition and canopy area occupied within each stand. The plot-based assessments are designed to characterise the growing stock in the stand and also to quality-assure the stand-level assessments.

The processing and analysis of the survey measurements for each 1 hectare square follows the principles described for a two-stage survey. The summary results for all the 1 hectare squares are used to derive estimates of the growing stock (and carbon stocks) for the total forest area from which they have been sampled, with due regard to the statistical design of the inventory.

As with plot-based and two-stage surveys, there is a case for adopting a formal system for continuous periodic checking, quality assurance, updating and refinement of such standard relationships and assumptions used in calculation of survey results.

The national inventory approach is designed to work in close conjunction with the recently updated Forestry Commission forecast system. This should permit the simulation of future carbon stocks and stock changes in forests in England, Scotland and Wales based directly on the baseline national inventories and appropriate scenarios for future forest management.

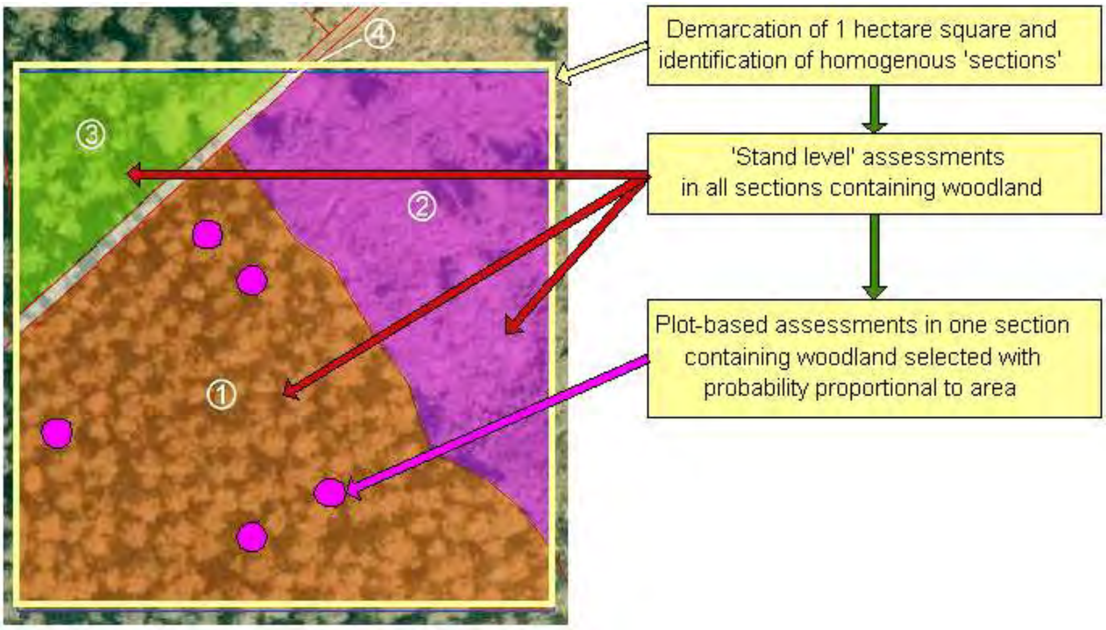


Figure 1.7 Illustration of the assessments applied in the 1 hectare sample squares of the NFI inventory. This example square contains four 'sections' – three distinct stands and one distinct area not containing trees. Conventions are set for the minimum size of sections, including a minimum area of 0.05 hectare.

2. Boundaries of the assessment

A fundamental requirement of any form of inventory is that the extent of the resource is unambiguously delineated. The easiest way of achieving this is usually to clearly indicate the boundaries of the assessment on some form of map, whether this is paper-based or contained in a geographic information system (GIS). This information should subsequently be included with the *Project Design Document* (PDD) required in order to comply with the Forestry Commission's Woodland Carbon Code (Forestry Commission, 2010), which states:

> *"The project area should be clearly defined using appropriate maps, identifying all relevant aspects of the woodland resource, including any special characteristics and/or sensitive areas. Description of the woodland resource should include all relevant aspects of physical, silvicultural, ecological, archaeological, social and landscape features and any other special characteristics, including adjacent areas that provide critical ecosystem services (e.g. hydrological services, erosion control) or habitats for any protected or threatened species."*

It is essential this map should clearly indicate any areas of open ground in order that the subsequent calculations, on which the carbon assessment is based, exclude unproductive areas within the project.

The reader is directed to the latest published version[2] of the code for more detail of the current requirements. Specific information about mapping can be found on the relevant Woodland Carbon Code web page (www.forestry.gov.uk/forestry/INFD-8TQTMA#mappingrules).

[2] At the time of writing, latest version of the code can be freely downloaded from the Forestry Commission's website at: www.forestry.gov.uk/carboncode

3. Stratification

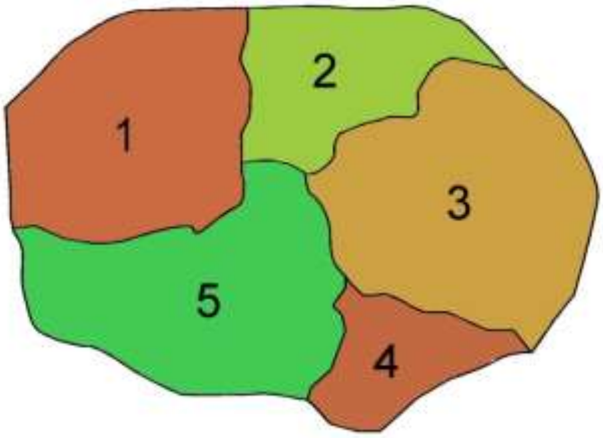
Woodland areas are commonly a composite of several populations of trees owing to differences in species, age-class distribution, stocking density and growth rate, each with a different volume per hectare. If you were to assess such a variable *population* as a single entity you would, at best, need to take a very large sample in order to account for the variation in your population of trees and, at worst, may also end up with a biased sample.

Assessing the amount of carbon in a standing woodland resource is therefore easier to achieve if the woodland area is first sub-divided into relatively uniform blocks, or *strata*. Each *stratum* will comprise an area of woodland of approximately the same type and stage of growth, be this a single contiguous block or a number of physically separate stands. It is therefore essential that the identity of the stratum is defined without ambiguity. For example, division may be done on the basis of age class, species and age class, volume per hectare, altitude, *etc.* If at all possible, the characteristics used as the basis for stratification should be the same those to be estimated by the sampling procedure. In the case of carbon assessment, this will be volume per hectare by tree species and storey.

Two common forms of stratification are: (i) area-based stratification, where spatially disparate areas of land are grouped together as a single stratum based on the characteristics of the woodland they contain (as illustrated in Figure 3.1) and (ii) storey-based stratification, where trees growing on the same area of land are grouped into strata based on height-class, size-class and/or species (as illustrated in Figure 3.2).

Irrespective of the basis of stratification adopted, the basic rules are as follows:

1. the variation within a stratum must be less than the variation between strata (otherwise stratification has either been incorrectly carried out or is unnecessary);
2. you must be able to unambiguously assign each sampling unit (for example, each tree) into one, and only one, stratum;
3. the sample plots within a single stratum ***must*** be of uniform shape and area, however different sized sample plots can be used in different strata;
4. each stratum must contain at least two *sampling units* in order to allow the calculation of a mean value and, if desired, a statistical variance.



Compartment	Species	YC	Planting year	Area (ha)	Stratum
1	OK	8	2008	2.4	I
2	BI	8	2007	2.1	II
3	OK	6	2006	2.6	I
4	SP	14	1978	1.5	III
5	AH	8	2006	2.8	II

Figure 3.1: A simple example of stratification within a small area of woodland. In this example, the five compartments are allocated into three strata. (For standard species abbreviations, please see Appendix 2).

Figure 3.3 on page 24 is given as an aid to stratification and to the classification of strata as "uniform" or "variable". In general, a stratum will be classed as "variable" if the variation exceeds 3 years in age or 4 metres in *top height* or if it has an unusually wide dbh range.

A rough estimate to establish whether the dbh range is unusual can be obtained by measuring the dbh of the largest and smallest marked measurable trees in a sample of 20, taken consecutively in a line through the stand. Add the measurements together and consult Table 3.1 on page 25 to find the normal maximum dbh range associated with this figure (*e.g.* if the smallest dbh is 14 cm and the largest dbh is 50 cm, total 64 cm, from Table 3.1 the normal maximum range is 27 cm). If the sample range is greater than the normal maximum dbh range given in Table 4.1, as in the above example, then the dbh distribution can be regarded as unusually wide. It is advisable to repeat this exercise at least 3 or 4 times to get a reasonable impression of the dbh range in a stand.

Once the stand has been stratified, a suitable sampling method must be chosen for each stratum and the detailed sampling and measurement instructions followed accordingly. Figure 4.1 on page 26 provides an aid to selecting the correct sampling method.

