SECTION 3

Comparison of the CFLOW and CARBINE carbon accounting models

Evaluation of the C-FLOW and CARBINE carbon accounting models

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Summary

In the United Kingdom the Centre for Ecology and Hydrology (CEH) model C-FLOW (Dewar and Cannell, 1990, 1991, 1992) and the Forest Research (FR) model CARBINE (Thompson and Matthews 1989) have been applied extensively to the quantification of forest carbon stocks and potential stock changes across a range of scales from stand to national levels. The principal objectives of this study are an evaluation of the completeness and robustness of the C-FLOW 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 C-FLOW and CARBINE.

Both models use a very similar methodology to estimate total tree carbon stocks. It is difficult to assess which model estimates total forest carbon more accurately as very little information was provided on the scientific basis for the expansion factors to relate stem carbon to other forest components. C-FLOW explicitly includes litter in the model while in CARBINE it is not clear if, where or how litter is included. Each model includes a soil carbon sub-model but the methodology used to estimate soil carbon is quite different. In C-FLOW this is linked to the litter sub-model and soil carbon changes are linked to litter inputs and decay, while in CARBINE the soil sub-model is run completely independently and soil carbon change is based on land-use change.

The two models CARBINE and C-FLOW usually predict very similar results (within 12% of each other) in terms of carbon stocks in trees. The accuracy of predictions of carbon stocks in forest biomass produced by C-FLOW and CARBINE was first assessed by comparison with the independently-developed BSORT model. Both models were observed to make predictions that were systematically inconsistent with those of BSORT, although differences were less significant for conifer species than for broadleaf species. The accuracy of predictions of forest biomass carbon stocks made by C-FLOW and CARBINE was further assessed by comparison with results derived from site-specific permanent mensuration sample plot data. Although this analysis can only be regarded as an initial investigation, the results indicated that the accuracy of predictions made by both models is well within short-term fluctuations observed for individual stands (±10%). There may be further, significant issues of accuracy arising from the limited range of combinations of species, yield class and management regime covered by both models. Both tree species and yield class can be expected to have a significant influence on the timecourse of accumulation of forest biomass carbon stocks. Most significant of all is likely to be management regime. Variations in planting spacing over quite a narrow range, and/or variations in thinning regime can lead to significant differences in carbon stocks – with a range of up to ±25%. Yield models underpinning C-FLOW and CARBINE need to be reviewed to confirm that appropriate management regimes are represented. Relevant models should be fully implemented and readily available within C-FLOW and CARBINE.

No benchmark information was available for litter, soil and wood product carbon and so it was not possible to assess accuracy of predictions for these pools. It is recommended that this information be collated or collected as soon as possible to allow testing of model predictions for these components.

The CARBINE model requires both an overview document to generally describe the model and specifically describe the overall source code scope and structure, and more documentation inside the source code. Full documentation of all CARBINE sub-models and programming would facilitate further understanding and model transparency. The C-FLOW model has been published in international journals but a document to specifically describe the overall source code scope and structure, and more documentation inside the source code would facilitate transparency. The addition of parameter and area units would also greatly facilitate user friendliness.

The similarity of C-FLOW and CARBINE, in terms of objectives and structure, is striking. The possibility of combining the two models should be considered. Of greater importance, the potential for integrating each model or a unified version with other relevant models should be investigated, notably integration with BSORT, ASORT and RothC.

Introduction

In the United Kingdom the Centre for Ecology and Hydrology (CEH) model C-FLOW (Dewar and Cannell, 1990, 1991, 1992) and the Forest Research (FR) model CARBINE (Thompson and Matthews, 1989) have been applied extensively to the quantification of forest carbon stocks and potential stock changes across a range of scales from stand to national levels. The principal objectives of this study are an evaluation of:

- The completeness and robustness of the C-FLOW 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 C-FLOW and CARBINE.

Models such as C-FLOW and CARBINE have been described as 'book-keeping' models, and are typical of a general approach that has been adopted by international research groups and applied in different countries (Matthews and Robertson, 2003). The similarity of these models means that they share common strengths and weaknesses. As a consequence, cross-validation of C-FLOW and CARBINE is informative but is not a sufficient test of model completeness or robustness. A series of evaluations are conducted, consisting of consideration of model scope and overall structure (in terms of sub-models), including identification of objectives, and comparison of:

- Scope and potential applications of models in conjunction with general model structure;
- Evaluation and comparison of individual sub-models;
- Evaluation and comparison of accuracy of predictions;
- Evaluation of strengths and weaknesses in the implementation of the models.

As part of the comparison of predictions made by C-FLOW and CARBINE, reference to 'benchmark' estimates derived by alternative methods constitutes the strongest test of the two models.

Overview of model applications, scope and structure

Model applications

Before making an assessment of the structure, robustness and implementation of C-FLOW and CARBINE, it is worth considering more closely the intended objectives including the ways in which these two models are (or potentially might be) used, as well as the target user community.

Objectives

It is not immediately clear what specific objectives and applications are being addressed by the current versions of CARBINE and C-FLOW. Four possible applications or objectives can be identified for carbon accounting models:

- Stand-specific evaluation
- Generalised stand-level scenario analysis
- Estate-level evaluation
- Estate-level scenario analysis.

Stand-specific evaluation

A carbon accounting model might be used to assess the quantity of carbon stocks, or stock change over time, of an actual stand of trees. The most likely circumstance in which this would happen would involve a forest owner, manager or advisor needing to carry out an environmental impact assessment or evaluate actual or potential carbon sequestration for a specific forestry project. In order to apply C-FLOW or CARBINE in this way, the models would need to be able to accurately reflect observed growth rates and tree size-class structures for the stand or stands in question.

Generalised stand-level scenario analysis

Carbon accounting models are often used to provide answers to general questions about forest carbon dynamics. Examples of such general questions are:

- How much carbon is sequestered in an average stand of Sitka spruce in the UK?
- Which tree species are most effective at sequestering carbon in the UK?
- What impact does yield class, thinning or changing stand rotation have on carbon sequestration?

For this purpose, C-FLOW or CARBINE would need to be able to simulate carbon dynamics in 'average' or 'typical' stands in the UK of varying species, yield class and management regime.

Estate-level evaluation

Estimates of forest carbon stocks and stock changes are sometimes needed, upscaled for a collection of particular forest stands, either belonging to a forestry company or estate, or making up the forests of a district of the UK. Ultimately estimates of carbon stocks and stock changes are required for the complete UK forest estate. Such applications would require C-FLOW and CARBINE to be able to represent at least the main features of variation across stands in the UK in terms of site/soil type, species, growth rate and management. For some of this variation, application of C-FLOW or CARBINE across relevant forest areas based on average values may be sufficient. For example, if the yield class of stands of a particular tree species was found to vary significantly, then the models could be provided with the specific yield classes of individual stands as input data. On the other hand, it is possible that there may be no loss of accuracy if an estimate of the average yield class of stands was to be assumed to apply. The validity of such an assumption would depend on the linearity (or otherwise) of the relationship between output carbon-stock estimates and input yield class values. The form of this relationship could be determined by carrying out appropriate generalised stand-level scenario analyses as described earlier.

Estate-level scenario analysis

Carbon accounting models may also be used to project the impact on carbon stocks of introducing alternative management programmes or policies within a forest estate. To meet this objective, models such as C-FLOW and CARBINE would need to be able to represent a wide range of tree species, yield classes and management regimes as in generalised stand-level scenario analysis. The models would also need to encompass the variability in the forest estate of interest, probably more so than for estate-level evaluation, where the emphasis is on estimation of current carbon stocks and 'business as usual' forest management. This additional requirement arises because the management or policy interventions being considered may be explicitly concerned with potential impacts of reducing or increasing aspects of the variation observed in the forest estate.

It is unclear which of the above four objectives are regarded as the most important for addressing by application of C-FLOW or CARBINE. Historically, the two models have been applied to the greatest extent for generalised stand-level scenario analysis and estate-level evaluation. However, users of UK carbon accounting models will want to be able to analyse and evaluate emerging or proposed policies or management regimes aimed at addressing the forest carbon issue. In this context, it is suggested that the future development of C-FLOW or CARBINE should be carried out more explicitly with the aim of meeting user requirements.

