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ORIGINAL PAPER

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Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland

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Abstract The assessment of a forest resource in national inventories provides a firm basis for the calculation of biomass and carbon (C) stocks of forests. Biomass expansion factors (BEFs) and conversion factors provide a robust and simple method of converting from forest tree stem volume to total forest biomass. These factors should be constructed on the basis of nationally specific data in order to take account of regional differences in growth rates, management practices, etc. The objective of this study is to improve the accuracy of biomass estimation by calculating a range of age-dependant BEFs from representative data that more accurately describe the allometry of present forests. The results from this study show that the allocation of biomass to compartments in forest stands and throughout a rotation varies considerably, and that the use of BEFs for the calculation of C stocks in forests of sub-timber dimensions is highly impractical.

Keywords Biomass expansion factors · Aboveground biomass · Belowground biomass · Conversion factors Sitka spruce · Ireland

Introduction

Forests play an important role in the global carbon cycle (Masera et al. 2003). Forest management activities, practices, forest succession and disturbance form significant links in influencing regional carbon pool dynamics. Forests' characteristic long and gradual build-up of biomass interspersed with short periods of massive loss mean that forests switch from being a sink for carbon to a source. The potential of forests to mitigate the anthropogenic increase of atmospheric CO_2 concentrations has been recognised under the Kyoto Protocol. As a signatory of the United Nations Framework Convention on Climate Change (UNFCCC), Ireland has agreed to reduce its CO_2 emissions to 13% above 1990 baseline levels. This places a requirement on the improvement of the accuracy of national forest carbon storage and sequestration inventories (Coomes et al. 2002).

Assessment of biomass in forests is normally calculated from national forest inventory data using biomass expansion factors (BEFs). Generically, BEFs describe multiplication factors which are used to *expand* growing stock (Schoene 2002) or growing stock biomass to account for non-merchantable biomass components (needles, branches, lop and top, bark, stump, roots, etc.) (Kilbride et al. 1999; Milne et al. 1998). Or more practically, when used in conjunction with *conversion* factors, BEFs convert readily available estimates of merchantable stem wood volumes ($m^3\ ha^{-1}$) to total biomass carbon values ($Mg\ C\ ha^{-1}$) which can then be used to estimate carbon budgets (Fukuda et al. 2003; Kilbride et al. 1999). The basic equation employed (Dewar and Cannell 1992; Penman et al. 2003) is:

$$\text{Carbon mass} = \text{volume} \times d \times f_c \times \text{BEF} \qquad (1)$$

where d ($Mg\ m^{-3}$) is the stem wood basic density (converting volume to dry weight biomass) and f_c is the mean carbon fraction of dry tree biomass (converting biomass to carbon).

However, care is required in the use of conversion and expansion factors. Winjum et al. (1998), having carried out a sensitivity analysis to determine the impact of various factors in their C-fate calculations, warned that a 10% change in a factor could cause a change of over 7% in the total emission estimate for a country, and

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that where the factors had a multiplicative function (i.e. biomass conversion and expansion factors) their influence could be much greater than where they were additive.

Dewar and Cannell (1992) developed a model to evaluate carbon sequestration in various UK forest ecosystems and to explore the options of carbon storage by using plantations of different species and productivities. This model is based mainly on the British Forestry Commission yield models (Edwards and Christie 1981). Based on a sensitivity analysis on the major parameters and assumptions of their model, some important parameters of high uncertainty were identified. First among these uncertainties was the fraction of total woody biomass that occurs in branches and woody roots. This highlighted the difficulties of determining the ratio of total biomass to merchantable volume. For the generation of regionally relevant allometric functions, belowground biomass and its allocation is another area of poorly available data (Coomes et al. 2002). This is also the case for Ireland. Wills (1999) and Carey and O'Brien (1979) have provided the most recent work on the root biomass of Sitka spruce.

In the recent past, Ireland has been using a BEF value of 1.3 for C-reporting (Löwe et al. 2000). It has long been felt that this value underestimates biomass particularly for the younger stands so important in the UNFCCC reporting process (Black et al. 2004). Because of the problems associated with the application of the wide range of differently defined BEF values available, it has been increasingly felt that locally derived BEFs should automatically compensate for local deviations in definitions (Schoene 2002). The added advantage of using locally derived and updated biomass equations and factors is that while they compensate for regional environmental conditions, they will also redress contemporary differences in growth patterns, such as the increased productivity suggested by Mund et al. (2002) and Kauppi et al. (1995).