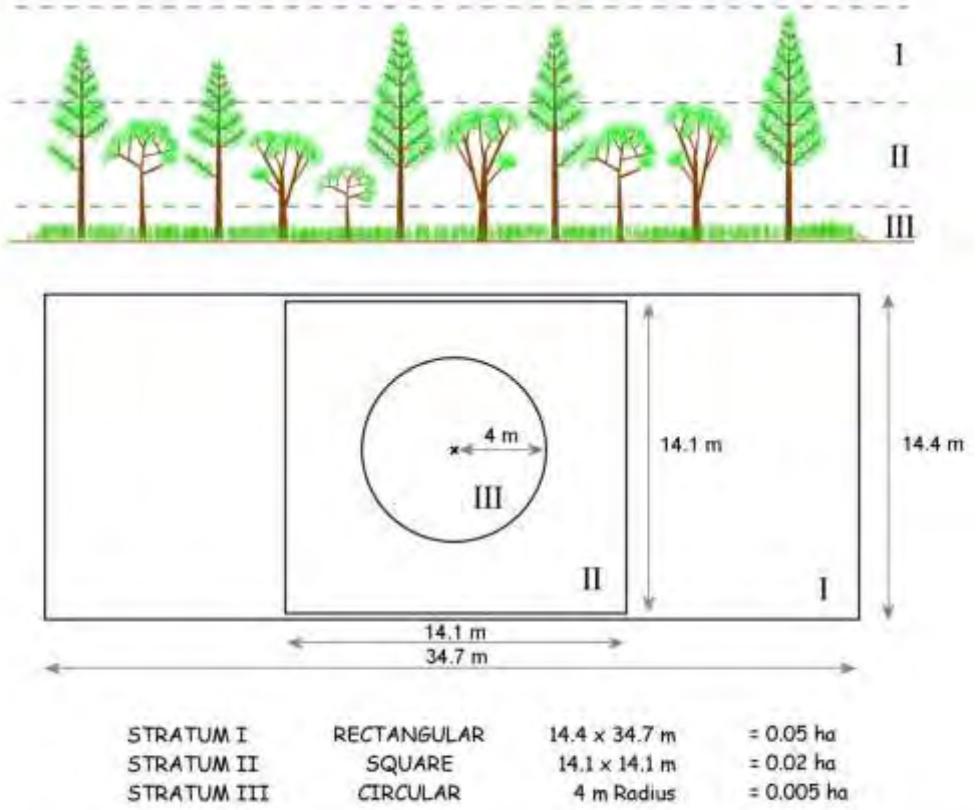


Figure 3.2: A simple example of stratification within a single stand containing three identifiable storeys. In this example, concentric sample plots are being used in order to sample the different strata – overstorey (I), understorey (II) and regeneration (III). A 0.05 hectare rectangular plot has been selected in order to sample sufficient of the relatively sparse overstorey trees (stratum I). A 0.02 hectare square plot has been selected in order to contain sufficient numbers of the more closely spaced understorey trees (stratum II). A circular 0.05 hectare plot has been selected for sampling the dense regeneration on the forest floor (stratum III).

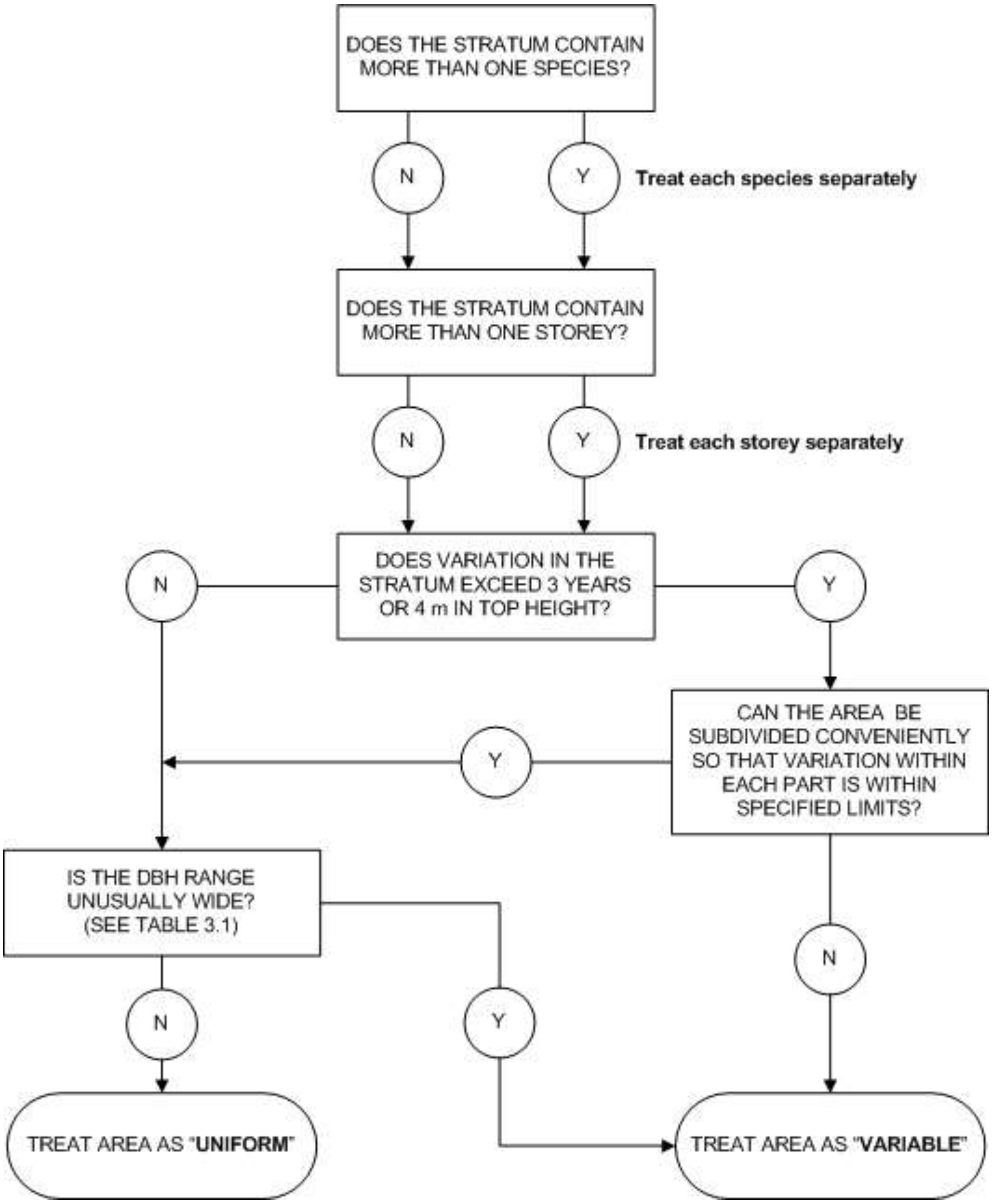


Figure 3.3: Key to stratification and deciding whether a stratum is classed as "uniform" or "variable.

Table 3.1: Evaluation of dbh range (from Matthews & Mackie, 2006).

Largest + smallest dbh (cm)	Maximum dbh range (cm)	Largest + smallest dbh (cm)	Maximum dbh range (cm)	Largest + smallest dbh (cm)	Maximum dbh range (cm)
18	7	46	19	74	32
20	7	48	20	76	33
22	8	50	21	78	34
24	9	52	22	80	35
26	10	54	23	82	36
28	11	56	24	84	37
30	12	58	25	86	38
32	13	60	26	88	39
34	14	62	27	90	40
36	15	64	27	92	41
38	16	66	28	94	42
40	16	68	29	96	43
42	17	70	30	98	44
44	18	72	31	100	45

4. Estimating the volume of the tree growing stock

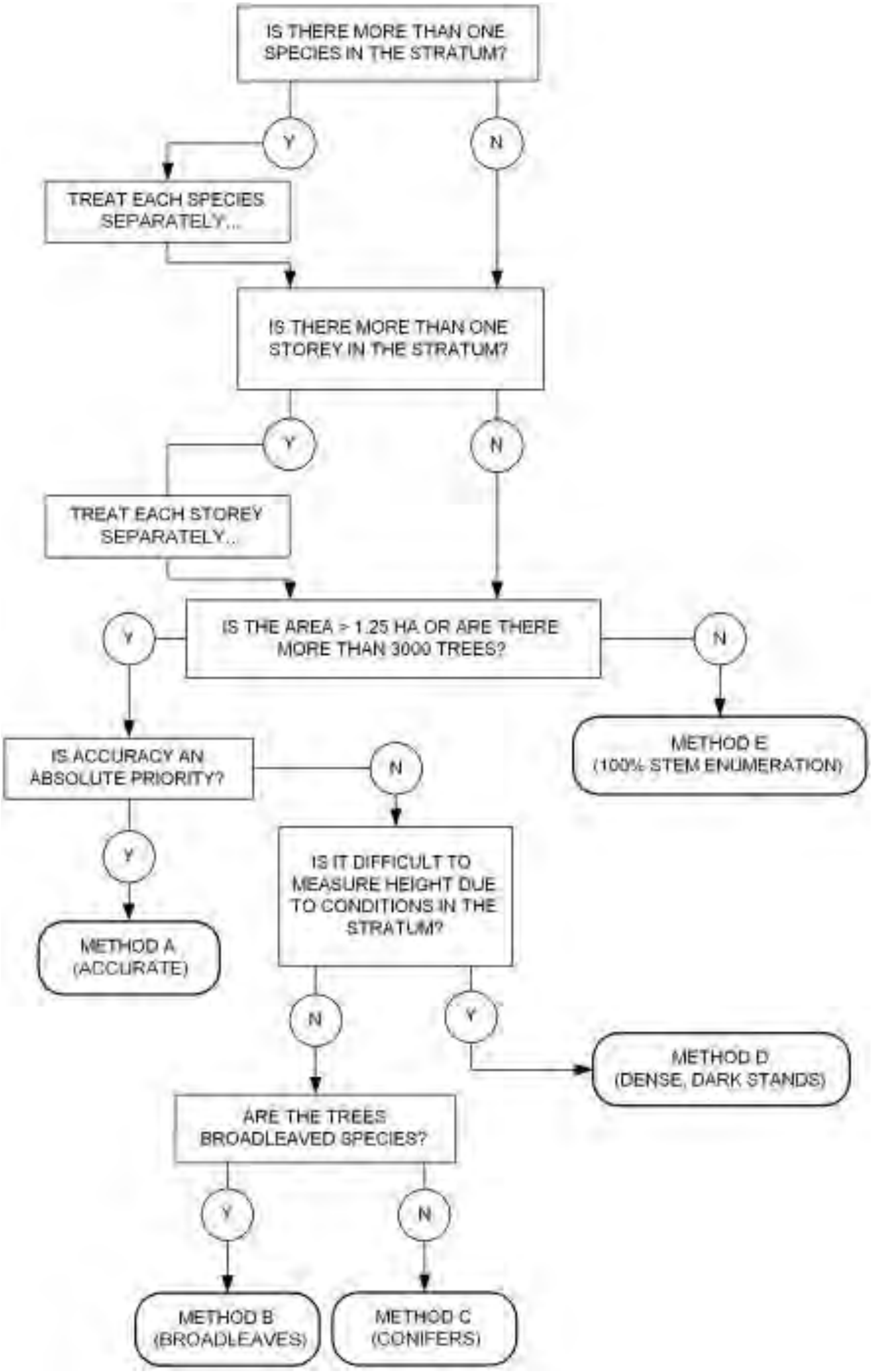


Figure 4.1: The decision tree for determining the most appropriate method of achieving a tree volume estimate.