Recommendation: Consider options for involving model users (current and potential) in setting the scope for development of C-FLOW and CARBINE.

User community

In this report, it is assumed that the main users are the model developers at CEH and FR, but others may benefit from access to the models, or may require a certain level of understanding of their construction and function in order to interpret results. In principle, the models could be used by a large group of scientists and commercial, NGO and government analysts and advisors. For example, the models could be used by such groups to inform development of policies and measures for the land use (and energy) sectors, or to quantify carbon credits from afforestation projects. However, for such uses there are issues concerning the accessibility of the models and their user-friendliness. The reader is referred to the section on model implementation later in this report. More generally, this report includes a number of recommendations aimed at improving the flexibility, accessibility, transparency and verifiability of the models and their outputs.

Model scope and structure

C-FLOW and CARBINE were developed independently but have very similar system boundaries and internal structures. Many of the features are also shared by carbon accounting models developed in other countries over the same period. Flow diagrams illustrating the structure and sequence of computations carried out in CARBINE and C-FLOW are shown in Figures 1 and 2 respectively.

CARBINE

The objective of the model is to estimate:

1) The carbon stocks of stands and forests (in living and dead biomass and soil), and any associated harvested wood products;

2) The greenhouse gas emissions avoided through the use of wood products that displace fossil fuels and fossil-fuel intensive materials. Arguably, this objective is

marginal to the main purpose of a forest carbon accounting models and to this evaluation.

The model is applicable at the stand, forest and national level. It uses as input data estimates of stand structure and growth obtained from yield tables that are applied at the stand level (Edwards and Christie, 1981). When stand-level carbon estimates are combined with area/age-class information, forest and national carbon stocks can be estimated. CARBINE can be used to estimate historical forest carbon stocks (if information on area is available), as well as current and future carbon stocks under different forest area and management scenarios. Using the same set of yield tables for all estimates assumes the same growth rates/patterns would be observed at any time: historic, current or future. This means that changes that might affect growth rate or form are excluded e.g. improvement of planting material or better site quality. Carbon stock changes are inferred from differences in carbon stock estimates at different times.

The model consists of four sub-models or 'compartments' which estimate carbon stocks in the forest, soil, and wood products and, additionally, the impact on the greenhouse gas balance of direct and indirect fossil fuel substitution attributable to the forestry system (Figure).

The model is able to represent all of the introduced and native plantation and naturally-occurring species relevant to the UK. The forest carbon sub-model is further compartmentalised to represent fractions due to tree stems, branches, foliage, and roots. The impact of different forest management regimes can only be assessed for the range of tree species, yield classes and management regimes represented in published yield tables (Edwards and Christie, 1981). However, at present not all of these are implemented in CARBINE.

Wood products are represented as long-lived and short-lived sawn timber, particleboard and paper. Carbon in harvested stemwood is allocated to these wood product categories using an assortment forecasting model that accounts for variation in product out-turn due to tree species and tree size class distribution at time of harvest (Rollinson and Gay, 1983). Wood products in primary use are assumed to decay over time with no account taken of carbon stocks in landfill or greenhouse gas emissions (due to wood products) from landfill. 'Inherited' emissions from wood products replaced are not considered.

The soil carbon sub-model runs independently of the forest sub-model. Initial soil carbon is estimated based on land use/cover and soil texture (sand, loam, clay and peat). The timecourse of any soil carbon stock change is assumed to follow an exponential form with the magnitude of the stock change and rate constant dependent on the soil type and on the particular land-use transformation imposed (e.g. arable agriculture to forest or grassland to forest). This information is based on published literature.

There is no explicit representation of a litter compartment or sub-model, and it is unclear if, where or how litter is included in the model.

C-FLOW

The objective of the model is to estimate the annual carbon stock change in a forest stand and its timber products. The cumulative sum of annual stock changes gives the stock change over time. Together with forest inventory information, the model can be used to estimate carbon stocks at the forest and national level. C-FLOW is currently used in developing the national estimates of UK forest carbon stocks for the annual greenhouse gas inventory. Results are presented in terms of annual carbon stock change. If an estimate of stock change over a rotation is required then this must be calculated as a cumulative sum of the annual stock changes predicted by the model. C-FLOW contains four sub-models or 'compartments' which are used to estimate carbon stocks in

the forest, litter/soil, and wood products. The forest carbon sub-model includes compartments representing stem, branches, foliage, roots and (unlike CARBINE) litter. The model covers a range of key plantation species relevant to the UK, including Sitka spruce, lodgepole pine, beech, oak and willow. Forest management regime options are limited, usually with only one 'standard' management regime for each species although, as with CARBINE, in principle a more complete range could be implemented.

The wood products sub-model consists of the representation of a single, generic wood product for the main stand (clear-fell) harvest. All harvested wood is allocated to this pool which is assumed to decay according to a generalised exponential timecourse, with the time constant set to cause all stocks to decay over a period equal to the stand rotation. Wood products from thinnings are assumed to be very short lived, decaying over a 5 year period. No account is taken of carbon stocks in landfill or greenhouse gas emissions from decomposition of products in landfill.

All sub-models of C-FLOW are linked and run dynamically (Figure). Litter is included explicitly in the model, with inputs being received from the forest sub-model throughout the rotation, at thinning and final harvest. The soil carbon sub-model is linked to the litter sub-model with half of the litter carbon assumed to enter the soil carbon pool.

Evaluation of sub-models

Forest carbon sub-model

Both CARBINE and C-FLOW rely on UK Forestry Commission yield tables to provide basic input data on stand growth and structure. Currently these models are limited to the representation of pure-species, even-aged stands. As a result, neither model can be used to evaluate mixed-species stands, and no account is taken of understorey species. Both models can be 'forced' to approximate uneven-aged or mixed tree stands by assuming a large number of even-aged patches of different species and varying age class.

Recommendation: The requirement for C-FLOW and CARBINE to represent a wider range of silvicultural options, including mixed-species, mixed-age stands, should be reviewed.

CARBINE

The forest carbon pools included in the sub-model are stem, branches, foliage, and roots. The model utilises pre-existing yield models developed for each species, yield class and management regime to estimate the development of merchantable stem volume at an annual time-step. Potentially, there are over 1000 different yield models available for different combinations of species, yield class and management regime. However, in general only one or two examples for each tree species are represented in CARBINE, although a comprehensive range of species relevant to the UK is covered (Table 1).

Yield Table (merchantable volume m³ha⁻¹)

TREES
- Total/merchantable ratio including stem, branches foliage & roots
- Wood density & carbon content (Cha⁻¹)
- Forest area and age class
- Total tree carbon stock

WOOD PRODUCTS
- Thinning and harvest volume
- Stand volume assortment forecast - sawn timber, roundwood & waste
- Product allocation - long-lived & short-lived sawn timber, particleboard & paper
- Wood density and carbon content
- Carbon retention curves
- Wood products carbon stock

MATERIALS SUBSTITUTION
- Wood product end use
- Emission savings factor
- Greenhouse gases avoided

SOIL (not fully integrated)
- Initial soil carbon, land use & soil type
- Land use change
- Final (asymptotic) soil carbon and time constant
- Soil carbon stock

Figure 1: Structure of CARBINE

Yield Table (merchantable volume m³ha⁻¹)

TREES

Forest area

Wood density & Carbon content (stem Cha⁻¹yr⁻¹)

Branch & root conversion factor (% stem C)

Foliage & fine root carbon (Cha⁻¹yr⁻¹)

Total tree annual carbon stock change (Cha⁻¹yr⁻¹)

WOOD PRODUCTS

Thinning & harvest volume (m³ha⁻¹yr⁻¹)

Wood density & Carbon content (stem Cha⁻¹yr⁻¹)

'Generic' or 'average' wood product

Product decay over rotation length

Wood products annual carbon stock change (Cha⁻¹yr⁻¹)