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important and widely planted commercial tree species in Ireland which, since the late 1970s, has accounted for roughly 60% of the national planting program (Joyce and O'Carroll 2002). The objectives of this study were to determine the above- and belowground biomass stock of an age sequence of Sitka spruce stands, to calculate a series of nationally pertinent BEFs and to quantify the changes in BEF over a rotation under normal commercial stand development. As little research of this nature has taken place in Ireland in the past (Byrne and Perks 2000), this new information can then be used to improve currently used biomass and C-store estimates for Irish forests and assist in national carbon accounting processes. This work is part of an overall project, CARBiFOR, which was initiated to work on an initial estimate of the carbon store and sequestration potential of current and new forests in Ireland.

Methods and materials

Sample sites

A chronosequence, consisting of five even-aged monospecies stands (9, 14, 28, 30 and 45 years old), representing the typical commercial rotation of Sitka spruce in Irish forest conditions was identified, Table 1. The general yield class of stands to be chosen was 18 m^3 ha^{-1} a^{-1}, the national average for Sitka spruce.[1] Stands on mineral soils were chosen, as this best represents the majority of better quality sites supporting post-1990 plantations of Sitka spruce in Ireland. An additional stand of a higher productivity was selected to compare differences due to yield class. Accordingly, six stands were located in the midlands of Ireland, in County Laois (52°57′ N, 7°15′ W, each at an approximate altitude of 260 m), each on a wet surface-water mineral gley soil. Efforts were made to standardise the site conditions as far as possible (i.e. stands growing under homogenous environmental conditions) in terms of topography, soil type and drainage conditions as heterogeneity of vegetation across the landscape is a source of error in biomass estimation at all scales.

Data

A total of 36 trees were harvested from across the chronosequence (six trees from each stand in the time series) and destructively sampled. Sample trees were cut at ground level, and their dbh and height were measured. They were divided into their component parts (stem, dead branches and live branches). Dead branches usually included very few or any needles, whereas the live branch component included practically all the tree's needles. The point along the stem where it was deemed that live branches predominated (i.e. where $>75\%$ of the whorl's branches were live/photosynthetically active) was marked, and all branches originating from the stem below this point were considered dead. These components were weighed in the field with a portable spring balance (precision 0.1 kg). Sub-samples were taken from the components and dried to constant weight at 70°C, and fresh to dry weight ratios were used to calculate the dry weight of each tree component (Mund et al. 2002). Sub-samples of branches were dried and separated into branch wood and needles, and again the subsequent dry weight ratios of needles to branch wood were used to separate the dry weight of the foliage into its two constituent fractions.

Excavation was carried out within a square of side 2 m centred on the rootstock, and to a depth sufficient to recover all live tree roots with a diameter ≥2 mm, both belonging to the sample tree and its neighbours. The size

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[1] A yield class of 18 m^3 ha^{-1} a^{-1} means that the stand has the potential to produce 18 m^3 per ha per year over a full rotation.

Table 1 Description and main characteristics of stands used in the CARBiFOR study

Forest	Age (years)	Stand area (ha^{-1})	Stocking density (ha^{-1})	Mean dbh (cm)	Mean height (m)	Yield class (m^3 h^{-1} a^{-1})	Basal area (m^2 ha^{-1})	Stem volume (m^3 ha^{-1})
Baunoge	9	12.0	2,333	6	3.5	18	6.3	60.4
Clontycoe	14	15.6	2,533	13	7.3	18	34.0	173.6
Dooary	14	25.8	2,467	16	9.5	24	52.2	290.0
Glenbarrow	28	5.3	1,250	22	14.3	18	48.9	363.4
Dooary	30	3.3	1,433	24	16.8	20	60.7	500.3
Cullenagh	45	11.1	767	32	26.7	18	65.3	835.3

of the excavation square was increased to 3 m × 3 m in the oldest two stands to account for the lower stocking density. Roots were cleaned using compressed air and then sub-sampled to establish wet weight/dry weight ratios.

