SECTION 9

Forest Research Projects

The role of the Forestry Commission permanent sample plot network in forest carbon balance research

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Summary. Since its formation, the Forestry Commission has upheld a commitment to establish and maintain a network of permanent mensuration sample plots. The principal use of sample plot data is for calibration of models of forest growth and yield, but sample plots are ubiquitous in their applications and a wide range of research projects have depended on sample plots as a key source of data. The objectives of this report are to provide an overview of the Forestry Commission Sample Plot Research programme, to summarise the data available from sample plot records and to consider the potential applications of sample plot data and the potential role of sample plots in research into the carbon balance of forest ecosystems. In general, the pattern of sample plot establishment has followed a strategy aimed at underpinning development and validation of yield models, with roughly equal numbers of plots representing the key and emerging tree species. The sample plot network has provided, and continues to provide, a national reserve of periodic growth and yield data to support measurement, growth and yield studies.The current permanent plot network covers a wide range of species, sites, yield classes and management treatments. Establishment of plots has, however, been subject to constraints and at times has needed to be opportunistic. There are a number of gaps in data for particular tree species combinations or management practices. Very recently, strategy for establishment and maintenance of sample plots has been the subject of a fundamental review within the Forestry Commission. The findings of the Sample Plot Programme Review are likely to have a strong impact on priorities for establishment, maintenance and retention of sample plots. A key part of the review has been the acknowledgement that different types of sample plot are needed to provide data for different aspects of growth and yield model development, calibration and validation. Data collected over nearly 90 years from the sample plot network constitute a rich source of information on forest growth and yield in Britain, subject to interpretation within the context of the strategy for sample plot establishment and maintenance outlined above. There are many potential applications of sample plot data to the development, calibration and validation of forest carbon balance models. However, given past, current and future strategy for establishment and maintenance of mensuration sample plots, radical changes would be needed if the network was required to serve as a form of inventory system for monitoring the forest carbon at the estate or national level.

Introduction

Since its formation, the Forestry Commission has upheld a commitment to establish and maintain a network of permanent mensuration sample plots. By the conclusion of the peak of the research effort in the 1950s through to the 1970s, a total of 1006 sample plots were under active management. Currently the sample plot network comprises just over 500 permanent plots, supported by campaigns involving establishment of temporary or short-term mensuration plots to meet the needs of specific research projects. The data collected from these plots now amounts to a considerable resource of information about the growth and yield of trees and forest stands in Britain, forming a significant component of the recently created Forest Research Ecosystem Database. The principal use of sample plot data is for calibration of models of forest growth and yield, but sample plots are ubiquitous in their applications and a wide range of research projects have depended on sample plots as a key source of data.

Objectives

The objectives of this report are to:

- Provide an overview of the Forestry Commission Sample Plot Research programme.
- Summarise the data available from sample plot records.
- Consider the potential applications of sample plot data and the potential role of sample plots in research into the carbon balance of forest ecosystems.

Overview of Sample Plot Programme

The requirement for permanent sample plots was identified as a key priority in the Acland Report and the associated reports of Lord Robinson that led to the formation of the Forestry Commission in 1919. Emphasis was placed on research in support of the development of:

- Yield tables, latterly growth and yield models, which were viewed as fundamental to economic assessment of forestry enterprises including silvicultural options, and also essential for production forecasting and operational planning.
- Volume tables, better understood today as the various charts, tables and equations underpinning the measurement systems in everyday use by the British forest industry.
- ‘Best practice’ forest management, through demonstration of the impacts of forest stand structure, growth and yield of alternative silvicultural regimes. Recently the rise in importance of forestry certification schemes has seen a resurgence of interest among some stakeholders in this application of sample plots.

Of these three applications, development of growth and yield models was held to be of greatest importance, a view which has been sustained to this day. Consequently, the requirement for data to underpin development of growth and yield models has been pivotal in determining the strategy for establishment and maintenance of sample plots.

An important distinction must be made between the requirements for sample plots used in a monitoring capacity, for example as part of a system of periodic national inventory, as opposed to providing data for model development and calibration.

Sample plots as the basis for inventory and monitoring

In some countries, networks of permanent sample plots are used as the basis for periodic forest inventories and for estimating future production, either at the national level or for certain estates or for particular forest types. In such circumstances, key requirements of the sample plot network are that the network should be:

- Representative of the forest types of interest.
- Founded on a rigorous statistical design to permit a reliable upscaling of sample assessments to estimates for the population (or components) of interest.

When applied in this capacity, sample plot networks will tend to be purely descriptive of current and evolving forest growth trends and management practices. If the range of silvicultural practices is narrow, it is not possible to use data from these plots to construct models of forest growth and yield other than for the range of management regimes represented. It is therefore difficult to use the data collected to assess the impact of alternative silvicultural regimes or to verify that the conventional systems of management may be regarded as 'best practice', regardless of the criteria considered.

Sample plots as the basis of growth and yield model development

The alternative to the direct inventory/monitoring approach is to use sample plots as a source of data for the development and calibration of reliable models of forest growth and yield, capable of representing a wide range of tree species, site types, forest stand structures and management regimes. Provided that it is possible to develop sufficiently flexible and representative models, these can be used in conjunction with an abbreviated system of forest inventory for the purposes of production forecasting and operational planning at various scales. The models can also be used for the evaluation of alternative silvicultural options and can also contribute to verifying particular systems of management as consistent with 'best practice'. Given these objectives, the criteria for establishment and management of permanent sample plots are drastically different from those in support of inventory, specifically:

- The site types, forest species compositions and silvicultural treatments represented by sample plots needs to be very wide in order to ensure robust model development and calibration. As such, the sample plot network is unlikely to be representative of forests at the national or estate level.
- If robust growth and yield models are to be developed successfully, the requirements for data collected from sample plots are likely to be more rigorous and comprehensive compared to the requirements for simple inventory plots.

In terms of numbers of sample plots required, there are advantages and disadvantages of the yield modelling approach compared to the inventory approach. In general, similar numbers of sample plots will be required for each yield model that needs to be developed in terms of tree species and forest types represented. This may mean that for the most important species in terms of area occupied and economic value, less sample plots will be required for the development of yield models than would be required to support a direct inventory of these forest areas. On the other hand, it is likely that more sample plots will be required in stands representing species and forest types regarded as minor, compared to the investment that would be made in terms of simple inventory plots.

Strategy for establishment of Forestry Commission sample plots

Early developments. At the turn of the century the percentage of land under forest in Britain was down to 5%. The Forestry Commission was created with the objective of expanding the forest area in Britain, and as noted the need for reliable timber production forecasts for the newly created forests was recognised at the outset. Because the total area, species composition and silvicultural treatment of British forests were changing rapidly, the Forestry Commission was committed to an approach to inventory, production forecasting and operational planning based on yield tables and models. Yield models were also required to evaluate options for management of the newly created forests. Accordingly, permanent sample plots were established in the young forests, and where possible in existing mature stands, and the periodic measurements were used for the construction of yield models. The majority of measurements were from young plantations, thus considerable extrapolation beyond the range of available data was necessary. Single measurements from temporary sample plots were used to augment the limited data available from permanent plots, although temporary sample plot data gave no indication of growth trends. In effect, therefore, the published yield models preceded and preempted much of the sample plot data. Provisional yield models for some species were published as early as the 1930s, and by the 1960s yield models were available for all the major plantation forest species.

Refinement and validation of published models in the 1970s and 1980s. Policy on establishment and management of sample plots in the 1970s and 1980s was dominated by efforts to validate many of the assumptions made during the construction of the published yield models, for example a series of large-scale, replicated thinning experiments were established with the objective of confirming that the intensity of thinning recommended in the published yield models was in fact the optimum intensity. Increasingly, the silvicultural treatment of the sample plots became based on theoretical prescriptions derived from yield models, rather than reflecting current field practices.