LITTER

Branch & root litter carbon (Cha⁻¹yr⁻¹) During rototation & at thinning & at harvest

Foliage & fine root litter carbon (Cha⁻¹yr⁻¹) During rotation & at thinning & at harvest

Unharvested stemwood carbon (Cha⁻¹yr⁻¹)

Decay - different rates for each component

Litter annual carbon stock change (Cha⁻¹yr⁻¹)

SOIL

Litter to soil (50%) (Cha⁻¹yr⁻¹)

Soil organic matter decomposition (Cha⁻¹yr⁻¹)

Soil annual carbon stock change (Cha⁻¹yr⁻¹)

Figure 2: Structure of C-FLOW

Table 1. List of species, yield class and management regimes represented in CARBINE

Species	Yield class	Planting spacing (m)	Thinning regime
Cedar, Western red	14	1.5	Standard
Fir, Douglas	16	1.7	Standard
Fir, grand	18	1.8	Standard
Hemlock, Western	14	1.5	Standard
Larch, Japanese	8	1.8	Standard
Pine, Corsican	14	2.0	Standard
Pine, lodgepole	8	2.0	Standard
Pine, Scots	8	2.0	Standard
Spruce, Sitka	12	2.0	Standard
Spruce, Sitka	12	2.0	No-thin
Spruce, Norway	10	2.0	Standard
Ash	4	1.5	Standard
Beech	6	1.2	Standard
Birch	4	1.5	Standard
Poplar	12	4.6	Solitary
Sycamore	4	1.5	Standard

Note: Other species are represented by applying the model for the nearest equivalent species in the table above

The choice of yield class represented for a given species takes into account typical site productivity and any genetic improvements due to breeding (notably for poplar). The yield models are based on an extensive permanent sample plot network maintained across the UK and are considered to be robust. However, a recent study has highlighted possible deficiencies in the predictions of volume development made by the models, particularly for the latter stages of a rotation typical in the UK at present (Matthews, 2003). The yield tables take stem mortality throughout the rotation into account, and predictions are given for live stem volumes, i.e. net of mortality. The fate of dead standing trees or litter from any mortality (trees, branches or foliage) is allocated to the 'waste' compartment in the wood products sub-model.

Volume estimates obtained from yield tables are multiplied by relevant forest areas to give merchantable stem volume for the entire area. It is assumed that the area provided is the net planted area. Volume is converted to total tree volume (including stem, branches, foliage and roots) using total/merchantable (T/M) ratios (commonly referred to as expansion factors) for each of the major species groups. These expansion factors are assumed to vary with stand top height. The variation of T/M ratio with top height is assumed to handle site- and age-dependent effects. The T/M ratios are derived from published biomass studies, but the studies were not designed explicitly to address carbon sequestration issues. Consequently there is some uncertainty as to the robustness of the conversion from stem to total tree volume.

Total tree volume is converted to carbon using published values of specific wood density (Lavers and Moore, 1983) and an assumed carbon content of 50% (Matthews,

1993). The same density is assumed for all woody tree components. The same carbon content is assumed for all woody components, based on the review of Matthews (1993). It is unclear whether field tests have confirmed this as a valid approach in the UK. Default carbon content values generally can be used, but they should be supported by a validated sample (IPCC 2000).

Forest areas and age-class distributions can be used by CARBINE to estimate total (estate-level) forest carbon. Results are presented as total forest carbon stocks and are not broken down into the individual pools of stem, branches, foliage and roots. To increase verifiability and transparency, the carbon stocks for each of the forest pools could be presented individually. For ease of comparison between carbon stocks for a range of forest management scenarios, results should be more readily available on a per-unit area basis. This would also enable the easy comparison with forest sequestration results reported in other studies.

CARBINE may be biased in terms of the forest management regimes represented. The standard thinning regime assumed for most species is based on recommended practice (Edwards and Christie, 1981). However, in reality actual forest management departs significantly from these recommendations due to economic constraints and/or requirements to meet varying objectives in different localities within the UK. For example, in certain regions of the UK, thinning operations are less frequent and, overall, involve removal of less volume than indicated by the "standard" thinning regime. In other parts of the UK, a policy shift encouraging so-called 'continuous cover forestry' is leading to stands being thinned much more heavily than would be suggested by the standard regime, sometimes effectively involving partial felling of stands. Variations in thinning regime will result in variations in forest carbon stocks for which predictions based on the assumption of standard management will be biased. This may not be a large source of bias in national carbon estimates, if the alternative management regimes vary both positively and negatively around the 'average'. On the other hand, CARBINE may not predict carbon stocks well for individual stands or even districts when forest management is different from the management options available in the model. More information may be required on current and potential future management practices to justify the use of the 'average' regime in all circumstances, or to inform modification of assumptions.

Recommendation: Conduct a review of national forest management practices.

Unmanaged or 'semi-natural' forest is poorly modelled as it is assumed to follow the same growth patterns as unthinned productive forest up to the maximum potential carbon stock.

C-FLOW

The C-FLOW model estimates annual carbon stock changes in even-aged, pure species forest stands. The model also allows an analysis to be made of the impact of future planting options on carbon stocks. The forest carbon pools included in the model are stem, branches, foliage, roots and litter. Like CARBINE, the model uses Forestry Commission yield models (Edwards and Christie, 1981) as input data to describe forest growth. Observations made in the discussion of CARBINE also apply to C-FLOW. At present a limited range of species and yield class combinations are implemented in C-FLOW, although in principle more could be added.

Stem volumes are converted to carbon using estimates for wood density and carbon content of dry matter. The model parameter for wood density defaults to standard values for conifer, broadleaf and coppice stands but this can be adjusted in the model if stand-specific information is available. Carbon in branch and root components is estimated as

percentages of stem volume. These percentages are effectively expansion factors for branch and root carbon, similar to the T/M ratio used in CARBINE. However, C-FLOW assumes that these percentages remain constant with stand age. These values taken by these percentages can be changed by the user. During the early part of the rotation until canopy closure, when stem volume may not be significant, the percentages of branch and root material may be underestimated, therefore underestimating the carbon stocks in these components. In a later model version (not available at the time of review) this assumption has been updated so that before age 20 a greater proportion is allocated to branches and woody roots.

In early versions of the model, non-woody biomass (foliage and fine roots) was not included. This has now been updated. Quantities of foliage and fine roots are assumed to increase exponentially up to 90% of their asymptotic value at canopy closure, which in turn is assumed to occur after one quarter of the rotation length as defined in standard yield models. No information has been provided on how these functions and underlying parameters have been derived.

Over the rotation, branch and root carbon is transferred to the litter pool at a constant rate. Half of the litter is assumed to enter the soil. Each litter component (branches/stemwood, foliage, and roots) then decays at a component-specific rate. The decay of litter and soil matter is assumed to depend only on tree species and in particular unaffected by other factors which vary with location such as rainfall and temperature.

Recommendation: Some climate and soil factors are known to affect decay rates, and this could be tested for significance in the UK.

Litter sub-model

CARBINE

As already observed it is unclear if, where and how litter is included in CARBINE. Potentially, litter could be accounted for in one of two places – either the forest or soil carbon pools. It is recommended that the litter pool is represented explicitly and information on where and how it is included in the model documented.

Recommendation: If the litter is not included in the current model, it is recommended that this be explicitly included in the model and linked to forest component mortality and management system.

C-FLOW

C-FLOW includes a compartment for the carbon stock of the litter pool. Throughout the rotation branches, roots and foliage are assumed to enter the litter pool at a constant rate. At harvest and thinning, further carbon input is received from all forest components. Each component is assumed to decay at a different rate. Default rates are provided and these can be varied by the user if site-specific information is available. The origin of the default, assumptions is not known. The model takes into account different litter decay rates for conifers and broadleaves but takes no account of other parameters that may affect litter decomposition rates such as latitude, temperature and rainfall.

Soil sub-model

CARBINE

CARBINE contains a very basic sub-model to estimate carbon stocks and stock changes in this pool. This sub-model runs completely independently of other sub-models. Initial soil carbon is estimated based on land use/cover and soil texture (sand, loam, clay and peat). Changes in soil carbon are assumed to take place in response to land-use change and the magnitude and timecourse are estimated according to soil type (texture) and major land use category. This information is based on RothC, a UK soil carbon model, and published literature (Coleman *et al.*, 1997).