Timber volume

The over bark timber stem volume of the sample trees was determined from ten diameter measurements at every 10% of height (to 7 cm over-bark top diameter), beginning at ground level. Tree stem diameters were taken as averages of two diameter measurements made in perpendicular directions per disk (Drexhage et al. 1999; Mund et al. 2002). Two bark thicknesses per diameter were also measured and averaged in a similar way. Smalian's formula was used to calculate timber volume (Hetherington and Jenkins 1997; Husch et al. 1982):

$$V = 0.00007854 \times L \times \left(\frac{d_0^2}{2} + d_1^2 + d_2^2 + \cdots + d_9^2 + \frac{d_{10}^2}{2} \right) \tag{2}$$

where V, the merchantable volume (m^3), is calculated from L, the tree section length, i.e. 10% of timber height (m), and $d_0 \ldots d_{10}$ the diameters (cm) at the 10% intervals along the stem.

Biomass expansion factors

To convert stem volume to dry biomass, the following equation was used to calculate a stand level BEF:

$$\mathrm{BEF}_{\mathrm{Timber}} = \frac{\mathrm{TB}}{\mathrm{TSB}} \tag{3}$$

where TB is the estimated total dry weight of biomass from plots and *TSB* the timber stem wood biomass. TB incorporated all belowground root material to a cross-sectional diameter of 2 mm (i.e. fine roots were not included), stem material from ground level to terminal bud, including bark, dead branches, live branches and needles. Dead branches still attached to the stem were considered as necromass and in line with the IPCC reporting process (Penman et al. 2003) were not included in the TB quantity. TSB was defined as biomass of the merchantable portion of the stem (i.e. to the height of 7 cm top diameter over bark) from plots. Data used in these calculations were averaged plot data per age class. In order to compare with other previously used BEF values, a further two ranges were calculated using variations of Eq. 3. $\mathrm{BEF}_{\mathrm{Above}}$ was the ratio of total aboveground biomass to complete stem biomass [as used by Brown (2002), Porté et al. (2002) and Levy et al. (2004)], and $\mathrm{BEF}_{\mathrm{Total}}$, the ratio of total tree biomass to complete stem biomass. Neither under storey biomass nor fine root biomass (<2 mm in diameter) was included in any of the BEF calculations.

In order to test the range of BEFs thus produced, they were used to predict total C mass per hectare from measured volume in conjunction with the calculated conversion factors (Eq. 1).

Conversion factors

Basic wood density, normally defined as the ratio of oven dry weight of timber divided by its green volume (Porté et al. 2002), was determined using the stem disks already used for measuring diameters. Volume was measured using the water displacement method, described and used by Olesen (1971), O'Sullivan (1976), and Woodcock and Shrier (2003). Mean stem basic density was calculated for stands and used as a factor to convert from volume to biomass.

To determine the C conversion factor, sample material for all tree components was oven dried at 70°C and ground using a hammer flail mill (screen size: 1.0 mm. Culatti DFH 48, Glen Creston Ltd, UK). For calibration purposes a standard was prepared from carefully homogenised ground stem material gathered from the stems of a range of sampled trees. It was felt that a standard composed of material similar to that being tested (instead of using a standard prepared from, e.g., ground apple leaves) would be more useful in the recalibration of the analysis instrument. Both samples and standards were re-dried for at least 16 h and cooled in a desiccator before weighing out small sub-samples (0.2 g) that were analysed for C% in a LECO SC-144DR elemental analyser.

Statistical analysis

Initial descriptive statistics were calculated by the MS Excel program and regression analysis was carried out using SAS (SAS Institute 1989: proc glm procedure). Uncertainties, except where otherwise indicated, are presented as ± the 95% confidence interval, expressed as a percentage of the estimate, and the propagation of uncertainty in the C stock estimates was calculated using the following:

$$\text{C stockuncertainty}^2 = E_{\text{vol}}^2 + E_{\text{BEF}}^2 + E_{\text{C\%}}^2 + E_{\text{BD}}^2 \quad (4)$$

where E_{vol} is the error associated with the volume estimate, E_{BEF} the error from the BEF, $E_{\text{C\%}}$ and E_{BD} the errors from the C fraction and basic density conversion factors, respectively.