Before the quantity of carbon within a woodland can be calculated, the volume of timber contained within the growing stock must be estimated. The method used to make this estimation is dependent on the nature and extent of the resource being assessed. In a small woodland resource, this may be achieved through a 100% assessment (census) of the growing stock. It is usually considerably more efficient to estimate the volume of growing stock in a larger forest resource through some form of sampling. The method of sampling and number of samples is determined by the extent and variability of the area of interest. Figure 4.1 above illustrates the decision tree that should be used in order to determine the most appropriate method of achieving a tree volume estimate.

4.1. METHODS A-D: Plot-based assessments

4.1.1. Introduction

These methods are applicable for use in woodlands greater than 1.25 hectares in extent or where there are more than 3000 tree stems and involve setting up sample plots, counting and measuring all trees within the plots. Sample trees are allocated to one of three categories according the size criteria given in Table 4.1.1. Each category should be sampled separately according to the methods detailed in section 4.1.4 and subsequent calculations carried out as specified in section 4.1.5. The plot-based results are used to derive per hectare values for each tree category which are then scaled up to the net size of the stand.

Table 4.1.1: A definition of the size categories used in the plot-based assessment.

Size category	Definition
Seedling	A living stem less than 50 centimetres tall.
Sapling	A living stem greater than 50 centimetres tall and with a dbh less than 7 centimetres.
Tree	A living stem with a dbh greater than 7 centimetres.

There are four plot-based methods of carbon assessment for trees. Method A is the most accurate and can be used for all species, but requires the felling of a number of sample trees. Method B applies only to broadleaved tree species and all measurements are made on standing trees. Method C applies only to conifers and all measurements are again made on standing trees. Method D applies only to pure even-aged stands where conditions make tree height measurements difficult to take from most trees.

The following *aide memoir* may help you to remember which method to use:

- Method A – ***A***ccurate, but will only rarely be used in practice
- Method B – ***B***roadleaves will almost always be assessed this way
- Method C – ***C***onifers will usually be assessed using this method
- Method D – ***D***ense and ***D***ark stands may require this technique.

The sample plots do not need to be permanently marked, as the plot-based methods listed above, and fully described below, do not require that the same sample plots are enumerated on successive measurement occasions. It may however aid checking, in the event of seemingly erroneous data becoming apparent during the subsequent calculations, if plots are temporarily marked in order to assist relocation in the short-term.

4.1.2. Pre-field work

A plot size containing 7 to 20 trees should be chosen. Where the plant rows can still be clearly seen rectangular plots should be used, otherwise use circular plots. Table 4.1.2 for circular and square plots) and Table 4.1.3 (for rectangular plots) give possible plot dimensions. The chosen plot size and shape ***must*** be used for ***all*** plots in the stratum.

The net area of the stand must be measured carefully (*i.e.* the stocked area minus any unproductive land such as roads and rides). It is important that this is done with accuracy and that stand boundaries are checked on the ground as this can introduce a large source of error when scaling up the per hectare averages.

Table 4.1.2 Circular and square plot dimensions for specified plot areas

	Plot area (ha)							
	0.005	0.01	0.02	0.05	0.10	0.20	0.50	1.00
Circular plot radius (m)	4.0	5.6	8.0	12.6	17.8	25.2	39.9	56.4
Square plot side length (m)	7.1	10.0	14.1	22.4	31.6	44.7	70.7	100.0

Table 4.1.3 Rectangular plot dimensions for specified plot areas in stands where rows are clearly visible

Average spacing between rows (m)	Plot width (number of rows included) 3 rows		4 rows	6 rows	9 rows
	Distance in metres along the row to give a plot area of				
	0.005 ha	0.01 ha	0.02 ha	0.05 ha	0.10 ha
1.5	11.1 m	22.2 m	33.3 m	55.6 m	74.1 m
1.6	10.4 m	20.8 m	31.2 m	52.1 m	69.4 m
1.7	9.8 m	19.6 m	29.4 m	49.0 m	65.4 m
1.8	9.3 m	18.5 m	27.8 m	46.3 m	61.7 m
1.9	8.8 m	17.5 m	26.3 m	43.9 m	58.5 m
2.0	8.3 m	16.7 m	25.0 m	41.7 m	55.6 m
2.1	7.9 m	15.9 m	23.8 m	39.7 m	52.9 m
2.2	7.6 m	15.2 m	22.7 m	37.9 m	50.5 m
2.3	7.2 m	14.5 m	21.7 m	36.2 m	48.3 m
2.4	6.9 m	13.9 m	20.8 m	34.7 m	46.3 m
2.5	6.7 m	13.3 m	20.0 m	33.3 m	44.4 m
2.6	6.4 m	12.8 m	19.2 m	32.1 m	42.7 m
2.7	6.2 m	12.3 m	18.5 m	30.9 m	41.2 m
2.8	6.0 m	11.9 m	17.9 m	29.8 m	39.7 m
2.9	5.7 m	11.5 m	17.2 m	28.7 m	38.3 m

4.1.3. Equipment required

For fieldwork, you will require:

- sufficient blank data collection forms (see Appendix 7), possibly printed on weather-resistant paper
- a pencil or pen with waterproof ink
- a centimetre rule or carpenter's tape (suitable for measuring the heights of seedlings up to 50 cm tall, if present)
- a length tape (such as a 20 or 30 m logger's tape) suitable for laying out sample plots and measuring other horizontal distances
- a rounded-down diameter tape or tree callipers (for measuring tree diameters at breast height)
- an instrument (hypsometer or clinometer) suitable for measuring tree heights

4.1.4. Field work

An appropriate number of sample plots must be located at random throughout each stratum (the number of plots is determined by the size and variability of the stratum, refer to Table 4.1.4 for a guide). Rectangular plots should be of the same size and shape, two of the sides should be parallel to the planting rows and mid way between two adjacent rows. The centre points of circular plots should be located randomly. All plots must be at least 5m from the edge of the stand.

Where stands have been line thinned previously, and so there are gaps in the canopy which will not close before the next thinning, these should be treated as open land and should not be included in any plot. However, plot boundaries can be less than 5m away from the edge of thinned lines within a stand.

Table 4.1.4 The recommended number of sample plots

Area of stratum	Uniform stratum	Variable stratum
0.5 – 2.0 ha	6	8
2.0 – 10.0 ha	8	12
Over 10.0 ha	10	16

Seedlings

At each sampling point, count and record the number of living seedlings of each species within a 5.6 metre radius (0.01 hectare) sample plot. Using a ruler, estimate and record the height (in centimetres) of 20 seedlings of each species. Individuals making up this seedling height sample should be representative of the seedlings present and should be selected from positions distributed evenly within the regeneration in the plot. Where there are fewer than 20 seedlings present, all should be assessed for height.

In situations where there is a relatively dense carpet of regeneration (>5000 seedlings per hectare), the above method is likely to be unworkable due to the high number of seedlings that would be included in each plot. In such situations, reduce the plot radius to 4.0 metres (0.005 hectare) or 1.8 metres (0.001 hectare) such that there is likely to be a minimum of 20 seedlings per plot.

A pro-forma seedling data collection form is presented in Appendix 7.

N.B. The same plot size and shape must be maintained within a single stratum.

Saplings

At each sampling point, count and record the number of living saplings of each species within a 5.6 metre radius (0.01 hectare) sample plot. Measure and record the heights of the 3 saplings of each species closest to the centre of each plot. Where there are fewer than 3 saplings of a particular species, the heights of all should be measured.

Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative species present in the woodland.

A pro-forma sapling data collection form is presented in Appendix 7.

Trees

Please note: where sample plots are being used, Method B or Method C will normally be the most appropriate to use in the assessment of carbon projects. Method A should ***only*** be used in situations where accuracy is of paramount importance and where it is possible to fell volume sample trees without compromising the project. Method D should ***only*** be used when stand conditions make the accurate measurement of height sample trees extremely difficult to achieve.

Method A: Fell sample trees

This is the most accurate method, but is expensive and only possible if trained tree fellers are available. A pro-forma data collection sheet is presented in Appendix 7.

1. Within each plot, measure and record by species the dbh of every living tree where this is 7 centimetres or greater.
2. Identify the two trees of each species nearest to the plot centre; these will be your height sample trees. Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative present in the woodland (see Appendix 3).
3. The sample trees should be felled and their dbh, total length (conifers only), timber length (broadleaves only) and mid-diameter recorded.

Method B: (Broadleaves only) Measure the timber height of sample trees

This is the default method for assessing strata containing broadleaved trees. A pro-forma data collection sheet is presented in Appendix 7.

1. Within each plot, measure and record by species the dbh of every living tree where this is 7 centimetres or greater.
2. Identify the two trees of each species nearest to the plot centre; these will be your height sample trees. Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative present in the woodland (see Appendix 3).
3. Measure and record dbh and timber height of the two height sample trees of each species.