Current strategy. By the late 1980s, demand was rising for improved, more flexible, growth and yield models taking advantage of developments in statistics and mensuration science and exploiting modern computing methods, capable of representing contemporary and developing forestry practice. As a result, in recent years, management of sample plots has been less strongly aligned to the validation of existing yield models, rather there is again greater emphasis on representing contemporary silvicultural practices, site types and modern planting and harvesting systems. Currently, the criteria used for identifying and selecting forest types and locations for establishment of sample plots are as follows:

- The forest stand containing the sample plot should represent a combination of species composition, stand structure and site type relevant to current or emerging forestry practice in Britain.

- Management of the forest stand containing the sample plot should be representative of current or evolving silvicultural practice in the locality.
- There is a specific demand from local managers for information from sample plots, and a commitment to support their establishment and maintenance.
- There is an option to establish a small series of plots representing an range of alternative silvicultural treatments.

The number and composition of permanent sample plots, as illustrated in Figure 1, has evolved according to a pattern that reflects the developing policy on sample plot establishment and maintenance outlined above.

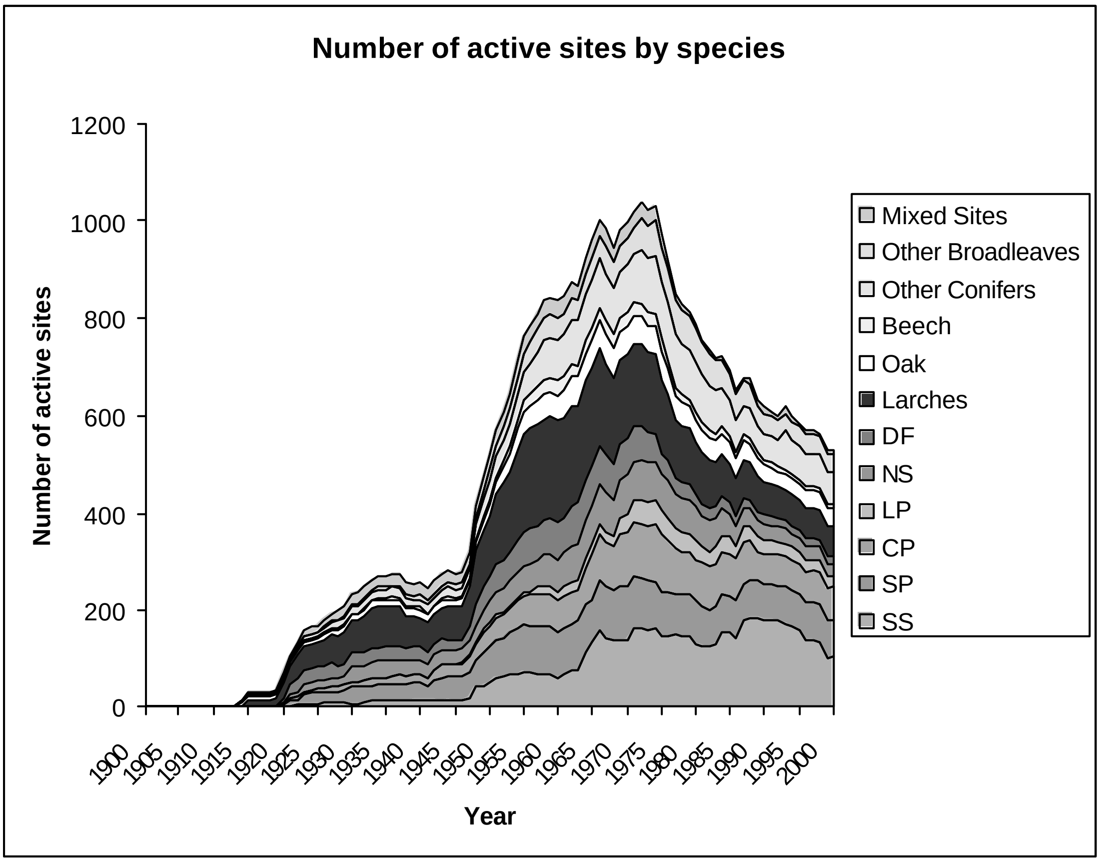

Figure 1. Numbers of viable Forestry Commission permanent mensuration sample plots in Britain, by species composition, over the period 1900 to 2000.

In general, the pattern of sample plot establishment has followed the strategy of underpinning development and validation of yield models, with roughly equal numbers of plots representing the key and emerging tree species. There are exceptions, however, for example relatively few plots have been established in oak and beech stands, or in broadleaves in general, while the number of plots in lodgepole pine stands is barely sufficient for calibration of yield models. Obviously there have always been physical and resource constraints which have caused the actual sample plot holding to depart from the ideal. Nevertheless it is clear from Figure 1 that, in terms of representation of species types to support development of yield models, the goals of the strategy have been achieved. It is notable that there have been only a small number of plots in stands of species mixtures. However, yield models for species mixtures are usually derived from some combination of the appropriate pure-species models, with plots serving in the capacity of validation, rather than development or calibration.

Figure 2 illustrates how a range of silvicultural treatments is represented by data from the permanent sample plot network. Although a diversity of treatments is covered, including a number of highly experimental silvicultural practices, nearly one half of the sample plots have been thinned to the standard Management Table prescription, to a large extent reflecting the commitment made in the 1970s and 1980s to validation of the published yield tables. Plots in unthinned stands account for a quarter of the sample plot network but in fact very few of these plots have received a strictly no-thin treatment, instead receiving a treatment based on very light silvicultural thinning. Data is therefore scare to support the calibration of models predicting levels of tree survival in response to inter-tree competition in the absence of silvicultural intervention.

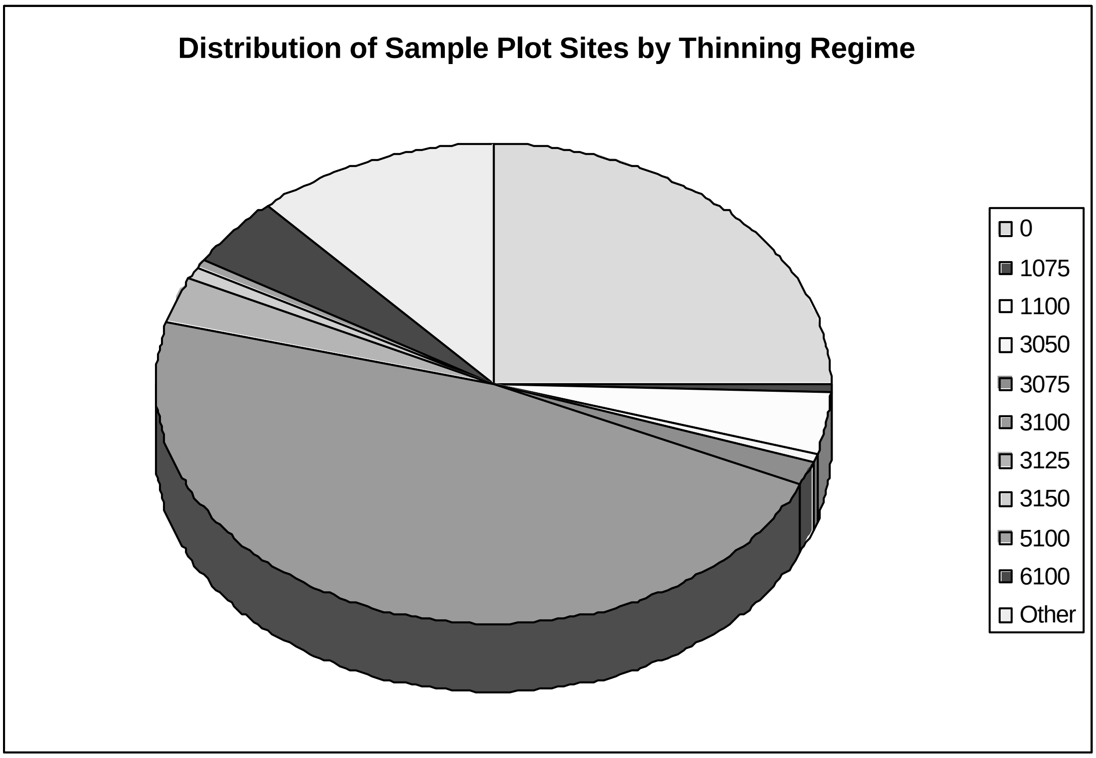

Figure 2. Different thinning treatments represented in viable and abandoned permanent mensuration sample plots. Key to thinning codes. 0: no thinning; 1075 and 1100: grades of low thinning; 3050-3150: grades of intermediate thinning, in order of increasing intensity, with 3100 representing standard Management Table intensity; 5100: types of line thinning; 6100: types of crown thinning; Other: includes eclectic and exploitation thinning treatments.