Results

Moisture content of tree fractions

As expected, the fraction with the lowest moisture content was deadwood. The average percentage across all age classes was 22.47%. Apart from the deadwood, the lowest moisture contents were generally from the youngest stand (Fig. 1). Values for root tissue, while being the highest at year 9, ranged from 51.64% to 56.69% between the ages of 9 and 14, had already been overtaken by the other three live fractions by the third stage in the chronosequence. By the end of the chronosequence, stem wood had the lowest moisture content of all the live fractions, at 47.71%. When percentage of moisture was plotted against total biomass (Fig. 1), the moisture content of all live tissues followed a clear trend in the trees' lifecycle. Moisture content peaked early as the trees' components were developing freely without hindrance by competition for resources. The moisture content levelled off as more and more of the trees' resources relating to active growing were converted to increased biomass storage.

Stand biomass

Average plot total dry biomass ranged from 32.9 t ha^{-1} on the Baunoge site, 124.9 t ha^{-1} at Clontycoe, 210.8 t ha^{-1} at Dooary (planted in 1988; P88), 237.3 t ha^{-1} at Glenbarrow, 415.4 t ha^{-1} at Dooary (P72), to 490.7 t ha^{-1} at Cullenagh (Table 3). Average plot dry stem biomass appears first as 8.64 t ha^{-1} at year 9, 26.2% of the total biomass of its age class, and increases rapidly to account for over 71% of the total biomass at year 46, 349.9 t ha^{-1}. While aboveground dry biomass increased markedly over the chronosequence from 23.34 t ha^{-1} at year 9 to 403.93 t ha^{-1} at year 46, the increase of belowground biomass was far more sedate (9.6–86.9 t ha^{-1}), remaining just below 20% of total dry biomass from about year 20 onwards.

BEFs, calculated on the basis of average plot data (ha^{-1}), decreased with stand age (Table 3, Fig. 2). The rate of decrease was similar for the $\text{BEF}_{\text{Timber}}$ and $\text{BEF}_{\text{Above}}$ values. $\text{BEF}_{\text{Total}}$ began at the lowest value 3.8 t t^{-1} at the Baunoge stand (9 years) and reduced to 1.4 t t^{-1} at Cullenagh (45 years). Associated uncertainty also decreased over the period of the chronosequence, but much more markedly in the $\text{BEF}_{\text{Timber}}$ and $\text{BEF}_{\text{Above}}$ ranges than with the $\text{BEF}_{\text{Total}}$ range.

Wood basic density

Woody stem basic density values were found to be quite variable (Table 2). Stem density values ranged from 475.2 ± 17.1 kg m^{-3} at Baunoge (P93) to 352.3 ± 43.89 kg m^{-3} at Cullenagh (P56), demonstrating an overall decrease over time.

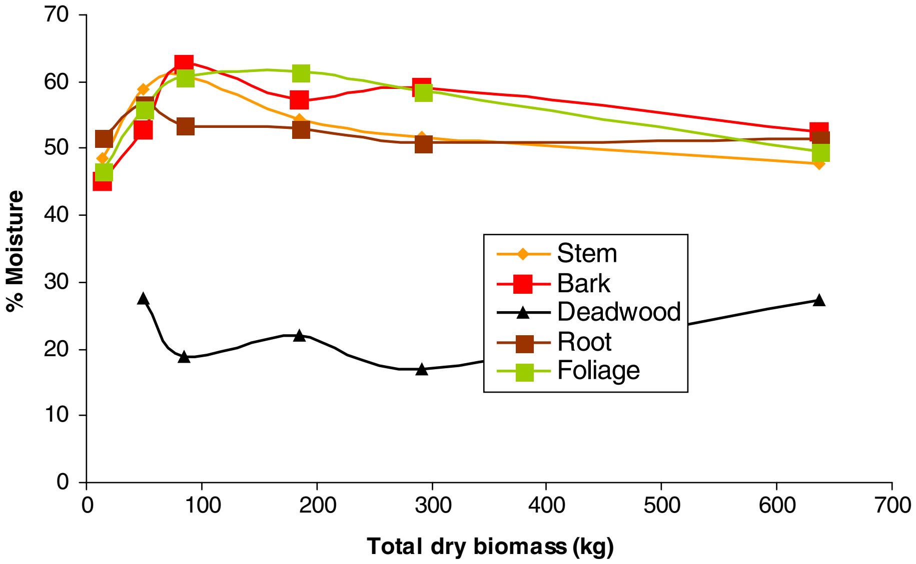

Fig. 1 Moisture content of tree component parts (expressed as a percentage) against total dry biomass