C-FLOW

C-FLOW differentiates between litter and soil, with soil including both the humus and underlying mineral soil layers. The soil sub-model is explicitly linked to the litter sub-model in that it is assumed that half of the carbon in litter enters the soil carbon pool. Soil carbon is then assumed to decay by a constant percentage (3%) each year. The basis of this assumption is not known. After discussion with model developers it is understood that the model predicts annual carbon stock change, not total carbon stocks. Information on initial soil carbon stocks, for example, prior to afforestation is not included in the model. This would be a useful addition and allow the estimation of total soil carbon stocks.

Recommendation: Document (the basis for) all assumptions and default values.

Recommendation: Include facility to specify initial conditions for soil carbon stocks.

Wood products sub-model

Both models assume that any harvested wood products make a contribution that is additional to current consumption. In reality, it is likely that some products manufactured will merely replace other wood products, hence there may be less change in carbon stocks than is predicted by the models. How long the model continues to overestimate stocks will be affected by product service lives and the period over which the model is run.

CARBINE

At thinning and harvest, the CARBINE model allocates merchantable stem volume to various wood products, while the remainder is transferred to the waste pool. The 'end-use' wood products represented are:

- long-lived sawn timber
- short-lived sawn timber
- particleboard
- paper.

During wood processing, conversion losses are assumed and enter the waste stream and decay within a year. The amount of carbon allocated to the raw stemwood product, categories of each of the wood products is estimated by first inputting the merchantable stem carbon derived from the forest yield model to a stand volume assortment forecasting model which estimates the volume allocated to sawn timber, roundwood and waste. This is implemented in CARBINE as a set of functions derived from the output of a more general and flexible assortment forecasting program known as ASORT (Rollinson and Gay, 1983). There is no reason why the full ASORT program could not

be integrated into CARBINE as a subroutine, providing much greater flexibility. Having allocated some of the stem carbon to sawn timber, roundwood and waste, fractions of the first two categories are further allocated, in different proportions, to the four 'end-use' wood product categories specified above. The proportions differ depending on the species harvested. This information is based on expert opinion rather than data or scientific research. A carbon retention curve is used to estimate product decay and return of carbon to the atmosphere. Each wood product category has its own carbon retention curve based on estimated service lives, taking into account not just the decay rate of wood products but the service life as influenced by socio-economic factors. The functions are used to calculate the amount of carbon retained in wood products in successive years after harvest.

Recommendation: Integrate ASORT directly into CARBINE.

Recommendation: Provide documentation regarding the assumptions used to estimate service lives of products. Estimates could be improved by conducting surveys of producers and users. An alternative is to determine the relationship between harvested volume and products from previous annual statistics on harvest volume and products manufactured.

CARBINE does not include a compartment which represents the carbon dynamics of wood products disposed of to landfill. On the one hand this could simply be noted and accepted as falling outside the system boundary of CARBINE. On the other hand the potential contribution to carbon stocks and greenhouse gas emissions (during decay) by landfilled wood products can be significant and this needs to be accounted for somewhere. There may be questions about whether encouraging landfill is desirable, but data from some countries suggests wood products in landfills represent a significant carbon sink. Currently emissions are assumed to be in the form of CO_2 but when wood products are landfilled methane is emitted which has a higher global warming potential.

Recommendation: Develop understanding of carbon dynamics in landfill and develop capability to estimate landfill carbon stocks and greenhouse gas emissions, either as part of CARBINE or separately.

C-FLOW

C-FLOW includes a very basic sub-model for carbon stocks in wood products. At thinning, the stemwood transferred to wood products is assumed to be converted to paper/packaging with a mean service life of 5 years. This would appear to be a conservative assumption. At final harvest, stemwood (minus a negligible unharvested fraction) is assumed to be converted to unspecified wood products, represented in the model by additions of harvested wood to a generic or 'average' wood product. On average, the wood products are assumed to decay over the period of one rotation. There are several real or potential flaws with this approach:

- Not all harvested stemwood is converted into wood products as there are conversion losses during wood processing, and these can be quite substantial. Hence this method is likely to overestimate stocks in products at all levels.

- Using the rotation length as the default retention time does not take into account the very varied wood products and the wide range of retention times. Since it is unlikely that the products will have a lifetime equal to the rotation length (a significant fraction is likely to be allocated to short-lived products) this is also likely to result in an overestimate of product stocks.

- As with CARBINE, no account is taken of carbon stocks in landfill or greenhouse gas emissions (due to decomposition) from landfill.

Recommendation: Improve representation of wood product carbon allocation and representation.

Recommendation: Include sub-model for landfill wood carbon.

An issue common to both models is that forest location can affect the accessibility of markets (processing plants, exports), which in turn will affect both the silviculture and cutting patterns to meet local demands or to target market specifications. Allowing the user to change products and markets could enable more accurate results at the stand or individual forest level.

Recommendation: Include more flexible representation of wood product allocation procedures. (In part this could be achieved through integration with ASORT.)

Wood product substitution sub-model

Only the CARBINE model includes a wood products substitution sub-model. Wood products can contribute to greenhouse-gas emissions reductions in two ways, through:

- Direct substitution, in which wood is used as a direct source of energy (i.e. bioenergy) in place of fossil fuels.

- Indirect substitution, in which wood is used in place of more energy-intensive materials, with implied reductions in fossil fuel consumption.

Both types of substitution can be taken into account using CARBINE, although the details of how this is done have not been formally documented. Each wood product is assumed to have a characteristic potential (emissions savings factor) to displace alternative materials or fossil fuels, thus determining the magnitude of avoided emissions. This is calculated by assuming an end use for wood products. These assumptions are based on expert opinion rather than data or scientific research. Greenhouse gas emissions over the life cycle of the wood product are compared to the greenhouse gas emissions for the most likely alternative product (for example steel or concrete), allowing for the possibility that the service lives of wood and non-wood products may be different .

Recommendation: Update emission savings (indirect substitution) factors and ensure that the methodology for their calculation is fully documented.

Currently the emissions savings factor for wood waste to bioenergy is assumed to be zero. This sub-model of CARBINE was developed in the early 1990s. At this time there was very limited research globally on greenhouse gas emissions over the life cycle of a bioenergy system. The substitution sub-model of CARBINE has not been updated since it was first developed. There has been much research into these issues both in the UK and internationally since that time.

Recommendation: Update emission savings (direct substitution) factors and document/publish the methodology for their calculation. Fully implement this sub-model within the model.

Summary of sub-model comparison

From the flow diagrams in Figures 1 and 2 and the above discussion of the sub-models, it is apparent that both models use a very similar methodology to estimate total tree carbon stocks. It is difficult to assess which model estimates stand- or estate-level forest carbon more accurately as very little information was provided on the scientific basis for the expansion factors to relate stem to other forest components. C-FLOW explicitly includes litter in the model, while in CARBINE it is not clear if, where or how litter is

included. Each model includes a soil carbon sub-model but the methodology used to estimate soil carbon is quite different. In C-FLOW this is linked to the litter sub-model and soil carbon changes due to litter inputs and decay, while in CARBINE the soil sub-model is run completely independently and soil carbon change is based on land-use change. Both models estimate the carbon in wood products derived from UK forests, not necessarily the total carbon stock in all wood products in use. The methodology used in CARBINE is sound but the coefficients (e.g. proportions or lifetimes) used require documentation to improve transparency. The C-FLOW approach is more basic and is likely to be less precise. Neither model includes the carbon stock in wood products in landfills, or greenhouse gas emissions from them. CARBINE includes a wood product substitution sub-model and while this sub-model is not backed up by strong and documented underpinning data the basic underlying methodology is sound. C-FLOW does not include wood product substitution.