In conclusion, it is evident from the above overview that:

- The sample plot network has provided, and continues to provide, a national reserve of periodic growth and yield data to support measurement, growth and yield studies.

- The current permanent plot network covers a wide range of species, sites, yield classes and management treatments.
- Establishment of plots has, however, been subject to constraints and at times has needed to be opportunistic.
- There are a number of gaps in data for particular tree species combinations or management practices.

Recent developments. Very recently, strategy for establishment and maintenance of sample plots has been the subject of a fundamental review within the Forestry Commission. This review took into account recent trends in forestry policy and practice in Britain, specifically that:

- Forestry has evolved an increasing multipurpose role (environment, sustainability and recreation alongside timber production).
- National forestry strategies favour diversification of management practice.

The review concluded that:

- Growth and yield models need to support multipurpose forest management, representing potential wood production from increasingly diverse forest stands.
- There remains an inextricable link between sample plots and modelling to inform decision-making in management practice.
- Even closer links need to be established between the growth and yield modelling programmes and sample plot programmes.

The findings of the Sample Plot Programme Review are likely to have a strong impact on priorities for establishment, maintenance and retention of sample plots. A key part of the review has been the acknowledgement that different types of sample plot are needed to provide data for different aspects of growth and yield model development, calibration and validation (Figure 3). The particular mix of plot types required will depend on the type of growth and yield model being developed. It is therefore envisaged that the emphasis placed on establishment and maintenance of different sample plot types will be closely allied to priorities for development of different types of growth and yield model as defined by Matthews and Methley (1998).

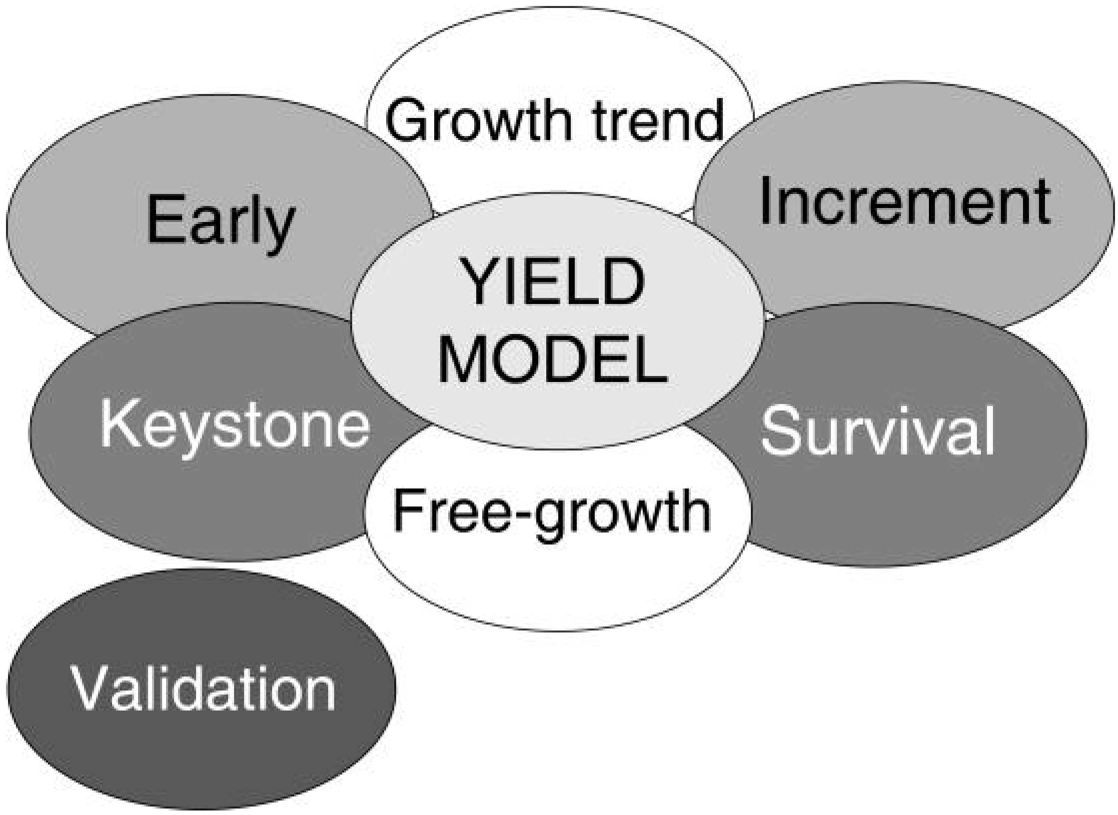

Figure 3. Different types of sample plot are needed for different aspects of growth and yield model research. Keystone and survival plots are true, temporary plots, measured only once and providing a snapshot of forest stand structure to inform development of growth and yield model initial conditions and models of tree survival respectively. Early and increment plots are required to provide sequences of periodic measurements for development and calibration of tree and stand projection models. They provide data on growth increments accounting for establishment practices and later silvicultural practices respectively. Periodic measurements are therefore taken but such plots usually have a viable life of no more than 15 years. Growth trend plots are traditional permanent sample plots, providing data on long-term growth patterns for calibration and/or validation of long-term projections of growth models. Free-growth plots are also permanent plots, but representing isolated specimen trees, to provide data on maximum growth potential of individual trees in the absence of competition. Validation plots are used to provide data purely for testing of growth and yield models, notably for species and age-class mixtures. For many applications these plots will only be measured once.

Location and design of sample plot

Once the decision has been taken to establish a sample plot in a forest area has been taken, the criteria for deciding on the location for the plot are simple, as illustrated in Figure 4. Where appropriate, a cluster of sample plots may be established, permitting the representation of different silvicultural treatments at the same location. In the past, a number of large-scale replicated experiments were established for testing and comparison of different management regimes, but currently this approach is not favoured because of high cost and high risk of damage to a complex experimental design. The design of a sample plot is also very simple, as illustrated in Figure 5.