Method C: (Conifers only) Measure the total height of sample trees

This is the default method for assessing strata containing conifers. A pro-forma data collection sheet is presented in Appendix 7.

1. Within each plot, measure and record by species the dbh of every living tree where this is 7 centimetres or greater.
2. Identify the two trees of each species nearest to the plot centre; these will be your height sample trees. Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative present in the woodland (see Appendix 3).
3. Measure and record the dbh and total height of the two height sample trees of each species.

Method D: Measure top height

This method applies only to even-aged strata, and particularly those that may be very dense, where it is difficult to ascertain the height of most trees. Where a species constitutes less than 10% of the total tree numbers in a mixed-species stand, this should be treated as a "minor species" and grouped with the most similar alternative present in the woodland (see Appendix 3). You should use a separate data collection form for each species (blank forms are presented in Appendix 7, starting on page 155).

1. Within each plot, measure and record by species the dbh of every living tree where this is 7 centimetres or greater.
2. Identify the tree of largest diameter within 5.6 metres of the plot centre (*i.e.* within a 0.01 ha area); this will be your top height sample tree. If two species are present, the top height sample trees will be the tree of largest diameter of each species within 8.0 metres of the plot centre (*i.e.* within a 0.02 ha area). If more than two major species are present, the radius of the circle should be proportionately increased as indicated in Table 4.1.5. If no measurable trees of any component of the mixture is present in the appropriately-sized plot, this fact should be recorded on the appropriate data collection form.
3. Measure and record the total height of each of the top height sample trees identified in the previous step.

Table 4.1.5 The distance from plot centre within which to select the largest diameter (top-height sample) trees in mixed-species strata.

Number of species present	Distance from plot centre (m)	Equivalent plot area (ha)
1	5.6	0.01
2	8.0	0.02
3	9.8	0.03
4	11.3	0.04
5	12.6	0.05
6	13.8	0.06

4.1.5. Office work

Seedlings

No office work is required at this stage.

Saplings

Calculate the arithmetic mean height of the saplings of each species. The results will serve as estimates of the height of the representative sapling of each species.

Trees

Elements of the office work are common to all the plot-based methods described above. The key exception is the estimation of relevant tariff numbers, the method of which will vary according to which plot-based method has been used. All equations used in this section have been taken from Appendix 8 of Matthews and Mackie (2006).

1. Separately by species, estimate the total number of trees in the stratum.
    a. Count the number of trees in each plot and add these together to give the total number of trees in all of the plots.
    b. Add the areas of all the plots to give the total area of all plots.
    c. Divide the total number of trees in all plots by the total area of all plots. The resultant figure is the average number of trees per hectare.
    d. Multiply the average number of trees per hectare by the *net area* (in hectares) of the stratum to give an estimate the total number of trees present.

2. In order to calculate the mean volume per tree, and for subsequent biomass allocation, the quadratic mean dbh must be estimated.
    a. From the trees measured, count the number falling into each rounded-down centimetre dbh class[3].
    b. Multiply the number of trees in each class by the square of the dbh. For example, if there were 5 trees in the 10cm dbh class, the calculation would be $5 \times 10^2 = 500$
    c. Sum the results and divide the total by the number of trees measured.
    d. Take the square root of the answer from the previous step. This is the quadratic mean dbh (the dbh of the tree of mean basal area)[4]. Round this number to the nearest 0.1 centimetres.

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3 All trees with dbh between 10.0 and 10.9 cm tree will fall into the 10 cm dbh class.

4 This calculation is outlined in section A1.2.2 on page 70 of Appendix 1 and illustrated in Figure A5.3 on page 100.

3. Find the appropriate tariff number. The exact mechanism of doing this will depend on which one of Methods A-D was used.

Method A: Using felled sample trees.

a. Calculate the volume of each sample tree using the mid-diameter method[5], that is:
   i. Measure the length of each sample tree in metres. If this is more than 15 m, it is recommended that the sample tree is measured in two sections. This *must* be done if the length is greater than 20 m. For lengths up to 10 m, measured lengths are rounded down to the nearest 0.1 m. For lengths up to 20 m, measured lengths are rounded down to the nearest whole metre.
   ii. Measure the diameter of the mid point of each sample tree (or section) in cm. The mid point of the sample tree (or each section) must be found by measuring half the rounded down length from the *butt end* of the log (or section). The measured mid diameter is rounded down to the nearest whole cm.
   iii. The volume is calculated by using the mid diameter volume tables given in Mackie and Matthews (2008) or Matthews and Mackie (2006), or by using the following equation:

$$\text{Volume in m}^3 = \left(\frac{\pi \times d^2}{40000}\right) \times L$$

Where d = mid diameter in cm
L = length in m.

[5] Further information on the mid diameter method of measurement is given in Matthews and Mackie (2006), Section 5.1, pages 112-113.

b. Use the sample tree's basal area and volume in **Equation 1** (below) to calculate the tariff number[6]. Round this to the nearest whole number.

Equation 1 – Calculation of tariff number from volume and basal area

$$T = (3.174106384 \times a_1) + 0.138763302$$

Where

T = tree tariff number

v = tree volume (m^3)

ba = tree basal area (m^2), calculated as $\frac{\pi \times dbh^2}{40000}$

a_1 = $\frac{(v - 0.005002986)}{(ba - 0.003848451)}$

c. Find the average tariff number of all the sample trees. If this is not a whole number it should be rounded down.

6 Alternatively, use Table 46 from Matthews and Mackie (2006).

Method B: Broadleaves only.

a. Use dbh, timber height and Equation 2 (below) to calculate the tariff number[7] of each sample tree. Round this to the nearest whole number.
b. Find the average tariff number of all the sample trees. If this is not a whole number it should be rounded down to the next whole tariff number.

Equation 2 – Estimation of a single tree tariff number (broadleaves)

$$T = a_1 + (a_2 \times h) + (a_3 \times dbh) + (a_4 \times dbh \times h)$$

Where
- T = tree tariff number
- h = tree timber height (m)
- dbh = tree diameter at breast height (cm)
- a_1, a_2, a_3, and a_4 = species-specific constants (see Table 4.1.6).

Table 4.1.6 Species-specific estimates of a_1 – a_4 for Equation 2 (above).

Tree Species	a_1	a_2	a_3	a_4
oak	5.88300	2.01230	-0.0054780	-0.0057397
beech	7.48490	1.92620	-0.0037881	-0.0082745
sycamore	9.76130	1.58670	-0.0569660	-0.0033867
ash	9.16050	2.02560	-0.0668420	-0.0044172
birch	5.62370	2.23800	0.0871700	-0.0332620
elm	6.28870	1.69950	0.0285120	-0.0069294
poplar	10.90625	1.05327	0.0	0.0

[7] Alternatively, use Single Tree Tariff Charts 13-19 from Matthews and Mackie (2006).

Method C: Conifers only.

a. Use dbh, total height and Equation 3 (below) to calculate the tariff number[8] of each sample tree. Round this to the nearest whole number.
b. Find the average tariff number of all the sample trees. If this is not a whole number it should be rounded down.

Equation 3 – Estimation of a single tree tariff number (conifers)

$$T = a_1 + (a_2 \times h) + (a_3 \times dbh)$$

Where T = tree tariff number
h = tree total height (m)
dbh = tree diameter at breast height (cm)
a_1, a_2, and a_3 = species-specific constants (see Table 4.1.7).

Table 4.1.7 Species-specific estimates of a_1 – a_3 for Equation 3 (above).

Tree Species	a_1	a_2	a_3
Scots pine	9.817387	1.177486	-0.114174
Corsican pine	5.070842	1.754053	-0.193834
lodgepole pine	8.855292	1.951643	-0.689619
Sitka spruce	8.292030	1.771173	-0.416509
Norway spruce	9.939311	1.985697	-0.650625
European larch	5.562167	1.908473	-0.426567
Japanese larch	8.478127	1.788768	-0.449816
Douglas fir	10.397480	1.477313	-0.325653
western hemlock	8.762511	1.959230	-0.586275
western red cedar	10.637312	1.735383	-0.630551
grand fir	6.565630	2.043490	-0.591550
noble fir	7.028548	1.930016	-0.373808

8 Alternatively, use Single Tree Tariff Charts 1-12 from Matthews and Mackie (2006).

Method D: Using top height.

a. Separately by species, calculate the average total height of the sampled trees from all plots; this is the estimated top height for the stratum.
b. Use the estimated stand top height with Equation 4 (below) to derive a stand tariff number[9] for each species present.

Equation 4 – Estimation of stand tariff number:

$$T = a_1 + (a_2 \times h) + (a_3 \times h^2)$$

Where T = stand tariff number
h = stand top height (m)
a_1, a_1, and a_3 = species-specific constants (see Table 4.1.8).

Table 4.1.8 Species-specific estimates of $a_1 - a_3$ for Equation 4 (above).

Tree species	a_1	a_2	a_3
Scots pine	8.630479	1.026729	0.0
Corsican pine	4.447056	1.393702	0.0
lodgepole pine	3.777514	1.410159	0.0
Sitka spruce	6.217023	1.207543	0.0
Norway spruce	7.083164	1.159687	0.0
European larch	2.950717	1.390514	0.0
Japanese/hybrid larch	4.602287	1.36538	0.0
Douglas fir	6.037857	1.129738	0.0
western hemlock	6.938617	1.228069	0.0
western red cedar	5.048266	1.069130	0.0
grand fir	3.322768	1.371692	0.0
noble fir	3.674419	1.347000	0.0
oak	7.060415	1.219095	-0.009778
birch	5.114527	1.137217	-0.008290

9 Alternatively, use Table 5 from Matthews and Mackie (2006).

4. Irrespective of which of plot sampling methods A-D was applied, use Tariff number and tree basal area with Equation 5 (below) to estimate the mean merchantable tree volume[10].