Table 2 C% was the average of sample tree component C quantity with uncertainty presented as the 95% confidence interval expressed as a percentage of the mean

Stand	Age	Mean of tree component C%	Uncertainty	B. Density (kg m^{-3})	Uncertainty
Baunoge	9	46.0 ± 0.57	1.24	475 ± 17.1	3.6
Clontycoe	14	45.9 ± 0.41	0.89	412.8 ± 53.5	12.96
Dooary	14	45.5 ± 0.48	1.06	375.3 ± 43.33	11.54
Glenbarrow	28	45.1 ± 0.48	1.07	389.3 ± 40.85	10.49
Dooary	30	45.8 ± 0.35	0.77	378.5 ± 57.2	15.11
Cullenagh	46	46.5 ± 0.84	1.81	365.2 ± 19.25	5.29

Table 3 Per ha data from plots in t of dry biomass, with uncertainty included as the confidence interval expressed as a percentage of the mean

Stand	Baunoge	Clontycoe	Dooary	Glenbarrow	Dooary	Cullenagh
Total	32.9 ± 37.98	124.9 ± 79.52	210.8 ± 37.2	237.3 ± 45.29	415.4 ± 20.67	490.7 ± 45.27
Stem	8.6 ± 53.37	48.6 ± 66.27	95.0 ± 49.35	155.7 ± 46.7	250.6 ± 34.07	349.9 ± 50.62
Above ground	23.3 ± 38.39	84.4 ± 67.65	159.3 ± 37.12	194.4 ± 46.44	337.2 ± 14.43	403.9 ± 46.23
BEF_{Timber} (t t^{-1})	39.8 ± 120.95	4.6 ± 24.19	2.3 ± 13.47	1.7 ± 8.89	1.9 ± 21.77	1.6 ± 5.35
BEF_{Above} (t t^{-1})	28.1 ± 119.95	3.2 ± 26.83	1.76 ± 13	1.4 ± 14.3	1.5 ± 10.38	1.3 ± 4.54
BEF_{Total} (t t^{-1})	3.8 ± 22.41	2.5 ± 22.35	2.2 ± 11.5	1.5 ± 9.21	1.7 ± 21.41	1.4 ± 5.17
R (t t^{-1})	0.41 ± 7.78	0.47 ± 40.41	0.33 ± 41.75	0.22 ± 42.08	0.23 ± 67.09	0.22 ± 5.02

The BEF factors and R (the ratio of below- to aboveground dry biomass) have also the same uncertainty attached

Carbon content

The plot mean weighted estimates produced for mean tree component C-content varied from 45.1 ± 0.48 to 46.5 ± 0.84 C% (Table 2). Mean C% displayed no significant differences with age or size of tree.

Estimated biomass

C stock per hectare was predicted using the three BEF ranges from this study (BEF_{Timber}, BEF_{Above} and BEF_{Total}) with the respective measured basic densities and C factors. C stock was also predicted by using figures presented by Kilbride et al. (1999), $BEF_{1.3}$, i.e. a BEF of 1.3 (ratio of total biomass to stem biomass), a basic density figure of 350 kg m^{-3} and C factor of 0.5. The results, shown in Table 4, clearly indicate how unrealistic the use of the BEF_{Timber} and BEF_{Above} is for stands of a young age where the stand has not yet achieved merchantable timber dimensions. BEF_{Timber} continually overestimated C stock across the chronosequence (an overall overestimate of over 85%). BEF_{Total} and $BEF_{1.3}$ both underestimated the same C stock quantity (total above- and belowground C per hectare); however, BEF_{Total} produced a large improvement on the historic $BEF_{1.3}$, moving from an underestimate of almost 25% to 3.5%.