In conclusion, C-FLOW and CARBINE are well designed for predicting forest carbon stocks in even-aged, pure species, managed stands of production forest in the United Kingdom. The models capture the main forest carbon stocks, species and key forest management regimes relevant to the UK. The underlying data are robust in terms of forest yield models although both models would benefit from access to yield models capable of representing a wider range of management regimes with greater flexibility. Model transparency could be improved by updating the stem-to-total biomass expansion factors and presenting results separately for all tree components. Provided there is enough information on forest area broken down by species and management regime and, provided relevant forest management regimes are represented in the models, C-FLOW and CARBINE can be applied to estimating forest carbon stocks at the forest and national levels and also to generalised stand-level and estate-level scenario analysis. The models are less well suited to stand-specific evaluation.

Accuracy of model predictions

As part of this study considerable effort was made to identify and obtain independent datasets that could be used to check the predictions made by C-FLOW and CARBINE for each of the constituent carbon pools (trees, litter, soil, products). It proved impossible to identify any datasets for forestry systems represented by either model that were complete enough to permit the testing of predictions for litter, soil or wood products.

Recommendation: Studies should be carried out to obtain datasets sufficient for testing the accuracy of estimates of litter, soil and wood products carbon stocks made using C-FLOW and CARBINE.

Fortunately, it was possible to identify or produce datasets to assess the accuracy of estimates of carbon stocks in forest biomass produced by the two models. The details of these assessments are given below.

Accuracy of model predictions of forest biomass carbon - comparison with more detailed model

Forest Research has been developing a new model, known as BSORT, for forecasting the accumulation of forest biomass (Figure 3). BSORT can provide forecasts of forest biomass based on any Forestry Commission yield model for all tree components of interest, and these can be converted to equivalent estimates of carbon provided a carbon content can be assigned for each component. Critically for the purposes of this study, the allometric relationships used in BSORT to estimate the biomass of non-stem tree

components are based on a statistical analysis of tree biomass data and have been developed independently of C-FLOW and CARBINE (Taylor, 2001).

Figure 3: Screenshot of the BSORT model showing an example of model inputs and predictions

At present, BSORT is still at the prototype stage and is known to contain some minor bugs. Nevertheless the model is now sufficiently developed for predictions to be compared with those of C-FLOW and CARBINE. Figure 4 shows comparisons of forecasts of carbon in forest biomass with respect to stand age as generated by the three models. In order to convert biomass estimates produced by BSORT into equivalent carbon stocks, a carbon content of 0.5 was assumed for all woody components, with 0.45 being applied to foliage. The particular species, yield class and management combinations included in Figure 4 were selected from among those which are represented in both C-FLOW and CARBINE and more details are given in Table 2. The yield classes were selected as being average or typical for each tree species.

Table 2. Details of tree species, yield class and management regime combinations used for comparison of C-FLOW, CARBINE and BSORT results

Species	Yield class	Planting spacing (m)	Thinning regime
Sitka spruce	12	2.0	Standard
Scots pine	8	2.0	Standard
Beech	6	1.2	Standard
Sycamore	4	1.5	Standard

Figure 4: Comparison of predictions of carbon stocks in forest biomass made by C-FLOW, CARBINE and BSORT for four example combinations of tree species, yield class and management regime (see Table 2).

In the two examples of results for conifers in Figure 4, CARBINE is observed to predict carbon stocks that are consistent with estimates made by BSORT at young stand ages, while C-FLOW predictions are observed to be lower. As already noted, the BSORT estimates are based on recent statistical analyses of the best and most extensive dataset on tree biomass currently available in the UK. Assuming, therefore that high

confidence should be attached to the BSORT estimates, the better agreement at young stand ages of predictions made by CARBINE and the underestimation made by C-FLOW is likely to be a reflection of differences in the T/M ratios applied in these models to derive total carbon from stem carbon. As noted earlier, C-FLOW assumes a T/M ratio that, while varying with tree species, is constant with respect to yield class and stand age. By contrast, assumptions in the CARBINE model attempt to take some account of dependence on these factors by relating T/M ratio to stand top height. At later stand ages, predictions made by CARBINE are observed to approach those made by C-FLOW, and both models are observed to underestimate carbon stocks compared to BSORT. The underestimation is only about 10% but is consistently observed. It is not known whether this pattern is observed consistently for all conifer tree species and further comparisons should be made of predictions made by C-FLOW, CARBINE and BSORT to clarify this.

Based on the examples in Figure 4, the position with regard to broadleaf tree species is less easy to interpret. For beech, a systematic underestimation is observed for both models. This is most serious at young stand ages where estimates of carbon stocks made by C-FLOW and CARBINE are up to 60% lower than estimates produced by BSORT. For older stand ages the magnitude of the underestimation drops to 20% for C-FLOW and 25% for CARBINE. For sycamore, both CARBINE and C-FLOW are in agreement with BSORT around stand age 15 years, but predictions made by CARBINE diverge significantly by age 20. Over most of the rotation, CARBINE underestimates carbon stocks relative to BSORT by between 15% and 30%. On the other hand, predictions made by C-FLOW are close to those of BSORT up to about age 30 years but beyond this point C-FLOW predicts progressively higher carbon stocks than suggested by BSORT – up to 15% higher by age 40.

Also evident in Figure 4 is the very different timecourse for accumulation of carbon stocks in biomass predicted by C-FLOW and CARBINE over the first ten to fifteen years. The more rapid accumulation predicted by C-FLOW is due to linear interpolation for stem volume between the time of planting and first thinning. Interpolation was required because the yield tables do not provide information for this period. The method of interpolation has been improved in a later version of C-FLOW by using a pattern that begins with an exponential before following a linear rise in stem volume that merges with the data after thinning from the yield tables.

The comparisons presented in Figure 4 have raised a number of questions about the accuracy of both C-FLOW and CARBINE but the analysis depends crucially on the assumed validity of estimates produced using BSORT. It is suggested that these matters should be regarded as of high importance and require further and more thorough investigation.

Recommendation: Forest Research and CEH researchers should review the allometric relationships and methodology of the BSORT model to confirm that high confidence should be attached to predictions.

> Recommendation: Further comparisons should be made between the predictions of C-FLOW, CARBINE and BSORT for a range of tree species, yield classes and management regimes. Any systematic discrepancies in predictions should be investigated and reconciled appropriately.

Accuracy of model predictions of forest biomass carbon- comparison with measurement based estimates

In order to further assess the accuracy of estimates of carbon stocks in forest biomass made by C-FLOW and CARBINE, data would be useful on the extent to which carbon stocks in individual stands may vary from the expected (average) values predicted by

the models for a particular combination of species, yield class and management regime. An exhaustive statistical analysis based on very large datasets was beyond the scope of this study. However, carbon stock estimates were derived for a limited selection of Forest Research permanent mensuration sample plots using a methodology developed for this study and employing newly-developed allometric relationships for the biomass of non-stem components of different tree species as illustrated in Figure 5 (Taylor, 2001). The list of sample plots used for the investigation of model accuracy in this way is presented in Table 3 and their locations are shown in Figure 6.

Figure 5: Schematic illustration of methodology used to derive periodic estimates of carbon stocks in forest biomass in Forest Research permanent mensuration sample plots.

Table 3. Description of 'benchmark' permanent sample plots used for comparison against predictions of carbon in forest biomass produced using C-FLOW and CARBINE

Sample plot number	Location	Species	Yield class	Thinning regime
1265	Dodd wood	Sitka spruce	12	Standard
3071	Curr Wood	Scots pine	8	Standard
1228	Colesbourne	Beech	6	Standard
1260	Bishop's Wood	Sycamore	5	Crown

These four sample plots were selected as 'benchmarks' in that they could be taken as representative of the growth patterns observed in the UK for the tree species, given average or typical yield class and standard management practice as specified in Edwards and Christie (1981). In Figure 7, periodic estimates of forest biomass carbon stocks for each sample plot are shown plotted as trajectories with respect to stand age. Superimposed are the equivalent predictions made by C-FLOW and CARBINE.

Figure 6: Locations within the UK of the four sample plots used as 'benchmarks' for comparison against predictions made using C-FLOW and CARBINE.