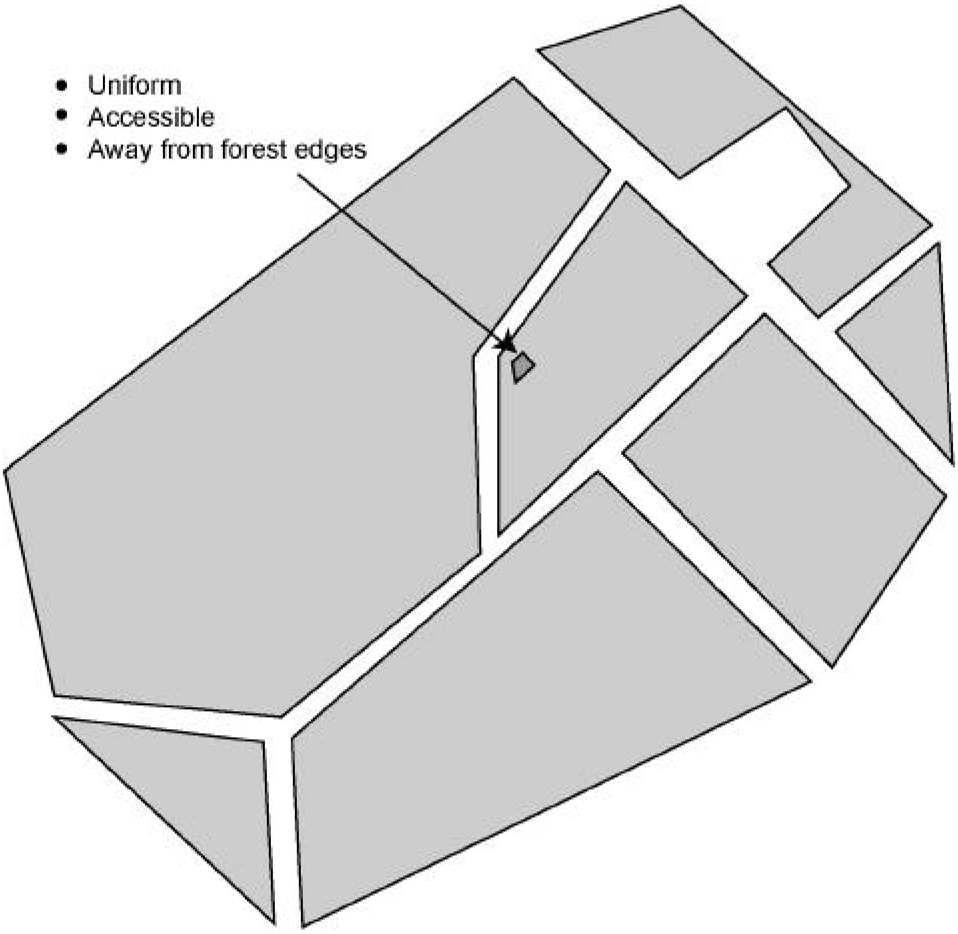

Figure 4. *Illustration of typical location of a mensuration sample plot.*

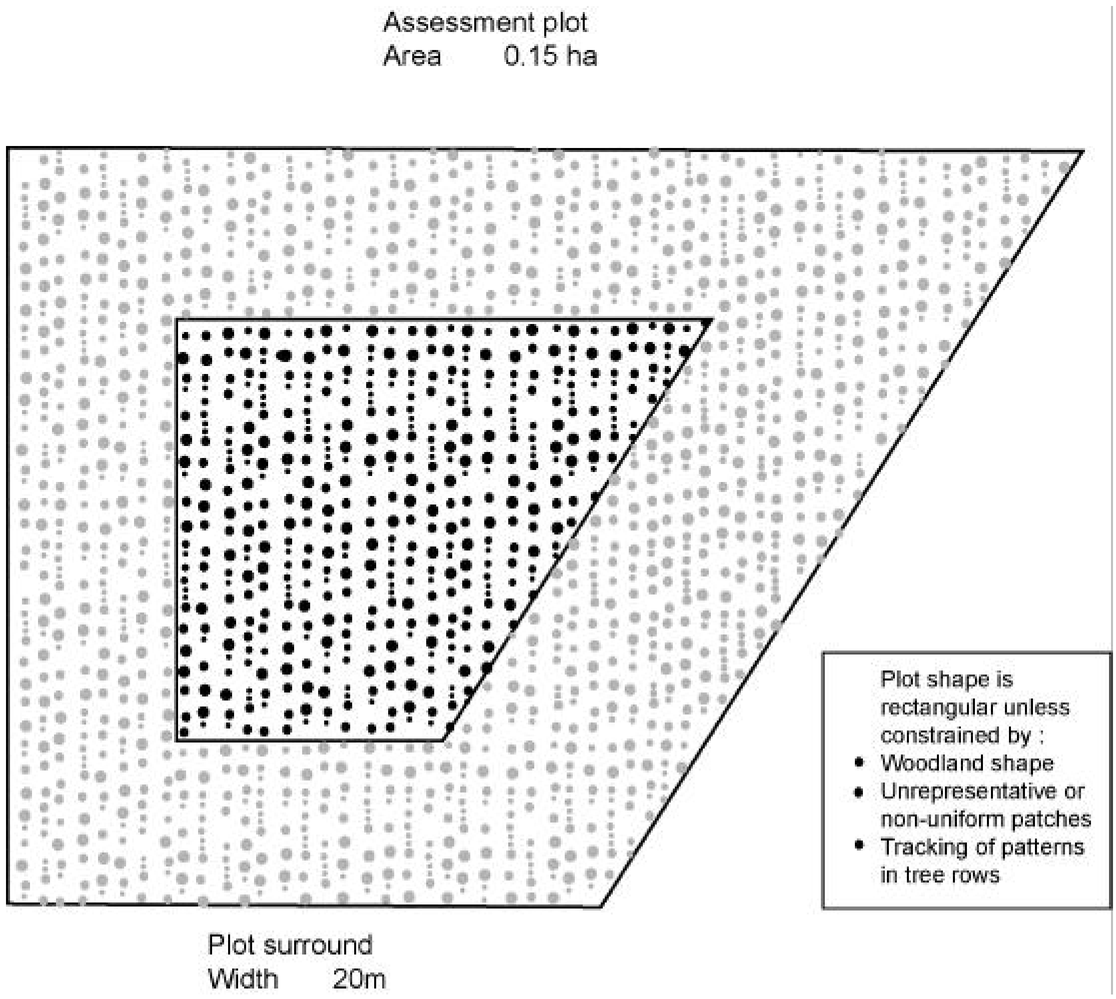

Figure 5. Design of a typical mensuration sample plot.

Data available from mensuration sample plot records

The standard programme of assessments and analyses carried out on mensuration sample plots is described in the Forestry Commission Sample Plot Code (Edwards, 1976) and is extensive. The key datasets and summary results derived from sample plots are described in Figure 6. Data such as these collected over nearly 90 years from the sample plot network constitute a rich source of information on forest growth and yield in Britain, subject to interpretation within the context of the strategy for sample plot establishment and maintenance outlined above. In addition to quantitative information, qualitative records are made on establishment and periodic remeasurement of stand characteristics and condition, including a description of any operations and silvilcultural interventions carried out.