Discussion

Stem biomass and BEFs

Great care should be taken in defining and using BEFs because of possible confusion of exactly what these

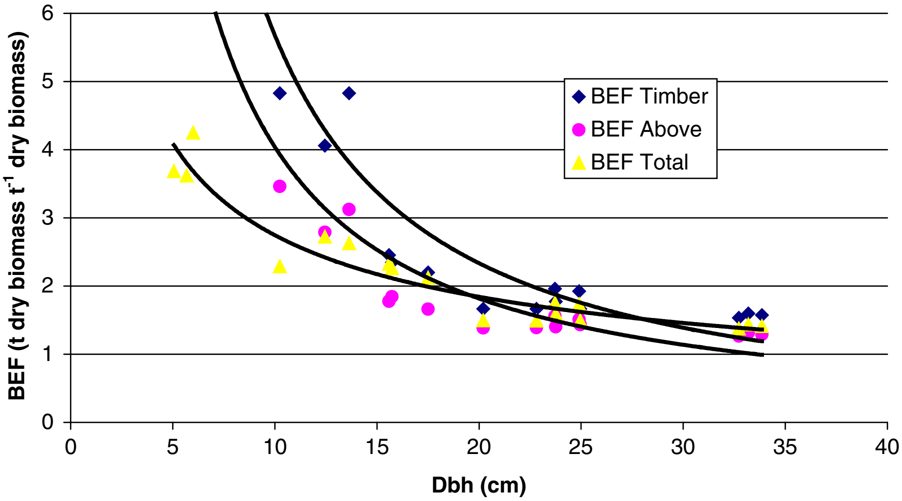

Fig. 2 The three calculated BEF ranges compared against dbh. Note that values for BEF_{Timber} and BEF_{Above} at the Baunoge stand are not shown because of the narrow magnitude of the y-axis scale

Table 4 Percentage difference between measured and estimated C ha^{-1}

Stand	BEF_{Timber}	BEF_{Above}	BEF_{Total}	$BEF_{1.3}$
Baunoge	−1607.14	−5.61	9.69	75.16
Clontycoe	−165.2	13.46	3.47	53.54
Dooary	−57.6	11.65	2.61	41.41
Glenbarrow	−35.55	6.41	−11.43	5.21
Dooary	−37.33	10.3	2.03	24.37
Cullenagh	−20.73	11.23	9.36	11.95
Chron.-diff.	−85.67	22.2	3.52	24.31

Chron. diff. is the percentage difference between the sum of the measured and estimated C stocks over the entire chronosequence

terms include or do not include. The BEF ranges calculated here serve to illustrate this frequently encountered problem. As expected, with increasing age all the BEFs calculated in this study decreased (Lehtonen et al. 2004), and became close to constant between the ages of 20–25 and 46 years, resembling the trends reported by Brown (2002) and Fukuda et al. (2003). BEF values began at a high level when stem biomass was low, but as growth progressed through the chronosequence BEF values decreased exponentially as emphasis was increasingly transferred from root development and biomass was built up mainly in the aboveground stem. This is shown by the decreasing ratio of belowground/aboveground (*R*), similar to that found by Helmisaari et al. (2002). The decline of root biomass after 20 years is very much in accordance with Dickson (1989) who reports that the standing root biomass tends to stabilise at about 20% of the aboveground standing biomass. Levy et al. (2004) recommended raising the national value of *R* used for C-reporting in the UK to 0.36, to account for a greater amount of carbon in UK forests than previously estimated. The mean chronosequence *R* value of 0.31 from this work is somewhat lower than that produced by Levy et al. (2004).

Because the imprecise and somewhat subjective nature of determining merchantable timber dimensions (i.e. the location along a stem where the diameter is 7 cm can be difficult to identify exactly) variability increases, all associated estimates are subject to a higher uncertainty. It is clearly illogical to attempt to use factors based on timber dimensions on young stands, where any timber volume present may be purely theoretical (as was the case at Baunoge) or perhaps not exist at all if the diameter has not reached 7 cm. But, through the rotation this uncertainty tended to decrease. Similarly with the other BEFs, the greatest uncertainty was associated with the youngest stands and once canopy closure had occurred (as was the case in the older four stands in the chronosequence), there was a noticeable drop in uncertainty levels. Using BEF_{Total} to estimate biomass from total stem volume data does overcome the difficulty and reduces uncertainty, but assumes the availability of such data. The BEF_{Total} range agrees well with and confirms the earlier work presented by Black et al. (2004).