Unsurprisingly, short-term fluctuations are apparent in the trajectories for carbon stocks estimated from sample plots. These fluctuations appear to have a maximum magnitude of approximately ±10%. In general, the trajectories and the predictions made by C-FLOW and CARBINE are remarkably consistent. An unexpected outcome is that, for each species, the sample plot trajectory is observed to form a pattern relative to the C-FLOW/CARBINE predictions that is qualitatively identical to that observed for the comparison with BSORT in Figure 4.

The results presented in Figures 4 and 7 indicate that, while there may be some issues to address with regard to bias in predictions of forest biomass carbon stocks made by both C-FLOW and CARBINE, potentially such model predictions are reasonably accurate, within the range of short-term fluctuations observed in periodic assessments for individual stands.

Recommendation: Further analyses such as presented in Figures 4 and 7 should be carried out to confirm conclusions about accuracy of predictions made by C-FLOW and CARBINE.

Figure 7: Comparison of periodic estimates of carbon stocks in forest biomass as assessed for four 'benchmark' sample plots (Table 3, Figure 5) against predictions made by C-FLOW and CARBINE. The trajectories shown in each sub-figure were constructed by joining successive estimates for carbon stocks in standing trees after removal of thinnings. (□ - mass removed by thinning)

It is important to recall that the BSORT estimates in Figure 4 and sample plot trajectories in Figure 7 were selected to be a fair test of predictions made by C-FLOW and CARBINE. For this purpose, combinations of tree species, yield class and

management regime were carefully selected from within the range of options provided by the two models. There may be further, significant issues of accuracy arising from the limited range of these combinations offered by both models. Both tree species and yield class can be expected to have a significant influence on the timecourse of accumulation of forest biomass carbon stocks. Most significant of all is likely to be management regime, as illustrated by the examples in Figure 8. Here, trajectories for the accumulation of carbon stocks are plotted based on series of permanent mensuration sample plots, all established at the same site but managed according to different regimes. Examples are shown for two series of sample plots, one managed according to a no-thin regime but with variable planting spacing while in the other series, both planting spacing and thinning regime was varied (Table 4). A map showing the location of these two series of plots is presented in Figure 9.

Table 4. Description of species, yield class and management regime combinations in series of permanent mensuration sample plots at Flaxdale and Rheola.

Sample plot number	Location	Species	Yield class	Planting spacing (m)	Thinning regime
1351	Flaxdale	Sitka spruce	20	1.5	No-thin
1352	Flaxdale	Sitka spruce	20	1.8	No-thin
1353	Flaxdale	Sitka spruce	20	2.1	No-thin
1354	Flaxdale	Sitka spruce	20	2.4	No-thin
2174	Rheola	Sitka spruce	16	0.9	No-thin
2175	Rheola	Sitka spruce	16	1.2	Light
2176	Rheola	Sitka spruce	16	1.8	Standard
2177	Rheola	Sitka spruce	16	2.4	Heavy

From Figure 8 it is evident that variations in planting spacing over quite a narrow range, and/or variations in thinning regime can lead to significant differences in carbon stocks – with a range of up to ±25%. The extent to which C-FLOW or CARBINE need to express this potential variation depends on the level of spatial resolution down to which the models are expected to make accurate and precise predictions. These results emphasise that, currently, neither C-FLOW nor CARBINE are suitable for evaluating carbon dynamics in individual stands of trees. More importantly, when these models are applied to the estimation of carbon stocks in estates, districts or at the national level, it is essential that the management regimes assumed are representative of actual practice.

The results in Figure 8 for the series of unthinned sample plots at Rheola also highlight another issue concerned with the capacity of C-FLOW and CARBINE to represent carbon dynamics in forest biomass. Although not part of the original experimental treatment, the results for the no-thin plot in the Rheola series show very clearly the potential impact of natural disturbance events. In the UK, disease, pest infestation, fire and windthrow are all potentially significant in their impacts on forest stand dynamics and resultant carbon stocks. The current versions of C-FLOW and CARBINE do not aim to represent such processes.

Figure 8: Comparison of periodic estimates of carbon stocks in forest biomass as assessed in two series of permanent mensuration sample plots managed according to varying regimes (Table 4). The trajectories shown were constructed by joining successive estimates for carbon stocks in standing trees after removal of thinnings and/or mortality. Note that at age 56 the Rheola experiment was subjected to a serious incident of windthrow, the impact being most obvious for the no-thin plot. (■ - mass removed by thinning)

Recommendation: The yield models underpinning C-FLOW and CARBINE should be reviewed to confirm that appropriate management regimes, representative of current and possible future practice in the UK, are included. Relevant models should be fully implemented and readily available within C-FLOW and CARBINE.

Recommendation: A review should be carried out and a decision taken on what, if any processes of stand disturbance should be represented in C-FLOW and CARBINE. Implementation of relevant sub-models should be carried out as required by the findings of this review.

Figure 9: Locations within the UK of the two sample plot series used to illustrate the potential impacts of management regime on carbon stocks in forest biomass.

Sensitivity analysis

Sensitivity analysis was performed on C-FLOW parameters of beech to ascertain which parameters the model was most sensitive to. Each of the parameters were varied by +/- 10%. Table 5 gives an overview of which parameters were tested for sensitivity and shows the parameter variation. Sensitivity analysis enables the identification of parameters where improvements are required in order to obtain more reliable model estimates.

Table 5: C- FLOW sensitivity analysis

Parameter	Default	+10 %	-10 %
Branch harvest fraction	0.18	0.198	0.162
Root harvest fraction	0.16	0.176	0.144
Asymptotic foliage mass (Mg/ha)	1.8	1.98	1.62
Asymptotic fine root mass (Mg/ha)	2.7	2.97	2.43
Wood decomposition	0.40	0.44	0.36
Foliage decomposition	3	3.3	2.7
Root decomposition	1.5	1.65	1.35
SOM decomposition	0.03	0.033	0.027
Asymptotic foliage litter (Mg/ha/yr)	2	2.2	1.8
Asymptotic fine root litter (Mg/ha/yr)	2.7	2.97	2.43
Transfer litter to soil (%)	0.5	0.55	0.45

Figure 10 shows the parameters that the model is most sensitive to at end of a rotation are the amount of litter entering the soil and the rate at which soil organic matter decomposes. Parameters from Table 5 not shown in Figure 10 yielded results that differ from the default by less than 1 tC/ha and are considered insignificant at this stage.

Figure 10: C-FLOW total carbon sensitivity analysis (includes: trees, litter, soil and wood products)

Sensitivity analysis could not be performed on parameters in CARBINE as the FORTRAN code could not be readily adapted for such an exercise.

Model implementation

In the following discussion, the presumption is made that model implementation should be driven by certain key criteria, notably:

- Intended applications of the model and the implicit need for flexibility.
- Requirements for portability and model re-use.
- Intellectual property rights and copyright protection requirements of the developers.

In this context, much of the following discussion considers options for model implementation as determined by the needs to provide practical solutions to a user community, in other words model distribution.

In the absence of any copyright protection requirements and specific end-user requirements, the choice will always be to distribute as pure source code (or simply as documentation describing the model and functions). The advantages/disadvantages of this type of distribution is discussed in more detail below, but the main aim is to provide

the model in the most flexible and future-proof way possible (with the least amount of additional work for the distributor) and leave the rest up to the end-users.

If the models/libraries/functions need to be protected in any way, the available choices are distribution as complete stand-alone programs, plug-ins or compiled function libraries. The main aim remains the same as for distribution as source code, with compiled function libraries the preferred choice in the absence of any other briefs.

Specific issues related to the service that needs to be delivered (i.e. an 'instant' solution for end-users with low computer skills) will dictate the type of delivery, and will most likely favour stand-alone programs or plug-ins, which are very easy to use but require much more effort on the part of the distributor.

If the distributor does not have access to software development resources, it is best to avoid complete stand-alone programs or plug-ins, since the development of an easy-to-use and flexible application/interface for a wide variety of end-users is a large task and best left to professional software developers. There are a few key considerations to keep in mind when distributing as function libraries or pure source code, which are discussed in more detail in a later section.