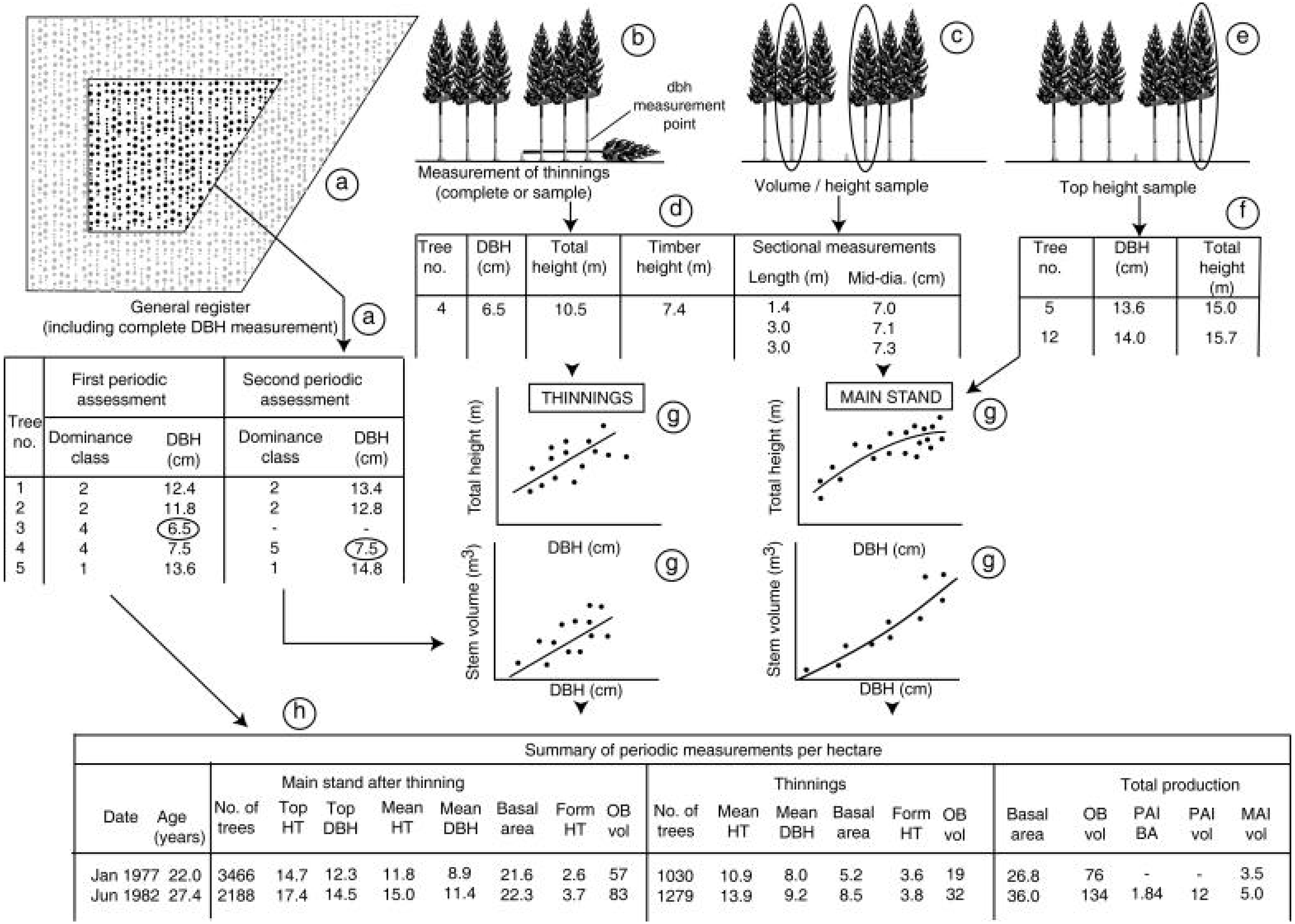

Figure 6. *Illustration of data collected and results calculated from mensuration sample plots at each periodic measurement. a: In the General Register, all trees are numbered, classified for dominance and the dbh recorded, while trees removed as thinnings are marked; b: Either all thinnings, or a large sample, are measured for total height, timber height and stem volume as sectional measurements; d: A sample of 10 trees left standing after thinning, selected to represent the range of dbh classes in the stand, is measured for total height and stem volume as sectional measurements; d: The height and volume sample measurements for both thinnings and standing trees are recorded in standard format; e: A sample of 10 trees, identified as representative of dominant (largest dbh) trees, are assessed for total height; f: The 'top height data' sample is recorded in standard format; g: The tree height and volume sample data are used to establish correlations between tree height and volume with dbh, separately for trees removed as thinnings and for trees left standing; h: The General Registr data and correlation analyses of height and volume samples are used to produce a summary of stand-level mensuration variables for each periodic assessment.*

Application of sample plots to forest carbon balance research

There are many potential applications of sample plot data to the development, calibration and validation of forest carbon balance models, including:

- Underpinning of development, calibration and validation of forest growth and yield models from which carbon balance models are derived;
- Underpinning of development, calibration and validation of models for estimating potential mixes of harvested wood products by size specifications;
- Estimation of quantities of carbon in main tree components (see for example Matthews, This volume), and total stocks of carbon in trees in forest stands;
- Decomposition of forest stand carbon flux measurements into tree and soil components.

However, given past, current and future strategy for establishment and maintenance of mensuration sample plots, radical changes would be needed if the network was required to serve as a form of inventory system for monitoring the forest carbon at the estate or national level.

References

Edwards, P.N. (1976) The Sample Plot Code. Mensuration Branch internal manual. Forest Research: Alice Holt.

Matthews, R.W. and Methley, J.M. (1998) Development of interactive yield models for UK conditions. Forest Research Annual Report 1997-98, 56-61. The Stationery Office: Edinburgh.

Evaluation and comparison of CFLOW and CARBINE models: a progress report

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Summary. In the United Kingdom the CEH model CFLOW and the Forestry Commission model CARBINE have been applied extensively to the quantification of carbon stocks and potential for stock changes across the full range of spatial scales. The principal objectives of this study are an evaluation of the completeness and robustness of the CFLOW and CARBINE models for estimating carbon stocks and potential stock changes in the forestry sector at the stand and national levels, and the reliability of underpinning data and parameter estimates used by CFLOW and CARBINE. Models such as CFLOW and CARBINE have been described as 'book-keeping' models, and are typical of a general approach that has been adopted quite generally by international research groups and applied in different countries. The similarity of these models means that they share common strengths and weaknesses. As a consequence, cross-validation of CFLOW and CARBINE is, informative but is not a sufficient test of model completeness or robustness. A series of evaluations is therefore proposed, consisting of consideration of models scope and overall structure (in terms of sub-models), developed from first principles, including identification of objectives; comparison of: scope of potential applications of models and overall model structure; evaluation and comparison of individual sub-models; evaluation and comparison of predictions, and finally evaluation of strengths and weaknesses in the implementation of the models. The comparison of predictions made by CFLOW and CARBINE against 'benchmark' estimates derived by alternative methods constitutes the strongest test of the two models. Work so far has concentrated on identifying and developing defendable estimates for use as benchmarks.

Introduction

Absolute quantities and changes in stocks of carbon sequestered from the atmosphere in forests, forest soils and harvested wood products can be quantified by two principal methods:

- Periodic inventory based on direct measurement and an associated statistical basis and sampling scheme;
- Application of a modelling approach in conjunction with conventional forest inventory information.

Approaches emphasising some sort of direct inventory are likely to require complex statistical theory and incur considerable expense in order to reduce uncertainties in estimates to levels that are acceptable for national and international reporting, or for use in project-based carbon sequestration schemes. Furthermore it is likely that recourse will be made in some aspects of any inventory procedure to a modelling approach in order to avoid excessive effort or expense relative to the level of accuracy achieved in carbon stock estimates. By contrast, a modelling approach can provide robust estimates and capture the significant components of variation in carbon stocks across landscapes, forest types and management regimes at a fraction of the cost of an equivalent inventory, provided that the models can be integrated effectively with existing conventional forest inventory information. Beyond more quantification, models of carbon stock dynamics in the forestry sector are essential for evaluating the impacts of alternative forest management and wood utilisation options on the carbon balance at the stand level as well as for estates, regions and the national level. In the United Kingdom the CEH model CFLOW (Dewar, 1990, 1991) and the Forestry Commission model CARBINE (Thompson and Matthews, 1989) have been applied extensively to the quantification of carbon stocks and potential for stock changes across the full range of spatial scales (Matthews, 1991a, 1991b, 1993b, 1996; Dewar and Cannell, 1992; Dewar, 1990, 1991; Milne et al., 1998; Thompson and Matthews, 1989).

The validity of estimates of carbon stocks and stock changes produced using CFLOW and CARBINE clearly depends on the comprehensiveness with which carbon pools in the forestry sector are represented. This is also true for the description within these models of associated process resulting in carbon stock changes in these pools. The accuracy of model estimates also depends critically on the reliability of underpinning data and model parameter estimates. To date, however, these fundamental aspects of CFLOW and CARBINE have not been subjected to a formal validation process.

Objectives of the study

The principal objectives of this study are, therefore, an evaluation of:

- The completeness and robustness of the CFLOW and CARBINE models for estimating carbon stocks and potential stock changes in the forestry sector at the stand and national levels.
- The reliability of underpinning data and parameter estimates used by CFLOW and CARBINE.