Conversion factors

Woodcock and Shrier (2003) acknowledged the difficulties in understanding the patterns of radial variation in wood specific gravity. As radial variation was only one aspect of many other causes of variation in specific gravity within trees, generalisation across a species where such wide variation existed was difficult. Great variations in the basic density of stem wood biomass were encountered at all sites in this study, reflecting a similar high variability as shown by Treacy et al. (2000) in a recent Irish study on the relative differences in density within Sitka spruce provenances. However, a distinct decreasing trend with age is noted in the chronosequence. Some variation may be accounted for by the varying quantities of sapwood/heartwood according to where the disks were positioned in the stem. In a nodal area with a large number of branch knots, overall basic density would have been greater than if the disk had been taken from a more knot-free or internodal area of the stem. The basic density values arising from this study concur well with those found by Ward and Gardiner (1976). Trees from the Glenbarrow stand were most similar in terms of age and productivity to the closest spaced trees used in that study, and the basic density reported is the same as in this study. The lower part of the chronosequence basic density range of 352.3 ± 43.89 kg m^{-3} to 475.2 ± 17.1 kg m^{-3} is also similar to the UK range of 343–399 kg m^{-3} reported by Savill (1992). When data from the youngest stand are omitted, the overall chronosequence mean became 387 kg m^{-3} which is very close to the value of 370 kg m^{-3} that Ireland has used in a preliminary reporting process (Löwe et al. 2000). As reported by Dewar and Cannell (1992) in the sensitivity analysis they carried out with their C sequestration model, basic density appeared to be of low importance. A small test of the sensitivity of the conversion factors calculated here was conducted using the BEF_{Total} calculation. When the range of basic density values was changed to a common figure of 387 kg m^{-3}, C stock only increased by 2%, whereas if the commonly used default value of 0.5 for the C factor was used, C stock increased by almost 8.5%. The tree C fraction appeared to be quite stable throughout the chronosequence, with no significant changes with tree size or age. It can be seen that the effect of an increase in yield class in the chronosequence has been to move the stand further along the developmental stage in the rotation. While stem basic density decreased in stands of higher productivity, there was no effect on the C fraction.

C-stock estimation

The BEF ranges were developed using Irish data collected from Sitka spruce stands that were selected to represent the types of forest that will form the core of the forest estate relevant for IPCC and related reporting processes. At the same time, these stands and their measurements will also be of use for other purposes, e.g. the study of allometry, allocation, etc. It should be noted that the age range of the chronosequence represents standard Irish forestry and is quite short in relation to the rotations used by other European countries, and that the management practices governing the stocking rates and biomass allocation within the forests may also be quite different.

The age-related $\mathrm{BEF}_{\mathrm{Total}}$ range, when used in conjunction with the basic density value of 387 kg m^{-3}, predicted the C mass per hectare closest to that measured; the percentage difference between the sum of the measured and estimated C stock over the entire chronosequence (chron. diff.) reduced from 3.52% (Table 4) to 1.55%. It is quite clear from these results that an obvious improvement in the estimation of biomass is achieved by using a range of age-adjusted BEFs, when compared with the results obtained when using the fixed $\mathrm{BEF}_{1.3}$ value.

Conclusions

The BEF range calculated for the CARBiFOR chronosequence clearly demonstrates the value of the use of age-defined classes in C-store estimation. The higher sequestration rates at the beginning of the chronosequence require higher BEF values than later on, reflecting large amounts of non-timber biomass though, as expected, the IPCC-defined $\mathrm{BEF}_{\mathrm{Above}}$ based on minimum diameter timber volumes (Penman et al. 2003) proved impractical for use in forest stands of sub-minimum dbh dimensions, where variation and uncertainty were very high. More research is needed to establish more fully the extent of changes due to YC.

To date, there is little available data for any other coniferous species in Ireland, and no published data for biomass distributions in semi-mature and mature broadleaf crops, so these areas remain still as obvious candidates for further research. Particularly so in the light of Kyoto and UNFCCC requirements, as the new National Forest Inventory will make its first report in the near future, providing species-specific diameter distributions among other data, further BEFs and biomass models will be required to make use of such new statistics and meet international C-reporting obligations.

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