A short list of the advantages/disadvantages of all the types of distribution is presented to assist in making the appropriate choice for the type of distribution. The list is only a short summary addressing the obvious issues including copyright protection, platform dependencies (portability), ease-of-use (and flexibility) and future-proof distribution.

Distribution options

Mathematical models /libraries/functions can be distributed as:

- Complete stand-alone programs

- Plug-in formats (i.e. ActiveX)

- Function libraries (i.e. DLLs)

- Source code

- Documentation only.

As noted above, the type of distribution will depend on the intended audience (and their level of computer skills) and special considerations including ease-of-use, future-proofing and copyright protection.

Distributing as complete stand-alone programs

Advantages:

- Easy to use – depends on the ease-of-use of the program (and installation).

- Future-proof – since a later version of the models/libraries/functions is simply wrapped up completely in a new version of the program, there are few synchronisation issues.

- Copyright protected – the program can control how the model is used – for instance, the user interface may restrict the user to single input/output runs which will make it very hard to generate a 'surface' of values spanning the model (which in turn can be used in any derived programs the user may want to create). All the detail of the model is hidden from the user.

Disadvantages:

- Major development task – the program needs to be created (and tested), which may also include creating stand-alone libraries that the program can link to at runtime.

- Some audiences (i.e. scientific community) may find the interface too restrictive. It is not necessarily possible to use the model inside a larger context i.e. where the inputs are automatically generated and output automatically graphed.

- Platform dependent – the application is normally developed for a specific platform (i.e. Windows/Unix etc), and depending on the complexity of the user-interface can be difficult to transfer to other platforms.

Distributing as plug-in formats

Advantages:

- Same as for stand-alone programs, but slightly more difficult to use (user has to have access to and knowledge of tools to implement plug-ins). The standard distribution can include implementations of the plug-in as working examples of how to use/implement the plug-ins.

- More flexible than a stand-alone program – the plug-in can be used in plug-in enabled hosts i.e. a web browser or spreadsheet.

- More platform independent: It is easier to have plug-ins that function in specific hosts (i.e. a web browser) running on different platforms.

Disadvantages:

- Bigger task than stand-alone programs – normally the same considerations as for stand-alone programs would apply to plug-ins, but additional work is needed to make the plug-in behave well in the intended host programs/platform.

- Some audiences (i.e. scientific community) may still find this implementation too restrictive.

Distributing as function libraries

Advantages:

- Very flexible – depending on the quality of the library interfaces (and the associated documentation), the end user can apply the libraries in a variety of ways, i.e. build into stand-alone programs, use from within a spreadsheet etc.

- Independent updates – since any program developed by the end-user functions independently of the libraries, it is possible to release new libraries with updated functions that will still work with the old programs (if the interfaces are not changed). This is the maximum flexibility that can be reasonably expected while still retaining a reasonable amount of copy-protection.

Disadvantages:

- Requires a thorough investigation into the best (and most future-proof) interfaces for all the functions – since end-user programs will be invalidated if these change in the future, the developer is restricted by the design once released (unless a very good reason exists to change it).

- No control over end use – the end user can use the functions in any way that the interface allows, including using reverse engineering techniques (i.e. applying heuristics/neural nets on generated 'surfaces' of values) to develop similar

functions. The library can also be included in distributed stand-alone programs (although this could be controlled through a license agreement).

Distributing as source code

Advantages:

- Very little work – porting mathematical functions/models into source code is not a significant task.

- Maximum flexibility – given a compiler for the source code language, a developer can build any type of 'wrapper' application utilising the functions, or translate into another language of their choice.

- Easily updated – new updates can simply be distributed, placing the responsibility of updating existing applications back on the end-user.

- Completely platform independent.

Disadvantages:

- No copyright protection – even with license agreements it is still very hard to control where/how the source will be used once distributed.

- End user programming skills required.

Distributing as documentation only

Advantages:

- Easy to understand – a document describing a model can be read/understood by anyone with knowledge in the specific area.

Disadvantages:

- End user has to build everything from the ground up, and there is likely to be duplicated effort.

Considerations for distribution as function libraries or as source code

These two methods of distribution are not mutually exclusive, since the source code for libraries can be released with the compiled libraries. If the source code is provided (on its own or with the libraries), the stipulation can simply be that it is provided 'as is' and that the end-user can make any changes to fit their requirements (alleviating the need for the distributor to consider the following points in any detail). In order to provide flexible and future-proof models, there are a few key considerations to keep in mind:

- Pure functions with function wrappers – it is very easy to make the mistake of tying in a specific implementation for a calculation sequence, and thereby severely limiting its use (without changing the source code). For example, a library function may require that the function inputs are typed in (through dialog boxes), loaded from file (with a prescribed format) or extracted from a spreadsheet before proceeding with the calculations. This limits the function to a specific kind of use. The better solution is to write pure functions that take pointers to memory structures/streams as inputs (and provides the outputs in the same fashion), and then complement this function with wrappers (preferably in a different library) that load inputs from a variety of sources and interfaces with the pure function to complete the calculations. The end-user can then choose to use the wrapper of their choice, or simply interface straight to the function library.

- Interfaces - the interfaces to all the pure functions warrant very careful consideration. It is good practice to build in some redundancy into the interface to allow for functional changes in the future without invalidating the function calls from any applications that rely on the format of the interface. For example, a function may take a pointer to a structure that describes a number of function inputs, which is normally strictly typed (to allow the function to extract the inputs). If the first part of the input structure has a built-in version code, it is very easy in the future to partially/completely change the type and number of inputs without invalidating any of the older applications that make the function calls with the older format. If the previous consideration has been implemented too (pure functions with function wrappers), the function wrappers can be modified to access the pure functions in the new format, which will allow old end-user applications to seamlessly implement the new functions by simply installing the new version of the libraries.

- Thorough documentation – source code with poor documentation is in most cases less useful than good documentation on its own. Document libraries/source code (in line documentation) thoroughly – it makes it easier for both the distributor and the end-user in the long run.

- Platforms – if the source code is not distributed, the intended end-user platforms have to be considered. Compiled libraries are very platform dependent (i.e. DLLs will only work in a Windows environment) and although Windows is currently a safe choice, this may not be appropriate for models which will mainly be used in a research environment (where Unix is still common).

- Source code language – if the source code is distributed, some consideration to the language is appropriate (although the end user has the option of translating it). C++/Object Pascal are two good choices since most developers are familiar with it, and both languages allow access to optimising techniques. If speed is a consideration, C++ is appropriate where calculation speed is critical.

Comments on distribution of C-FLOW model

Since the source code is distributed with the model, the 'as-is' stipulation can still apply, which in effect invalidates any further considerations. However, the following comments can be made:

- The source code language is appropriate.

- The end-user is superficially tied to the Windows platform (as far as the immediate library and examples go), but Unix users can quite easily port the model (if required).

- Documentation is poor – the model requires both an overview document to generally describe the model and specifically describe the overall source code structure and intent, and more documentation inside the source code (again, both at a general level which is normally at the top of the source code files, and in-line where appropriate). Even modest documentation can be very useful to reduce development time.

- Interfaces are poor – the functions rely too much on specific forms of input/output (see first two points in discussion of considerations above), and thereby restrict their use. This also impacts on how future-proof the model will be, since the requirement of fixed format input files (which can sometimes not be avoided) would reduce the amount of options available in the future. However, since the source code is available, the end-user can re-design this.

Generally any compiled library will be hard to use because of the lack of documentation and clearly defined interfaces. The fact that the source code is available makes it possible to get around these limitations, and this can be considered to be a satisfactory outcome and that the compiled library is simply one example of usage (and is not intended in its specific implementation for static/dynamic linking to end-user applications).

Comments on distribution of CARBINE model

Since the source code is distributed with the model, the 'as-is' stipulation can still apply, which in effect invalidates any further considerations. However, the following comments can be made:

- The source code language is dated. FORTRAN 77 compilers are not very common, and although the language is easy to follow (and therefore convert), it is unlikely that most developers will use the source as is, especially if the code needs to be included in a Windows interface.