An important part of this evaluation will be carried out through comparison (cross-validation) of CFLOW and CARBINE. Where appropriate, recommendations will be made for structural changes or revised parameterisation of CFLOW or CARBINE.

Overview of book-keeping models

Models such as CFLOW and CARBINE have been described as 'book-keeping' models, and are typical of a approach that has been adopted quite generally by international research groups and applied in different countries (see for example Schlamadinger and Marland, 1998; Nabuurs, 1996; Marland and Schlamadinger, 1995; Fischlin and Bugmann, 1994; Nabuurs and Mohren, 1993, 1995; Apps and Kurz, 1993; Kurz *et al*., 1993; Heath and Birdsey, 1993; Marland and Marland, 1992; Harmon *et al*., 1990).

Such models represent flows of carbon between various pools rather like transactions of money between bank accounts. A reduction of carbon stocks in, say, the forest pool must be balanced by increases in the soil and wood products pools, or by transfers to the atmosphere. The principle of conservation of mass is thus obeyed. Detailed, explicit representation of processes such as photosynthesis and the biological basis of turnover of organic matter in the soil is not strictly needed and is not normally included. Forest growth models, which may be based on simple yield tables of timber production, are adjusted to forecast changes in the stock of standing biomass or carbon of forest stands. The flows of carbon to and from the atmosphere and to the soil are inferred from predicted stock changes in the forest. The processes involved in retention and/or loss of carbon within the soil are represented but quite often in a very simplistic way, for example in terms one or more first order decay curves.

Flows of wood or carbon to the products pool are usually derived directly from yield tables and appropriate produce conversion tables. Transfers of carbon from wood products to secondary use, recycling, landfill and eventual oxidation to the atmosphere are estimated by applying time-dependent exponential decay or hazard functions to the stocks of products. This is still effectively a mass balance approach, with carbon flows from pools of wood products estimated by modelling the reduction of stocks. The similarity of these models means that they share common strengths and weaknesses, as outlined below.

General evaluation of main modules of book-keeping models

Forest biomass carbon pool. This is generally the most accurately represented, drawing on a considerable body of forest mensuration, growth and yield research. Projected increases and decreases of carbon in forest biomass are derived from yield models or yield tables appropriate for the tree species, site productivities and styles of forest management for the forests being considered. In many countries, the models can be used in conjunction with conventional national forest inventories to provide estimates of forest carbon stock changes. Most models are also able to forecast probable changes in forest carbon stocks in future years under different forest management regimes, and in principle such model results could be used to inform national forestry policies. However, the range of possible forest management options covered by the models is generally limited to a relatively narrow range encompassing existing practices. In some cases, only pure-species, even-aged stands are included in the models, and in general the representation of systems of forest management relating to mixed-species, mixed-aged stands is at best very approximate.

Forest soil carbon pool. Active management of forest soils for carbon sequestration might be considered to be unrealistic due to the complexity and long-term nature of the task. As a result, so far the emphasis in terms of research has been on evaluating how to improve carbon sequestration in forest biomass and wood products, while not compromising soil carbon stocks. As a result, the soil carbon pool may be represented quite crudely in models, and often first order differential equations are used to project the accumulation or loss of carbon from the soil. In some models, inputs of carbon to the soil are not even linked explicitly to changes in above-ground biomass. Instead the dynamics of the soil carbon pool may depend on alternative differential equations that are switched in and out to represent gross changes in land cover (for example arable land, grassland, peat bog, forest and so on). Most models make some allowance for variations in the soil carbon dynamics of different soil types.

Wood products carbon pool. The structure of models of the wood products pool is generally well detailed, with the complete range of wood products represented, however in many respects this apparent thoroughness is not underpinned by hard data. This is universally true for carbon accounting models developed by different research groups. In some countries, 'graveyard studies' give some indication of the potential maximum life span of some wood products, but in practice the actual life spans of wood products in primary use are determined more by social and economic factors, with environmental factors often having a secondary influence. Representation of carbon stocks in wood products is often limited to primary use, and in particular dynamics of carbon in landfilled wood products are frequently ignored. Invariably models take no account of trading in wood products between regions and nations. These weaknesses of wood products models mean that simulation results should at best be regarded as 'indicative' of potential carbon sequestration in wood products under different management regimes. It also means that such models are unsuitable for computing defendable national or regional estimates of carbon stocks in wood products until some sort of model validation exercise is carried out.

Fossil fuel substitution. Carbon book-keeping models can be extended to include credits for emissions avoidance implied by direct and indirect displacement of fossil fuel consumption through use of wood fuel and wood-based products. A number of models include sub-models to account for these potential impacts of wood use. Every time wood harvests are simulated in the model, the wood is converted into a particular mix of wood products. Each wood product is assumed to have a characteristic potential (emissions factor) to displace alternative materials or fossil fuels, determining the magnitude of the emissions avoidance credit (if any) awarded. The estimation of emissions factors depends on many assumptions including an assumed and static pattern of product consumption and potential substitutions, unchanging industrial processes used for production of different materials and fabrication of different products, and fixed life-spans for products made of different materials. These estimates have not been subject to rigorous scrutiny or review and validation is needed for this potentially very important part of the carbon balance of the forestry sector. However, for models strictly concerned with carbon sequestration in wood and vegetation, this application of carbon book-keeping models may not be considered relevant.

Method adopted for evaluation of CFLOW and CARBINE

Given the similar origins and evolution of forest carbon book-keeping models, cross-validation of CFLOW and CARBINE is informative but is not a sufficient test of model completeness or robustness. A series of evaluations is therefore proposed as follows:

1. Consideration of models scope and overall structure (in terms of sub-models), developed from first principles, including identification of objectives.

2. Comparison of:
   - Scope of potential applications of models;
   - Overall structure of models.

3. Evaluation and comparison of individual sub-models including:
   - Processes represented;
   - Data/experimental results underlying representation of processes;
   - Data/experimental results underlying parameterisation of processes;.
   - Analysis of sensitivity of model predictions to variation of parameter estimates over range of uncertainty.

4. Evaluation and comparison of predictions made by CFLOW and CARBINE at stand and national level:
   - Against each other;
   - Against 'benchmark' estimates derived by alternative methods.

5. Evaluation of strengths and weaknesses of implementation of models, notably in terms of:
   - rigor/robustness;
   - portability;
   - flexibility of user interface and provision of outputs;
   - future-proofing.

Progress on development of benchmark estimates

The comparison of predictions made by CFLOW and CARBINE against 'benchmark' estimates derived by alternative methods constitutes the strongest test of the two models. However, some effort has been required to identify or develop defendable estimates for use as benchmarks. Work so far has concentrated on this task, and in particular on working up estimates of standing tree biomass per hectare based on statistical analyses of available data. Assessments of volume per hectare in standing tree stems are readily available from records maintained on Forestry Commission permanent sample plots (Matthews, This volume). Such volume records can be converted to estimates of standing biomass per hectare (in units of oven dry tonnes per hectare) through multiplication by the appropriate average nominal specific gravity for the species of wood in question (Lavers, 1983). Multiplying the resultant stem biomass values by an assumed carbon content of 0.5 (Matthews, 1993a) provides a set of periodic estimates of standing stem carbon per hectare for the Forestry Commission sample plots, based on a small number of widely accepted and defendable conversion factors.