Equation 5 – Calculation of volume from basal area and tariff number

$$v = a_1 + (a_2 \times ba)$$

where v = tree volume (m^3)

ba = mean tree basal area (m^2), calculated as $\frac{\pi \times (\text{quadratic mean dbh})^2}{40000}$

a_1 = (0.0360541 × T) - (a2 × 0.118288)

a_2 = 0.315049301 × (T - 0.138763302)

T = tree or stand tariff number.

5. Calculate the mean total stem volume by multiplying the mean merchantable tree volume (obtained above) by the appropriate value in Table 4.1.9.

Table 4.1.9 Factors for converting mean merchantable volume to mean total stem volume.

Mean dbh (cm)	Multiplication factor	Mean dbh (cm)	Multiplication factor
7	1.30	21	1.02
8	1.19	22	1.01
9	1.15	23	1.01
10	1.12	24	1.01
11	1.09	25	1.01
12	1.07	26	1.01
13	1.06	27	1.01
14	1.05	28	1.01
15	1.04	29	1.01
16	1.03	30	1.01
17	1.03	31	1.01
18	1.02	32	1.01
19	1.02	33+	1.00
20	1.02		

[10] Alternatively, use Table 46 from Matthews and Mackie (2006).

6. To find the total estimated stem volume in the stratum, multiply the unrounded estimated mean volume by the estimated total number of trees in the same stratum.
7. The total volume and quadratic mean diameter for each species in the stratum should be carried forward in order to estimate the biomass allocation for those trees (Section 5.2 on page 49).

4.1.6. Example Calculations

Example calculations are presented for some illustrative cases:

- For a uniform coniferous woodland (see Appendix 4, page 79),
- For a small-scale broadleaved woodland (see Appendix 5, page 91), and
- For a large-scale project (see Appendix 6, page 101).

4.2. METHOD E: Full tree count and dbh assessment

4.2.1. Introduction

This method is applicable for use in woodlands up to 1.25 hectares in extent or where there are up to 3000 tree stems. Tree species will be allocated to one of three categories according the size criteria given in Table 4.2.1. Each category should be sampled separately according to the methods detailed in sections 4.2.2 and 4.2.3 (below).

Table 4.2.1: A definition of the size categories used in the plot-based assessment.

Size category	Definition
Seedling	A living stem less than 50 centimetres tall.
Sapling	A living stem greater than 50 centimetres tall and with a dbh less than 7 centimetres.
Tree	A living stem with a dbh greater than 7 centimetres.

An example calculation for a small mixed broadleaved woodland is given in Appendix 5.

4.2.2. Field work

Seedlings

At 10 systematically located points[11] within each stratum, count and record the number of living seedlings of each species within a 5.6 metre radius (0.01 hectare) sample plot.

In situations where there is a relatively dense carpet of regeneration (>5000 seedlings per hectare), the above method is likely to be unworkable due to the high number of seedlings that would be included in each plot. In such situations, reduce the plot radius to 4.0 metres (0.005 hectare) or 1.8 metres (0.001 hectare) such that there is likely to be a minimum of 20 seedlings per plot.

N.B. The same plot size must be maintained within a single stratum.

[11] A common way of doing this would be to locate the sample points at the intersections of a rectangular grid of appropriate dimensions to cover the whole stratum and yield the required number of sample points.

Saplings

Count and record the number of living saplings of each species within each stratum. Measure and record the heights and species of every n^{th} sapling, according to the height sampling fraction specified in Table 4.2.2 below. For example: if you estimate that there are approximately 55 saplings of a particular species within the stratum, you should measure and record the height of every 5^{th} sapling of that species counted.

Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative species present in the woodland.

Trees

Visit each tree stem in turn. Measure and record by species the dbh of every living tree where this is 7 centimetres or greater.

For broadleaves only

Measure and record the ***timber height***[12], the ***total height***[13] and dbh of the n^{th} broadleaved tree of each species according to the height sampling fraction specified in Table 4.2.2 below.

For conifers only

Measure and record the ***total height***[12] and dbh of the n^{th} broadleaved tree of each species according to the height sampling fraction specified in Table 4.2.2 below.

Where a species constitutes less than 10% of the total tree numbers, this should be treated as a "minor species" and grouped with the most similar alternative present in the woodland.

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[12] Required for the calculation of Tariff number.

[13] Required for the calculation of crown biomass in a number of broadleaved species.

Table 4.2.2: Sampling fractions.

Estimated number of individuals	dbh sampling fraction	Height sampling fraction
10-20	1:1	1:1
21-30	1:1	1:2
31-40	1:1	1:3
41-50	1:1	1:4
51-60	1:1	1:5
61-70	1:1	1:6
71-80	1:1	1:7
81-90	1:1	1:8
91-100	1:1	1:9
101-200	1:1	1:10
201-400	1:2	1:10
401-600	1:4	1:10
601-800	1:6	1:10
801-1000	1:8	1:10
1001-1200	1:10	1:10
1201-1500	1:12	1:10
1501-2000	1:15	1:10
2001-2500	1:20	1:10
2501-3000	1:25	1:10
>3000	1:30	1:10

4.2.3. Office work

Seedlings

a. Separately by species, calculate the average height of the seedlings. This will be known as the height of the representative seedling of that species.
b. Separately by species, estimate the total number of seedlings per hectare by adding together the total number of seedlings sampled and dividing by the total area of all the sample plots used.
c. Multiply the per hectare value by the net area of the stratum to give the total number of seedlings of each species in the stratum

Saplings

a. Separately by species, calculate the average height of the saplings. This will be known as the height of the representative sapling of that species.
b. Separately by species, estimate the total number of saplings per hectare by adding together the total number of saplings sampled and dividing by the total area of all the sample plots used.
c. Multiply the per hectare value by the net area of the stratum to give the total number of saplings of each species in the stratum

Trees

For each species:

a. Use dbh, timber height and Equation 2 (for broadleaves, presented below) or total height and Equation 3 (for conifers, presented below) to calculate the tariff number[14] of each sample tree. Round this to the nearest whole number.
b. Find the average tariff number of all the sample trees. If this is not a whole number it should be rounded down to the next whole tariff number.

Equation 2 – Estimation of a single tree tariff number (broadleaves)

$$T = a_1 + (a_2 \times h) + (a_3 \times dbh) + (a_4 \times dbh \times h)$$

Where
T = tree tariff number
h = tree timber height (m)
dbh = tree diameter at breast height (cm)
a_1, a_2, a_3, and a_4 = species-specific constants (see Table 4.2.3).

Table 4.2.3 Species-specific estimates of $a_1 - a_4$ for **Equation 2** (above).

Tree Species	a_1	a_2	a_3	a_4
oak	5.88300	2.01230	-0.0054780	-0.0057397
beech	7.48490	1.92620	-0.0037881	-0.0082745
sycamore	9.76130	1.58670	-0.0569660	-0.0033867
ash	9.16050	2.02560	-0.0668420	-0.0044172
birch	5.62370	2.23800	0.0871700	-0.0332620
elm	6.28870	1.69950	0.0285120	-0.0069294
poplar	10.90625	1.05327	0.0	0.0

14 Alternatively, use Single Tree Tariff Charts 13-19 from Matthews and Mackie (2006).

Equation 3 – Estimation of a single tree tariff number (conifers)

$$T = a_1 + (a_2 \times h) + (a_3 \times dbh)$$

Where T = tree tariff number
h = tree total height (m)
dbh = tree diameter at breast height (cm)
a_1, a_2, and a_3 = species-specific constants (see Table 4.2.4).

Table 4.2.4 Species-specific estimates of $a_1 - a_3$ for Equation 3 (above).

Tree Species	a_1	a_2	a_3
Scots pine	9.817387	1.177486	-0.114174
Corsican pine	5.070842	1.754053	-0.193834
lodgepole pine	8.855292	1.951643	-0.689619
Sitka spruce	8.292030	1.771173	-0.416509
Norway spruce	9.939311	1.985697	-0.650625
European larch	5.562167	1.908473	-0.426567
Japanese larch	8.478127	1.788768	-0.449816
Douglas fir	10.397480	1.477313	-0.325653
western hemlock	8.762511	1.959230	-0.586275
western red cedar	10.637312	1.735383	-0.630551
grand fir	6.565630	2.043490	-0.591550
noble fir	7.028548	1.930016	-0.373808

c. In order to calculate the mean volume per tree, and for subsequent biomass allocation, the quadratic mean dbh must be estimated as follows[15]:
   i. For the trees of each species measured, count the number falling into each rounded-down centimetre dbh class[16].
   ii. Multiply the number of trees in each class by the square of the dbh. For example, if there were 5 trees in the 10cm dbh class, the calculation would be 5 x 10^2 = 500
   iii. Sum the results and divide the total by the number of trees measured.

[15] This calculation is also outlined in section A1.2.2 on page 70 of Appendix 1 and illustrated in Figure A5.3 on page 100.

[16] All trees with dbh between 10.0 and 10.9 cm tree will fall into the 10 cm dbh class.

iv. Take the square root of the answer from the previous step. This is the quadratic mean dbh (the dbh of the tree of mean basal area). Round this number to the nearest 0.1 centimetres.

d. Use Tariff number and mean tree basal area with Equation 5 (presented below) to estimate the mean merchantable tree volume[17] for each tree species.

Equation 5 – Calculation of volume from basal area and tariff number

$$v = a_1 + (a_2 \times ba)$$

where v = tree volume (m^3)

ba = mean tree basal area (m^2), calculated as $\frac{\pi \times (\text{quadratic mean dbh})^2}{40000}$

a_1 = (0.0360541 × T) - (a2 × 0.118288)

a_2 = 0.315049301 × (T - 0.138763302)

T = tree or stand tariff number.

e. Calculate the mean total stem volume by multiplying the mean merchantable tree volume (obtained above) by the appropriate value in Table 4.2.5.

f. To find the total estimated stem volume in the stratum, multiply the unrounded estimated mean volume by the estimated total number of trees in the same stratum.

g. The total volume and quadratic mean diameter for each species in the stratum should be carried forward in order to estimate the biomass allocation for those trees (Section 5.2 on page 49).