- Documentation is poor – the model requires both an overview document to generally describe the model and specifically describe the overall source code structure and intent, and more documentation inside the source code (again, both at a general level which is normally at the top of the source code files, and in-line where appropriate). Even modest documentation can be very useful to reduce development time.

Generally any library based on CARBINE compiled source code will be hard to use because of the lack of documentation and clearly defined interfaces. The fact that the source code is available makes it possible to get around these limitations, and this can be considered to be a satisfactory outcome. As a stand-alone program, carb1.exe may be sufficient for some users, but it is more likely that any extensive use of the model will require translation to another language (including splitting out the actual functions to a library).

Conclusions and recommendations

Both CARBINE and C-FLOW aim to estimate the carbon stocks of stands and forests (in live and dead biomass and soil), and their associated wood products. Both models provide carbon estimates based on input data from yield tables that are applied at the stand level. When stand level carbon estimates are combined with area/age class information, forest and national carbon stocks can be estimated.

CARBINE covers all of the plantation species relevant to the UK. The forest carbon pools included in the model are stem, branches, foliage, roots and litter. The impact of different forest management regimes can be assessed for a limited range of the current regimes practised in the UK. It is unclear if litter is included in CARBINE and it is recommended that this be explicitly included in future and linked to forest mortality. Soil carbon is included in the model as a completely separate sub-model, it is recommended that it should be linked to the litter sub-model. CARBINE assumes the same carbon content for all forest pools for a given species. Results are presented as total forest carbon stocks and are not broken down into the various forest pools of stem, branches, foliage roots and soil. To increase verifiability and transparency, it is suggested that carbon stocks for each of the forest pools be presented individually. Wood products are also included in CARBINE. However, the assumptions behind wood product carbon stock predictions, particularly service life, need to be tested and

possibly updated. Includes a sub-model for estimating potential reductions in greenhouse gas emissions through substituting wood directly or indirectly for fossil fuels but this is not documented. Full documentation of CARBINE is recommended.

C-FLOW covers a range of plantation species relevant to the UK, although not for all relevant species. The forest carbon pools included in the model are stem, branches, foliage, roots, litter and soil, and results are broken down into tree, litter and soil carbon. C-FLOW takes into account different litter decay rates for conifers and broadleaves but takes no account of other climate and soil factors that may affect litter decomposition rates and these could be tested for significance in the UK. It has been assumed that harvest occurs at maximum mean annual increment. Some climate and soil factors are known to affect decay rates, and this could be tested for significance in the UK.

Neither model covers the full range of potential forest management regimes although CARBINE has more forest management options than C-FLOW. More information may be required on current and potential future management practices to justify the use of the 'average' regime in all circumstances. It is recommended that a national survey of forest management practices is conducted.

No benchmark information was available for litter, soil and wood product carbon. It is recommended that this information be collated or collected as soon as possible to allow testing of model predictions for these components.

Each of the models was tested to see how well they predict carbon stocks in tree biomass, in terms of accuracy. Information on actual tree carbon stocks were available for a range of tree species and management regimes. However for all species except sitka spruce the benchmark data was from only one site within the UK. It is recommended that both models be further tested using data from a range of site across the UK.

Accuracy was first tested by comparison of predictions made by C-FLOW and CARBINE with those produced by the newly-developed BSORT model. For two examples of conifer stands, CARBINE was observed to predict carbon stocks that are consistent with estimates made by BSORT at young stand ages, while C-FLOW predictions were observed to be lower. The better agreement at young stand ages of predictions made by CARBINE and the underestimation made by C-FLOW is likely to be a reflection of differences in the T/M ratios applied in these models to derive total carbon from stem carbon. At older stand ages, predictions made by CARBINE were observed to approach those made by C-FLOW, and both models were observed to underestimate carbon stocks as compared to BSORT. The underestimation was only about 10% but is consistently observed. It is not known whether this pattern is observed consistently for all conifer tree species and further comparisons should be made of predictions made by C-FLOW, CARBINE and BSORT to clarify this. For a comparison based on a model stand of beech, a systematic underestimation was observed for both CARBINE and C-FLOW relative to BSORT. This was most serious at young stand ages where estimates of carbon stocks made by C-FLOW and CARBINE were up to 60% lower than estimates produced by BSORT. At later stand ages the magnitude of the underestimation drops to 20% for C-FLOW and 25% for CARBINE. In a comparison based on a model stand of sycamore, both CARBINE and C-FLOW were in agreement with BSORT around stand age 15 years, but predictions made by both CARBINE and C-FLOW diverged from those of BSORT at older stand ages. Over most of the rotation, CARBINE underestimated carbon stocks relative to BSORT by between 15% and 30%. On the other hand, predictions made by C-FLOW were close to those of BSORT up to about age 30 years but beyond this point C-FLOW predicted progressively higher carbon stocks than suggest by BSORT – up to 15% higher by age 40.

These tests raised a number of questions about the accuracy of both C-FLOW and CARBINE but the analysis depends crucially on the assumed validity of estimates produced using BSORT. It is suggested that these matters should be regarded as of high importance and require further and more thorough investigation. Specifically, the allometric relationships and methodology of the BSORT model should be reviewed to confirm that high confidence should be attached to predictions. In addition, further comparisons should be made between the predictions of C-FLOW, CARBINE and BSORT for a range of tree species, yield classes and management regimes. Any systematic discrepancies in predictions should be investigated and reconciled appropriately.

In order to further assess the accuracy of estimates of carbon stocks in forest biomass made by CFLOW and CARBINE, an investigation was made of the extent to which carbon stocks in individual stands (as observed in records for permanent mensuration sample plots) vary from the expected (average) values predicted by the models. Comparisons were made based on four sample plots selected as 'benchmarks' that could be taken as representative of the growth patterns observed in the UK for the tree species. Short-term fluctuations are apparent in the trajectories for carbon stocks estimated from sample plots. These fluctuations appear to have a maximum magnitude of approximately ±10%. In general, the trajectories and the predictions made by C-FLOW and CARBINE were remarkably consistent and within the range of short-term fluctuations observed in periodic assessments for individual stands, suggesting good accuracy. However, further analyses should be carried out to confirm these conclusions.

There may be further, significant issues of accuracy arising from the limited range of combinations of species, yield class and management regime offered by both models. Both tree species and yield class can be expected to have a significant influence on the timecourse of accumulation of forest biomass carbon stocks. Most significant of all is likely to be management regime. Variations in planting spacing over quite a narrow range, and/or variations in thinning regime can lead to significant differences in carbon stocks – with a range of up to ±25%. The extent to which C-FLOW or CARBINE need to express this potential variation depends on the level of spatial resolution down to which the models are expected to make accurate and precise predictions. These results emphasise that, currently, neither C-FLOW or CARBINE are suitable for evaluating carbon dynamics in individual stands of trees. More importantly, when these models are applied to estimation of carbon stocks in estates, districts or at the national level, it is essential that the management regimes assumed are representative of actual practice. It is recommended that the yield models underpinning C-FLOW and CARBINE should be reviewed to confirm that appropriate management regimes, representative of current and possible future practice in the UK, are included. Relevant models should be fully implemented and readily available within C-FLOW and CARBINE.

Currently CARBINE is implemented in FORTRAN that is an older, seldom used programming language. It is recommended that CARBINE be made available in a more widely used programming language. The model requires both an overview document to describe the model and specifically describe the overall source code structure and intent, and more documentation inside the source code. Full documentation of all CARBINE sub-models and programming would facilitate further understanding and model transparency.

C-FLOW is available as a Microsoft Excel program that superficially ties the user to the Windows platform. The source code language is appropriate. The model requires a document to specifically describe the overall source code structure and intent, and more documentation inside the source code. The model relies on specific forms of input/output, and thereby restricts the end use. This also impacts on how future-proof

the model will be, since the requirement of fixed format input files would reduce the options available in the future.

It should be noted that peer reviewed published information on models is often a major consideration in international acceptability. Full documentation of both models or of any descendants would greatly facilitate transparency and verifiability.

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