Estimating carbon per hectare in the coarse woody roots, wood branches and leaves or needles of standing trees is more problematic, because estimates for whole stands have only been collected in a limited number of studies, often to different standards. On the other hand, quite rich sources of data are available for individual trees, from Forestry Commission databases and published in the scientific literature. A comprehensive review of these data sources has been carried out and relevant data have been collated and processed into a consistent dataset for analysis. Allometric equations for estimating root, branch and foliage biomass from standard tree mensuration variables collected in sample plots have been developed and calibrated for the key tree species relevant to the United Kingdom. An example of one such allometric analysis is illustrated in Figure 1, which shows data for woody branch biomass in beech trees plotted against equivalent tree diameter at breast height (dbh), along with curves illustrating the fitted allometric equation. Equations such as this can be used in conjunction with sample plot records (Figure 2) to derive per-hectare estimates of biomass for the non-stem tree components, which can be converted to estimates of carbon using appropriate carbon content values. A methodology similar to that adopted for sample plots can be applied to the Forestry Commission's yield tables to derive 'national average' estimates of standing carbon per hectare for a range of tree species, yield classes and management regimes

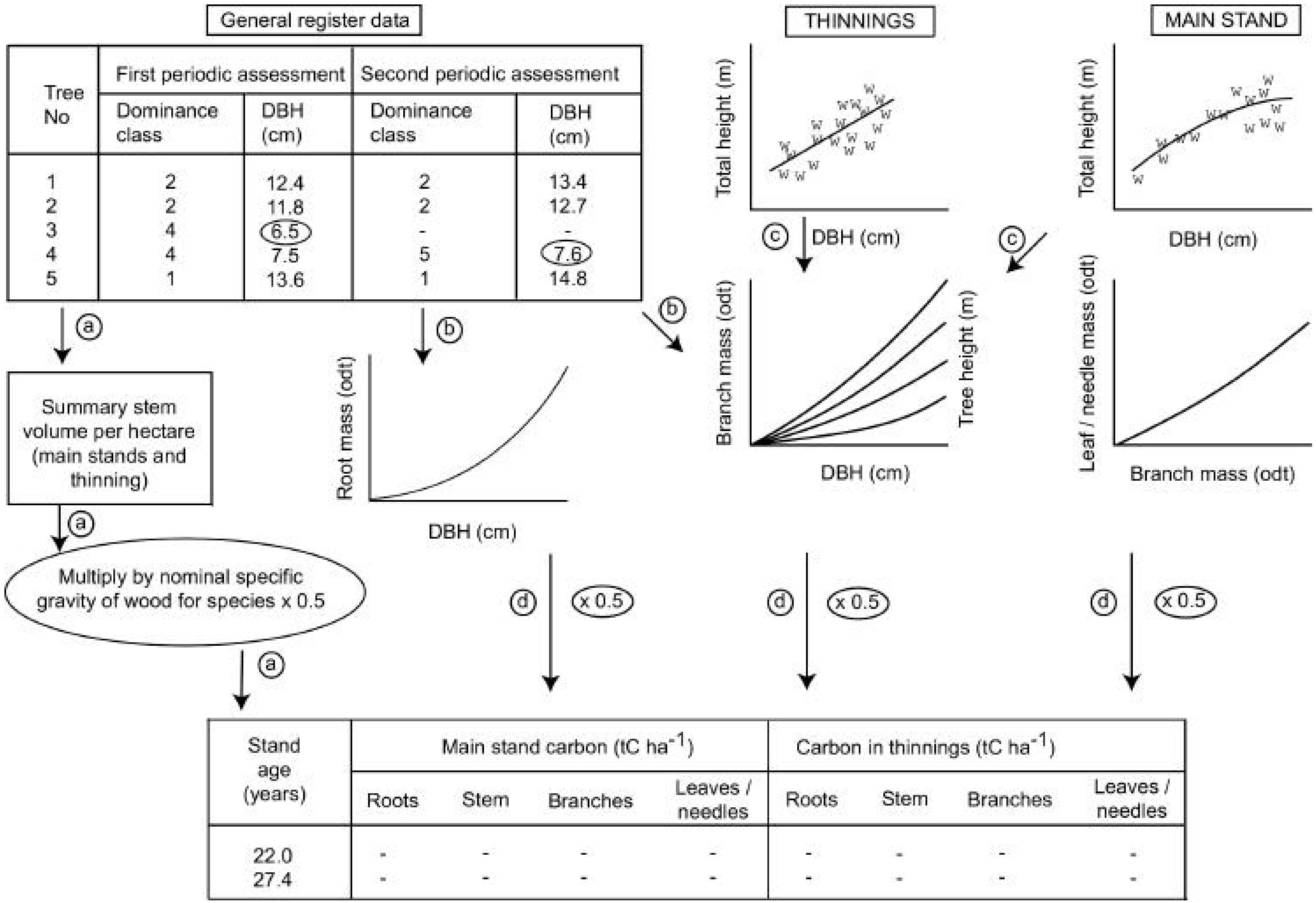

Figure 2. Development of stand-level estimates of carbon in principal tree components. (a) Conversion of summary stem volume per hectare values from permanent sample plot records to standing stem carbon per hectare. (b) Use of General Register data from permanent sample plot records as input to allometric equations for tree root, branch and foliage mass per hectare, in order to upscale to per-hectare estimates. (c) Reference to tree height-diameter relations derived from standard permanent sample plot measurements in conjunction with General Register data where necessary in application of allometric equations. (d) Conversion of per-hectare biomass estimates to carbon using appropriate estimates for carbon content.

Only a few estimates are available of the timecourse of carbon dynamics in soils under forest in response to forest growth and management interventions. Cross-validation with the independently developed and well established ROTH-C model of soil carbon dynamics (Coleman and Jenkinson, 1996). may serve as a valuable alternative approach. For the wood product pool, only very limited data and estimates are available that can serve as benchmarks, however it may be possible to make comparison with results from the inventory studies of Alexander (1997) and Pingoud et al. (1996, 2000), provided that compatible upscaled estimates can be produced using CFLOW and CARBINE.