17 Alternatively, use Table 46 from Matthews and Mackie (2006).

Table 4.2.5 Factors for converting mean merchantable volume to mean total stem volume.

Mean dbh (cm)	Multiplication factor
7	1.30
8	1.19
9	1.15
10	1.12
11	1.09
12	1.07
13	1.06
14	1.05
15	1.04
16	1.03
17	1.03
18	1.02
19	1.02
20	1.02

Mean dbh (cm)	Multiplication factor
21	1.02
22	1.01
23	1.01
24	1.01
25	1.01
26	1.01
27	1.01
28	1.01
29	1.01
30	1.01
31	1.01
32	1.01
33+	1.00

5. Biomass allocation

5.1. Introduction

For the purposes of the Forestry Commission's Carbon Assessment Protocol, an estimate of the total biomass contained within a tree is derived by summing estimates of biomass contained in the crown (including branches, twigs, leaves and any part of the main tree stem less than 7 cm diameter over bark), with the biomass estimates for the stem and roots.

The crown and root biomass equations stated in the original (2012) version of the Carbon Assessment Protocol overestimated the biomass content of larger trees. A new set of biomass equations has therefore been prepared for estimating the crown and root biomass, in oven-dry tonnes, of tree species grown in Great Britain.

The data available for calibrating biomass equations for use in Great Britain are generally limited, variable, and do not cover all species commonly grown as forest trees. In order to satisfactorily calibrate the biomass equations, it was therefore necessary to pool data. This approach has resulted in different species groupings for both crown and root biomass (see Table 5.2.2 and Table 5.2.3 for the eight species groups adopted for crown biomass, and Table 5.2.4 and Table 5.2.5 for the six species groups employed for root biomass).

Species for which no suitable calibration data exist are mapped to the relevant crown or biomass species grouping, based on perceived similarities in silvicultural and morphological characteristics of trees in the species groups which emerged during the development of the crown and root biomass equations. The resultant species mappings are presented in Table 5.2.6 (for broadleaves) and Table 5.2.7 (for conifers).

In this version of the Carbon Assessment Protocol, no separate biomass estimation is required for tree seedlings or saplings; the carbon content of these is estimated directly using the methods outlined in Sections 6.1 and 6.2.

5.2. Trees

The total biomass of the tree will fall into one of the following four categories:

- Roots: Consisting of below ground biomass and stump.
- Stem: The main trunk of the tree.
- Branches: Any woody material distal to the main stem including larger branches and twigs.
- Foliage: Leaves or needles.

For the purposes of this protocol, branches and foliage biomass will be estimated together (as "crown" biomass).

In order to estimate the total biomass for each tree species, you will:

1. estimate the biomass content of the entire tree stem of the average tree in the stratum by multiplying mean total tree volume (estimated in step 5 of Section 4.1.5, or in Section 4.2.3) by the requisite nominal specific gravity (from Table 5.2.1 in Section 5.2.1);
2. estimate the crown biomass of the average tree in the stratum (Section 5.2.2) using the quadratic mean dbh[18];
3. estimate the root biomass of the average tree in the stratum (Section 5.2.3) using the quadratic mean dbh[18];
4. estimate the total biomass for the average tree in the stratum by summing the stem, crown and root biomass components calculated in steps 1-3;
5. multiply the average tree value from step 4 by the estimated total number of trees in the stratum in order to derive the total biomass in the stratum.

5.2.1. Stem biomass

Multiply the mean total tree volume (estimated in step 5 of Section 4.1.5 or Section 4.2.3) by the nominal specific gravity indicated in Table 5.2.1 (below) to give the biomass of the average tree stem of each species, in oven dry tonnes.

[18] The calculation of quadratic mean dbh is outlined in section A1.2.2 on page 70 of Appendix 1 and illustrated in Figure A5.3 on page 100.

Table 5.2.1 The nominal specific gravity (NSG) of timber from various tree species grown in the UK (NSG values from Lavers and Moore, 1983).

Species	Allocated Species	Nominal Specific Gravity (NSG)
Scots pine (SP)	XP,	0.42
Corsican pine (CP)	AUP, BIP, RAP, PDP	0.40
lodgepole pine (LP)	MOP, MCP	0.39
maritime pine (MAP)		0.41
Weymouth pine (WEP)		0.29
Sitka spruce (SS)		0.33
Norway spruce (NS)	XS, XC, MC	0.33
Omorika spruce (OMS)		0.33
European larch (EL)		0.45
Japanese larch (JL)		0.41
hybrid larch (HL)		0.38
Douglas fir (DF)		0.41
western hemlock (WH)		0.36
western red cedar (RC)	JCR	0.31
Lawson cypress (LC)		0.33
Leyland cypress (LEC)		0.38
grand fir (GF)	RSQ, WSQ	0.30
noble fir (NF)	XF	0.31
silver fir (ESF)		0.38
oak (OK)	POK, SOK	0.56
red oak (ROK)		0.57
beech (BE)		0.55
sycamore (SY)	NOM, RON, MB, XB	0.49
ash (AH)		0.53
birch (BI)		0.53
poplar (PO)		0.35
sweet chestnut (SC)		0.44
horse chestnut (HCH)		0.44
alder (AR)	CAR, GAR, RAR, SAR, VAR	0.42
lime (LI)	CLI, SLI, LLI	0.44
elm (EM)	EEM, SEM	0.43
wych elm		0.50
wild cherry, gean (WCH)	BCH	0.50
hornbeam (HBM)		0.57
raoul		0.37

For tree species not explicitly listed by name in Table 5.2.1 (above), refer to the "allocated species" column. (Standard species abbreviations are listed in Appendix 2 on page 75.)

5.2.2. Crown biomass (composed of branches, stem tips and foliage)

In order to minimise the risk of overestimating the biomass content of larger trees, two forms of crown biomass equation have been developed by the Forestry Commission (Randle *et al*., 2014) – one for use for trees with dbh between 7 and 50 centimetres (Equation 6), the second for use for trees with dbh greater than 50 centimetres (Equation 7). When used in the Carbon Assessment Protocol, the quadratic mean dbh[19] for each species should be used to represent the "average" tree of that species in the stratum being assessed.

Equation 6 – Estimation of crown biomass for trees between 7 cm and 50 cm dbh.

$$\text{Crown biomass}_{(7\text{ cm} \leq \text{dbh} \leq 50\text{ cm})} = b \times \text{dbh}^{p}$$

where Crown biomass is expressed as oven-dry tonnes
b and *p* = species-specific parameters (see Table 5.2.2)
dbh = diameter at breast height (1.3 m) between 7 cm and 50 cm

The values for the species-specific parameters for use in Equation 6 are presented in Table 5.2.2.

If the tree species of interest is not explicitly listed in Table 5.2.2, the appropriate species mapping for use with Equation 6 can be found in Table 5.2.6 (for broadleaves) and Table 5.2.7 (for conifers).

Table 5.2.2: Species/group-specific coefficients for Equation 6, the crown biomass equation for trees between 7 cm and 50 cm dbh.

Species/species group	*B*	*p*
Larches	0.0000438717	2.0291
Corsican pine	0.0000122645	2.4767
lodgepole pine	0.0000176287	2.4767
Scots pine	0.0000161411	2.4767
firs, spruces, cedars and hemlocks	0.0000144620	2.4767

[19] The calculation of quadratic mean dbh is outlined in section A1.2.2 on page 70 of Appendix 1 and illustrated in Figure A5.3 on page 100.

Douglas fir	0.0000168602	2.4767
Beech	0.0000188154	2.4767
Oak	0.0000168513	2.4767

Equation 7 – Estimation of crown biomass for trees greater than 50 cm dbh.

$$\textbf{Crown biomass}_{(dbh > 50\ cm)} = a + b \times \text{dbh}$$

where Crown biomass is expressed as oven-dry tonnes
a and *b* = species-specific parameters (see Table 5.2.3)
dbh = diameter at breast height (1.3 m) greater than 50 cm

The values for the species-specific parameters for use in Equation 7 are presented in Table 5.2.3.

If the tree species of interest is not explicitly listed in Table 5.2.3, the appropriate species mapping for use with Equation 7 can be found in Table 5.2.6 (for broadleaves) and Table 5.2.7 (for conifers).

Table 5.2.3: Species/group-specific coefficients for Equation 7, the crown biomass equation for trees greater than 50 cm dbh.

Species/species group	***A***	***b***
Larches	-0.129046967	0.005039011
Corsican pine	-0.299529453	0.009948982
lodgepole pine	-0.430536496	0.014300429
Scots pine	-0.394205622	0.013093685
firs, spruces, cedars and hemlocks	-0.353197843	0.011731597
Douglas fir	-0.411767824	0.013677021
Beech	-0.459518648	0.015263082
Oak	-0.411550464	0.013669801

5.2.3. Root biomass

Two equations have been developed for estimating the biomass contained in tree roots as a function of diameter at breast height. Equation 8 should be used for estimating the root biomass for trees up to and including 30 cm dbh. Equation 9 should be used for estimating the root biomass for trees exceeding 30 cm dbh. The quadratic mean dbh for each species should be used to represent the "average" tree of that species in the stratum being assessed.

Equation 8 – Estimation of root biomass for trees up to and including 30 cm dbh.

$$\textbf{Root biomass}_{(dbh \leq 30\ cm)} = b \times dbh^{2.5}$$

where Root biomass is expressed as oven-dry tonnes
b = species-specific parameters (see Table 5.2.4)
dbh = diameter at breast height (1.3 m) up to and including 30 cm

The values for the species-specific parameters for use in Equation 8 are presented in Table 5.2.4.

If the tree species of interest is not explicitly listed in Table 5.2.4, the appropriate species mapping for use with Equation 8 can be found in Table 5.2.6 (for broadleaves) and Table 5.2.7 (for conifers).

Table 5.2.4: Species/group-specific coefficients for Equation 8, the root biomass equation for trees up to and including 30 cm dbh.

Species/species group	*b*
western red cedar, noble fir, Corsican pine	0.000010722
Norway spruce	0.000011883
grand fir, Scots pine, western hemlock	0.000015404
Douglas fir, Japanese larch, lodgepole pine	0.000017326
Sitka spruce	0.000020454
red alder	0.000022700

Equation 9 – Estimation of root biomass for trees greater than 30 cm dbh.

$$\textbf{Root biomass}_{(dbh > 30\ cm)} = a + b \times \text{dbh}$$

where Root biomass is expressed as oven-dry tonnes
a and *b* = species-specific parameters (see Table 5.2.5)
dbh = diameter at breast height (1.3 m) greater than 30 cm

The values for the species-specific parameters for use in Equation 9 are presented in Table 5.2.5.

If the tree species of interest is not explicitly listed in Table 5.2.5, the appropriate species mapping for use with Equation 9 can be found in Table 5.2.6 (for broadleaves) and Table 5.2.7 (for conifers).

Table 5.2.5: Species/group-specific coefficients for Equation 9, the root biomass equation for trees greater than 30 cm dbh.

Species/species group	*A*	*b*
western red cedar, noble fir, Corsican pine	-0.082602857	0.004515233
Norway spruce	-0.091547262	0.005004152
grand fir, Scots pine, western hemlock	-0.118673233	0.006486910
Douglas fir, Japanese larch, lodgepole pine	-0.133480423	0.007296300
Sitka spruce	-0.157578701	0.008613559
red alder	-0.174882004	0.009559391

5.2.4. Total tree biomass

1. For each species in each stratum, add together the stem biomass, crown biomass and root biomass (see Sections 5.2.1, 5.2.2 and 5.2.3). This gives the estimated total biomass for the "average" tree of that species in the stratum.
2. For each tree species, multiply the above figure by the total number of trees of that species in the stratum. This gives the estimated total living biomass for that species in the stratum.
3. Repeat the above calculations for all species and all strata.
4. For each stratum, sum the total living biomass of each species to give the total biomass of each stratum.

5. Add together the total living biomass of each stratum to give the total biomass of the project.

N.B. Per hectare values may be obtained at steps 2, 5 and 5 by dividing by the appropriate net area.

Table 5.2.6: Species mappings for broadleaves.

Species name[1]	Mapping for Crown Biomass Functions	Mapping for Root Biomass Functions
alder	oak	red alder
apple, crab	oak	red alder
ash	oak	red alder
aspen	oak	red alder
beech	beech	red alder
birch	oak	red alder
blackthorn	oak	red alder
box	beech	red alder
broadleaves, other	oak	red alder
cherry	oak	red alder
chestnut, horse	oak	red alder
chestnut, sweet	beech	red alder
cottonwood, eastern	oak	red alder
elm	oak	red alder
eucalyptus	oak	red alder
hawthorn	oak	red alder
hazel	oak	red alder
hickory, shagbark	oak	red alder
holly	beech	red alder
hornbeam	beech	red alder
lime	oak	red alder
maple	beech	red alder
southern beech	beech	red alder
oak	oak	red alder
plane	beech	red alder
poplar	oak	red alder
rowan	oak	red alder
service tree	oak	red alder
sycamore	beech	red alder
tulip tree	beech	red alder
walnut	oak	red alder
whitebeam	oak	red alder
willow	oak	red alder

Note to Table 5.2.6:
[1] If the tree species of interest is not listed, use the coefficients for oak to represent the crown biomass (Section 5.2.2) of the "average" broadleaved species and the coefficients for red alder for root biomass (Section 5.2.3).

Table 5.2.7: Species mappings for conifers.

Species name[1]	Mapping for Crown Biomass Functions	Mapping for Root Biomass Functions
cedars (*Cedrus* spp.)	Scots pine	grand fir, Scots pine, western hemlock
cedar, Japanese	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
cedar, western red	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
conifers, other	firs, spruces, cedars and hemlocks	Norway spruce
cypress	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
Douglas fir	Douglas fir	Douglas fir, Japanese larch, lodgepole pine
fir, Bornmuller's	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
fir, grand	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
fir, Greek	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
fir, Nordmann/Caucasian	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
fir, red (pacific silver)	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
fir, Siberian	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
fir, silver	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
fir,noble	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
firs, other (*Abies* spp.)	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
hemlock, western	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
juniper	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine
larches	Larches	Douglas fir, Japanese larch, lodgepole pine
pine, Armand's	Scots pine	grand fir, Scots pine, western hemlock
pine, Austrian	Corsican pine	western red cedar, noble fir, Corsican pine
pine, Bhutan	Corsican pine	western red cedar, noble fir, Corsican pine
pine, Bishop	Corsican pine	western red cedar, noble fir, Corsican pine

Table 5.2.7 is continued on the next page.

Table 5.2.7 (continued): Species mappings for conifers.

Species name[1]	Mapping for Crown Biomass Functions	Mapping for Root Biomass Functions
pine, Calabrian	lodgepole pine	Douglas fir, Japanese larch, lodgepole pine
pine, Corsican	Corsican pine	western red cedar, noble fir, Corsican pine
pine, Korean	Scots pine	grand fir, Scots pine, western hemlock
pine, loblolly	Corsican pine	western red cedar, noble fir, Corsican pine
pine, lodgepole	lodgepole pine	Douglas fir, Japanese larch, lodgepole pine
pine, Macedonian	Corsican pine	western red cedar, noble fir, Corsican pine
pine, maritime	lodgepole pine	Douglas fir, Japanese larch, lodgepole pine
pine, Mexican white	Scots pine	grand fir, Scots pine, western hemlock
pine, Monterey/Radiata	Corsican pine	western red cedar, noble fir, Corsican pine
pine, mountain	lodgepole pine	Douglas fir, Japanese larch, lodgepole pine
pine, ponderosa	Corsican pine	western red cedar, noble fir, Corsican pine
pine, Scots	Scots pine	grand fir, Scots pine, western hemlock
pine, slash	lodgepole pine	Douglas fir, Japanese larch, lodgepole pine
pine, Weymouth	Corsican pine	western red cedar, noble fir, Corsican pine
pine, Yunnan	Scots pine	grand fir, Scots pine, western hemlock
pine. western white	Corsican pine	western red cedar, noble fir, Corsican pine
pines, other	Scots pine	grand fir, Scots pine, western hemlock
redwood, coast	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
redwood, dawn	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
spruce, Sitka	firs, spruces, cedars and hemlocks	Sitka spruce
spruces, other	firs, spruces, cedars and hemlocks	Norway spruce
Wellingtonia	firs, spruces, cedars and hemlocks	grand fir, Scots pine, western hemlock
yew	firs, spruces, cedars and hemlocks	western red cedar, noble fir, Corsican pine

Note to Table 5.2.7:

[1] If the tree species of interest is not listed, use the coefficients for "firs, spruces, cedars and hemlocks" to represent the crown biomass (Section 5.2.2) of the "average" conifer species and the coefficients for Norway spruce for root biomass (Section 5.2.3)

6. Carbon conversion

This section describes how to derive the estimated carbon content for the seedlings, saplings and trees within the project. It is important to ensure that all carbon values are ultimately expressed as tonnes of carbon dioxide equivalent (tCO_2e). To convert from tonnes of carbon (tC) to tCO_2e, the tC values should be multiplied by 44/12 (*i.e.* 1 tC = 3.67 tCO_2e).

6.1. Seedlings

1. For each species, use the height of the representative seedling (cm) to derive the mean carbon content per seedling (*i.e.* above and below ground) from Table 6.1.1 (for broadleaved species) or Table 6.1.2 (for coniferous species).
2. Multiply the above value by the total number of seedlings in the stratum. This gives an estimate of the total carbon (tonnes C/species) in the stratum for seedlings of that species.
3. For each stratum, sum the total carbon contained in the seedlings of each species (tonnes C/species) to give the total carbon in that stratum (tonnes C/stratum).
4. Add together the total carbon contained in the seedlings in each stratum (tonnes C/stratum) to give the total carbon, in tonnes, contained in all the tree seedlings in the project.
5. Multiply this figure by 44/12 to convert from tonnes of carbon to tonnes CO_2 contained in all the tree seedlings in the project.

6.2. Saplings

1. For each species, use the height of the representative sapling (m) to derive the mean carbon content per sapling (*i.e.* above and below ground) from Table 6.1.3 (for broadleaved species) or Table 6.1.4 (for coniferous species).
2. Multiply the above value by the total number of saplings in the stratum. This gives an estimate of the total carbon (tonnes C/species) in the stratum for saplings of that species.
3. For each stratum, sum the total carbon contained in the saplings of each species (tonnes C/species) to give the total carbon in that stratum (tonnes C/stratum).
4. Add together the total carbon contained in the saplings in each stratum (tonnes C/stratum) to give the total carbon, in tonnes, contained in all the saplings in the project.
5. Multiply this figure by 44/12 to convert from tonnes of carbon to tonnes CO_2 contained in all the tree saplings in the project.

6.3. Trees

1. Take the relevant total biomass values from Section 5.2.4 and multiply each by 0.5 (Matthews, 1993). This will give estimates of the total carbon contained in trees of each species in each stratum (tonnes C/species), the total carbon contained in each stratum (tonnes C/stratum), and the total carbon (in tonnes) contained in all the measurable trees in the project.
2. Multiply this figure by 44/12 to convert from tonnes of carbon to tonnes CO_2 contained in all the measureable trees in the project.