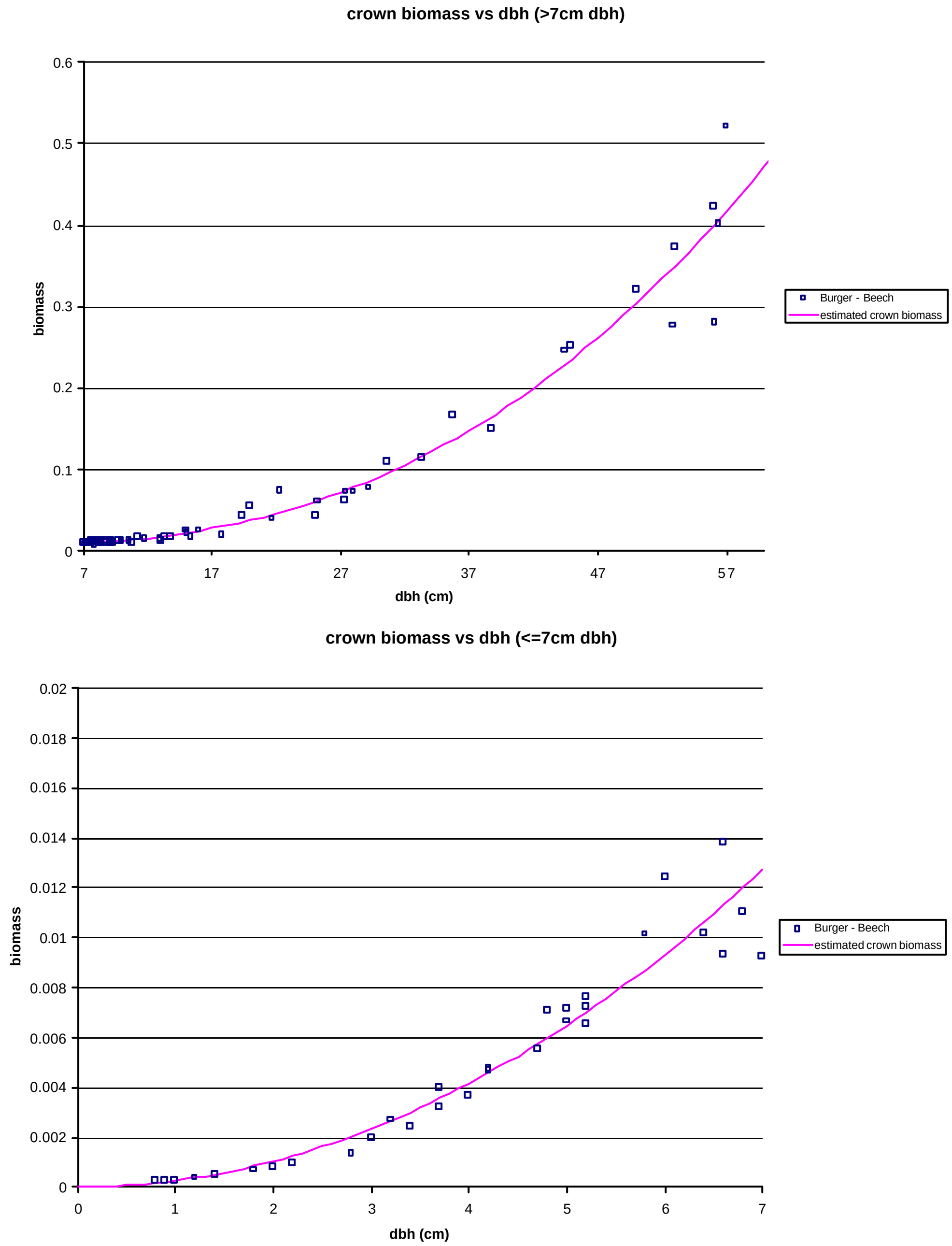

Figure 1. *Data on woody oven dry biomass of beech tree branch wood (oven dry tonnes per tree) versus tree diameter at breast height (dbh). The data and the fitted nonlinear regression equation are shown as two graphs covering the dbh ranges 7-60 cm and 0-7 cm.*

References

Alexander, M. (1997) *Estimation of national carbon stocks and fluxes of wood based products.* Thesis in part fulfilment of degree of MSc. University of Surrey: Guildford.

Apps, M.J. and Kurz, W.A. (1993) The Role of Canadian Forests in the Global Carbon Budget. In: Kanninen, M. (ed.) *Carbon balance of the world's forested ecosystems: towards a global assessment.* Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 14-39. Publications of the Academy of Finland: Helsinki.

Coleman K. and D. S. Jenkinson (1996) RothC-26.3- A model for turnover of carbon in soil. In: Evaluation of Soil Organic Matter Models Using Existing, Long-Term datasets, eds. D.S. Powlson, P. Smith and J.U. Smith, NATO ASI Series I, Vol. 38, Springer-Verlad, Heidelberg pp. 237-246.

Dewar, R.C. (1990) A model of carbon storage in forests and forest products. *Tree Physiology*, **6**, 417-428.

Dewar, R.C. (1991) Analytical Model of Carbon Storage in Trees, Soils, and Wood Products of Managed Forests. *Tree Physiology*, **8**, 239-258.

Dewar, R.C. and Cannell, M.G.R. (1992) Carbon Sequestration in the Trees, Products and Soils of Forest Plantations: an Analysis Using UK Examples. *Tree Physiology*, **11**, 49-71.

Fischlin, A. and Bugmann, H.K.M. (1994) Think Globally, Act Locally! A Small Country Case Study in Reducing Net CO_2 Emissions by Carbon Fixation Policies. In: Kanninen, M. (ed.) *Carbon balance of the world's forested ecosystems: towards a global assessment.* Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 256-266. Publications of the Academy of Finland: Helsinki.

Harmon, M.E., Ferrell, W.K. and Franklin, J.F. (1990) Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. *Science*, **247**, 699-701.

Heath, L.S. and Birdsey, R.A. (1993) Carbon Trends of Productive Temperature Forests of the Conterminous United States. *Water, Air, and Soil Pollution*, **70**, 279-293.

Lavers, G. (1983) *The strength properties of timber*. Building Research Establishment Report, third edition. HMSO: London.

Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J. (1993) *The Carbon Budget of the Canadian Forest Sector: Phase I.* Forestry Canada, Northwest Region, Northern Forestry Centre, Information Report NOR-X-326.

Marland, G. and Schlamadinger B. (1995) Biomass Fuels and Forest-Management Strategies: How Do We Calculate the Greenhouse Gas Emission Benefits? *Energy*, **20**, 1131-1140.

Matthews, G.A.R. (1993a) *The carbon content of trees*. Forestry Commission Technical Paper 4. Forestry Commission: Edinburgh.

Matthews, R.W. (1996) The influence of carbon budget methodology on assessments of the impacts of forest management on the carbon balance. In: Apps, M.J. and Price, D.T. (eds.) *Forest ecosystems, forest management and the global carbon cycle*. NATO ASI Series **I 40**, 233-243. Springer-Verlag: Berlin.

Matthews, R.W. (1993b) Towards a methodology for the evaluation of the carbon budget of forests. In Kanninen, M. (ed.) *Carbon balance of the world's forested ecosystems: towards a global assessment.* Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 105-114. Publications of the Academy of Finland: Helsinki.

Matthews, R.W. (1991a) Forests and arable energy crops in Britain: can they help stop global warming? In: Richards, K.E. (ed.) *Wood: Fuel for Thought.* Proceedings of the first international wood fuel conference, Bristol, 23-25 October 1991, 29-62. ETSU: Harwell.

Matthews, R.W. (1991b) Biomass production and carbon storage by British forests. In: Aldhous, J.R. (ed.) *Wood for energy: the implications for harvesting, utilisation and marketing.* Proceedings of a discussion meeting, Heriot-Watt University, Edinburgh, 5-7 April,1991, 162-177. Institute of Chartered Foresters: Edinburgh.

Milne, R., Brown, T.A.W. & Murray. T.D. (1998) The effect of geographical variation in planting rate on the uptake of carbon by new forests of Great Britain. Forestry, 71, 298 – 309.

Nabuurs, G.J. (1996) Significance of Wood Products in Forest Sector Carbon Balances. In: Apps, M.J. and Price, D.T. (eds.) *Forest ecosystems, forest management and the global carbon cycle*. NATO ASI Series **I 40**, 245-256. Springer-Verlag: Berlin.

Nabuurs, G.J. and Mohren, G.M.J. (1995) Modeling Analysis of Potential Carbon Sequestration in Selected Forest Types. *Canadian Journal of Forest Research*, **25,** 1157-1172

Nabuurs, G.J. and Mohren, G.M.J. (1993) *Carbon Fixation through Forestation Activities - A Study of the Carbon Sequestering Potential of Selected Forest Types, commissioned by the Foundation Face*. IBN Research Report, 93/4. Institute for Forestry and Nature Research (IBN-DLO): Wageningen.

Pingoud K., Savolainen, I., and Seppälä, H. (1996) Greenhouse Impact of the Finnish Forest Sector Including Forest Products and Waste Management. *Ambio*, **25**, 318-326.

Pingoud, K. Perälä, A. and Pussinen, A. (2000) Inventorying and modelling of carbon dynamics in wood products. In: Robertson, K.A. and Schlamadinger, B. (eds), *Bioenergy for Mitigation of CO_2 emissions: the power, transportation and industrial sectors.* Proceedings of the IEA Bioenergy Task 25 Workshop, Gatlinburg, 125-140. IEA: Graz.

Schlamadinger, B. and Marland, G. (1998) Substitution of Wood from Plantation Forestry for Wood from Deforestation: Modelling the Effects on Carbon Storage. In: Kohlmaier, G.H., Weber, M. and Houghton, R.A. (eds.), *Carbon Dioxide Mitigation in Forestry and Wood Industry*, 205-217. Springer-Verlag: Berlin.

Thompson, D.A. and Matthews, R.W. (1989) *The storage of carbon in trees and timber*. Research Information Note 160. Forestry Commission: Edinburgh