Table 6.1.1: Average Total Carbon Content – Broadleaved Seedlings

Broadleaves		Broadleaves	
Mean seedling height (cm)	C per thousand seedlings (tonnes)	Mean seedling height (cm)	C per thousand seedlings (tonnes)
1	0.00000423	26	0.00329199
2	0.00001742	27	0.00355599
3	0.00003990	28	0.00383041
4	0.00007182	29	0.00411526
5	0.00011331	30	0.00441057
6	0.00016446	31	0.00471634
7	0.00022535	32	0.00503259
8	0.00029605	33	0.00535935
9	0.00037661	34	0.00569663
10	0.00046708	35	0.00604444
11	0.00056752	36	0.00640279
12	0.00067796	37	0.00677171
13	0.00079843	38	0.00715121
14	0.00092899	39	0.00754129
15	0.00106965	40	0.00794198
16	0.00122045	41	0.00835330
17	0.00138143	42	0.00877524
18	0.00155260	43	0.00920783
19	0.00173399	44	0.00965108
20	0.00192564	45	0.01010501
21	0.00212755	46	0.01056962
22	0.00233976	47	0.01104493
23	0.00256229	48	0.01153095
24	0.00279516	49	0.01202769
25	0.00303839	50	0.01253517

Table 6.1.2: Average Total Carbon Content – Conifer Seedlings

Conifers		**Conifers**	
Mean seedling height (cm)	C per thousand seedlings (tonnes)	Mean seedling height (cm)	C per thousand seedlings (tonnes)
1	0.00000438	26	0.00402017
2	0.00001869	27	0.00435081
3	0.00004369	28	0.00469512
4	0.00007980	29	0.00505317
5	0.00012733	30	0.00542498
6	0.00018653	31	0.00581062
7	0.00025759	32	0.00621012
8	0.00034069	33	0.00662353
9	0.00043598	34	0.00705088
10	0.00054360	35	0.00749222
11	0.00066367	36	0.00794759
12	0.00079630	37	0.00841702
13	0.00094161	38	0.00890056
14	0.00109967	39	0.00939824
15	0.00127059	40	0.00991009
16	0.00145445	41	0.01043616
17	0.00165132	42	0.01097647
18	0.00186129	43	0.01153106
19	0.00208441	44	0.01209996
20	0.00232077	45	0.01268321
21	0.00257042	46	0.01328084
22	0.00283343	47	0.01389288
23	0.00310985	48	0.01451936
24	0.00339975	49	0.01516030
25	0.00370317	50	0.01581575

Table 6.1.3: Average Total Carbon Content – Broadleaved Saplings

Broadleaves		Broadleaves (continued)		Broadleaves (continued)	
Mean height (m)	Carbon per stem (tonnes)	Mean height (m)	Carbon per stem (tonnes)	Mean height (m)	Carbon per stem (tonnes)
0.6	0.0000182	3.8	0.0008488	7.0	0.0036315
0.7	0.0000250	3.9	0.0008987	7.1	0.0037737
0.8	0.0000328	4.0	0.0009504	7.2	0.0039209
0.9	0.0000418	4.1	0.0010039	7.3	0.0040731
1.0	0.0000519	4.2	0.0010593	7.4	0.0042307
1.1	0.0000631	4.3	0.0011166	7.5	0.0043939
1.2	0.0000754	4.4	0.0011759	7.6	0.0045628
1.3	0.0000889	4.5	0.0012372	7.7	0.0047378
1.4	0.0001036	4.6	0.0013005	7.8	0.0049192
1.5	0.0001194	4.7	0.0013660	7.9	0.0051072
1.6	0.0001365	4.8	0.0014336	8.0	0.0053023
1.7	0.0001547	4.9	0.0015034	8.1	0.0055046
1.8	0.0001742	5.0	0.0015756	8.2	0.0057147
1.9	0.0001949	5.1	0.0016501	8.3	0.0059328
2.0	0.0002168	5.2	0.0017270	8.4	0.0061594
2.1	0.0002400	5.3	0.0018065	8.5	0.0063951
2.2	0.0002645	5.4	0.0018885	8.6	0.0066401
2.3	0.0002903	5.5	0.0019732	8.7	0.0068952
2.4	0.0003174	5.6	0.0020606	8.8	0.0071608
2.5	0.0003459	5.7	0.0021509	8.9	0.0074375
2.6	0.0003757	5.8	0.0022440	9.0	0.0077260
2.7	0.0004069	5.9	0.0023402	9.1	0.0080271
2.8	0.0004395	6.0	0.0024396	9.2	0.0083414
2.9	0.0004736	6.1	0.0025421	9.3	0.0086699
3.0	0.0005090	6.2	0.0026480	9.4	0.0090134
3.1	0.0005460	6.3	0.0027574	9.5	0.0093730
3.2	0.0005845	6.4	0.0028703	9.6	0.0097496
3.3	0.0006245	6.5	0.0029870	9.7	0.0101445
3.4	0.0006661	6.6	0.0031076	9.8	0.0105590
3.5	0.0007093	6.7	0.0032321	9.9	0.0109945
3.6	0.0007541	6.8	0.0033608	10.0	0.0114525
3.7	0.0008006	6.9	0.0034939		

Table 6.1.4: Average Total Carbon Content – Conifer Saplings

Conifers	
Mean height (m)	Carbon per stem (tonnes)
0.6	0.0000222
0.7	0.0000304
0.8	0.0000400
0.9	0.0000509
1.0	0.0000631
1.1	0.0000767
1.2	0.0000916
1.3	0.0001080
1.4	0.0001257
1.5	0.0001449
1.6	0.0001655
1.7	0.0001876
1.8	0.0002111
1.9	0.0002361
2.0	0.0002626
2.1	0.0002906
2.2	0.0003202
2.3	0.0003513
2.4	0.0003840
2.5	0.0004184
2.6	0.0004543
2.7	0.0004920
2.8	0.0005313
2.9	0.0005724
3.0	0.0006152
3.1	0.0006598
3.2	0.0007062
3.3	0.0007545
3.4	0.0008046
3.5	0.0008567
3.6	0.0009108
3.7	0.0009669
Conifers (continued)	
Mean height (m)	Carbon per stem (tonnes)
3.8	0.0010250
3.9	0.0010853
4.0	0.0011477
4.1	0.0012123
4.2	0.0012792
4.3	0.0013484
4.4	0.0014200
4.5	0.0014940
4.6	0.0015705
4.7	0.0016496
4.8	0.0017314
4.9	0.0018158
5.0	0.0019031
5.1	0.0019932
5.2	0.0020863
5.3	0.0021825
5.4	0.0022819
5.5	0.0023845
5.6	0.0024904
5.7	0.0025998
5.8	0.0027128
5.9	0.0028296
6.0	0.0029502
6.1	0.0030747
6.2	0.0032034
6.3	0.0033363
6.4	0.0034737
6.5	0.0036157
6.6	0.0037625
6.7	0.0039143
6.8	0.0040712
6.9	0.0042336
Conifers (continued)	
Mean height (m)	Carbon per stem (tonnes)
7.0	0.0044015
7.1	0.0045753
7.2	0.0047552
7.3	0.0049415
7.4	0.0051344
7.5	0.0053343
7.6	0.0055415
7.7	0.0057564
7.8	0.0059792
7.9	0.0062105
8.0	0.0064505
8.1	0.0066999
8.2	0.0069589
8.3	0.0072283
8.4	0.0075085
8.5	0.0078002
8.6	0.0081039
8.7	0.0084204
8.8	0.0087504
8.9	0.0090948
9.0	0.0094544
9.1	0.0098301
9.2	0.0102231
9.3	0.0106345
9.4	0.0110655
9.5	0.0115174
9.6	0.0119917
9.7	0.0124900
9.8	0.0130142
9.9	0.0135662
10.0	0.0141482

Glossary

basal area	The cross-sectional area of a tree stem at 1.3 metres above ground. Basal area is always expressed in square metres.
dbh	Diameter at breast height. The diameter, in centimetres, of the tree stem at 1.3 metres above ground level.
Census	Data directly collected for an entire population, as opposed to a sample.
net area	Stand area not including roads, rides and other unproductive areas.
quadratic mean dbh	The square root of the mean of the sum of squared diameters at breast height. This is equivalent to the diameter of the tree of mean basal area.
Population	The complete set of individuals, items, or data from which a statistical sample is taken.
project design document (PDD)	A requirement for compliance with the Forestry Commission's Code of Good Practice for UK-Based Forest Carbon Projects.
Sample	A subset of a population usually chosen in such way that it can be taken to represent the population with respect to some characteristic, for example, height, dbh, species, or tree volume.
sampling unit	One member of a set of entities being studied. Examples of such entities are individual trees or a sample plots.
sapling	A juvenile tree. In this document, a sapling is defined as a living stem greater than 50 centimetres tall and with a dbh less than 7 centimetres.
seedling	A young plant that is grown from a seed. In this document, a seedling is defined as a living stem less than 50 centimetres tall.
strata	Plural of stratum.

stratum	A uniformly constituted subdivision of a population which has been explicitly established for the purposes of increasing the efficiency of sampling.
systematic sample	In a systematic sample, the sampling units (*e.g.* sample trees) are selected such that they are evenly distributed (for example at the intersections of a grid) within the boundary of the area being assessed.
timber height	The vertical distance, to the nearest 0.1 metres, between the base of the tree stem to the point at which the stem becomes 7cm diameter over bark or at which no main stem can be distinguished, whichever comes first.
top height	The average total height of the 100 trees of largest diameter per hectare.
total height	The vertical distance between the base of the tree and the highest growing point, recorded to the nearest 0.1 metres.
tree	In this document a [measurable] tree is defined as a living stem with a dbh greater than 7 centimetres.

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