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ORIGINAL PAPER

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Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.)

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Abstract Reporting carbon (C) stocks in tree biomass (above- and belowground) to the United Nations Framework Convention on Climate Change (UNFCCC) should be transparent and verifiable. The development of nationally specific data is considered 'good practice' to assist in meeting these reporting requirements. From this study, biomass functions were developed for estimating above- and belowground C stock in a 19-year-old stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.). Our estimates were then tested against current default values used for reporting in Ireland and literature equations. Ten trees were destructively sampled to develop aboveground and tree component biomass equations. The roots were excavated and a root:shoot (*R*) ratio developed to estimate belowground biomass. Application of the total aboveground biomass function yielded a C stock estimate for the stand of 74 tonnes C ha^{-1}, with an uncertainty of 7%. The *R* ratio was determined to be 0.23, with an uncertainty of 10%. The C stock estimate of the belowground biomass component was then calculated to be 17 tonnes C ha^{-1}, with an uncertainty of 12%. The equivalent C stock estimate from the biomass expansion factor (BEF) method, applying Ireland's currently reported default values for BEF (inclusive of belowground biomass), wood density and C concentration and methods for estimating volume, was found to be 60 tonnes C ha^{-1}, with an uncertainty of 26%. We found that volume tables, currently used for determining merchantable timber volume in Irish forestry conditions, underestimated volume since they did not extend to the yield of the forest under investigation. Mean stock values for belowground biomass compared well with that generated using published models.

Keywords Biomass allocation · Roots · Biomass expansion factors · Biomass functions · Uncertainty analysis · Sitka spruce · Peatland forestry · Ireland

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Introduction

Estimates of carbon (C) stocks and stock changes in tree biomass (above- and belowground) are required for reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and will be required for Kyoto Protocol (KP) reporting. The Intergovernmental Panel for Climate Change has recently published Good Practice Guidance (IPCC GPG) for the reporting of land use, land use change and forestry activities (Penman et al. 2004). This guidance highlights the importance of nationally specific information, regarding a country's forest resources, in order to increase the transparency and verifiability of national C inventories. For countries which have significant amounts of afforestation, deforestation and reforestation, nationally specific information that can be used in the development of C stock and stock change estimates will greatly enhance the quality of greenhouse gas (GHG) reporting to the UNFCCC and its KP.

Ireland has one of the lowest levels of forest cover in Europe (Pilcher and Mac an tSaoir 1995), currently at

9.7%. However, it also has one of highest rates of afforestation that is backed by a national policy to increase forest cover to over 26% by 2030 (Anon 1996a). Approximately, 17,800 ha per year were converted to managed forest land, between 1990 and 2002, equating to an approximate 3% of land use changed to forest land over that period. In terms of the national GHG inventory, afforestation activities are significant in Ireland.

The national forest estate is dominated by exotic tree species, predominantly Sitka spruce *Picea sitchensis* (Bong) Carr. and a variety of provenances of Lodgepole pine *Pinus contorta*. Due to its rapid growth in Irish conditions and its ability to withstand difficult site conditions, Sitka spruce is the most widely planted tree, either in single species stands or, more commonly in recent years, as the predominant species in mixed stands (Joyce and O'Carroll 2002). The national forest estate now comprises over 57% Sitka spruce (Horgan et al. 2003) and has a reportedly high annual increment when compared with its other European neighbours (Lowe et al. 2000).

The estimates of biomass, and therefore C, stocks can be generated using either biomass functions or by applying a biomass expansion factor (BEF). The choice of method is largely dependant on the type of information recorded in the national forest inventory (NFI) (Brown 2002). It is widely accepted that the forest inventory provides a statistically sound basis for the development of biomass stocks in above- and belowground biomass pools and forms the basis of reporting under the IPCC GPG.

Biomass functions, or allometric relationships, are based on resource allocation (Bazzaz and Grace 1997) and can be used to model plant allocation of water, important nutrients (i.e. nitrogen and phosphorus) as well as C. Relationships between C and merchantable timber measurements, such as diameter at breast height (DBH) and tree height ,can be developed based on the investment of C in structural tissue (i.e. stems, branches and roots). These relationships are generally of the power form

$$M = aX^b \tag{1}$$

where M is biomass, X is an easily measured tree characteristic and a and b are parameters (Zianis and Mencuccini 2004). Such relationships have been developed for a variety of tree species to improve the understanding of tree biomass distribution and to generate estimations of biomass stock (Grier et al. 1981; Bartelink 1996; Fuwape et al. 2001; Williams et al. 2003; Zianis and Mencuccini 2004).

A BEF relates stemwood or merchantable timber volume to biomass stocks (Brown et al. 1989, 1999; Brown 2002; Chhabra et al. 2002; Lehtonen et al. 2004) and is used to convert merchantable volume to stand biomass (B_{stand} in t ha^{-1}), according to Eq. 2 (Snowdon et al. 2002)

$$B_{\mathrm{stand}} = V \times D \times BEF \tag{2}$$

where V is the merchantable stem volume (i.e. to 7 cm diameter) of the stand (m^3 ha^{-1}), BEF is the biomass expansion factor, and D is wood density (t m^{-3}).

The type of data recorded in the NFI is a significant factor in approach selection. If forest inventory data reports individual tree diameters or stocking by diameter classes, then allometric relationships can be used; alternatively, if merchantable volume to a known minimum diameter (i.e. 7 cm) is reported, then an appropriate BEF is used (Brown 2002). Ireland is currently in the process of implementing a new NFI based on permanent plots that will provide data to allow either approach to be adopted for C stock reporting.

For belowground biomass, root:shoot (R) ratios are commonly applied in the development of total tree C stock. R ratios are an indicator of relative belowground biomass to aboveground biomass. Both biotic and abiotic factors are thought to influence it (Cairns et al. 1997).

The primary objective of this study was to contribute nationally specific data, through the destructive analysis of both above- and belowground biomass pools for the major tree species in Ireland to aid in the improvement of Irelands GHG inventory reporting. Additionally, comparisons between existing national C stock estimates, developed using a default BEF approach, and those generated from published biomass functions, are made with a focus on identifying variables that substantially contribute to uncertainty in these C stock estimates.

Methods

Site description

The study was located in an industrial cutaway peatland, which was afforested with Sitka spruce in 1983. The site was previously used for the extraction of peat for fuel and was located at Lullymore, Co. Kildare (Longitude W6 56′, Latitude 53 17′). The average recorded mean annual temperature and annual rainfall in the region is 8.8°C and 934 mm, respectively (observations based on a 30-year average at the Mullingar meteorological station, 46 km from the study site). The site, 20 ha in extent, consisted of residual *Phragmites* fen peat, varying in depth from 0.25 to 0.9 m, and overlying sub peat mineral soil consisting of a calcareous marl layer. With no site preparation prior to planting, parallel drains, 1.3–1.5 m wide and 15 m apart, characteristic of industrial cutaway peatlands, were present between which the commercial crop of Sitka spruce was planted at a spacing of 2.3 m.

Table 1 Stand characteristics of the study area

Mean DBH (cm)	18
Stocking (stems ha^{-1})	1,367
Mean tree basal area (m^2)	0.028
Basal area (m^2 ha^{-1})	38.44
Top height (m)	14.7
Volume (m^3 ha^{-1})	208[a]
Age (year)	19
Current annual increment (m^3 ha^{-1} year^{-1})	12.5

[a] Determined from British Yield Models

Stand inventory

Four 15×15 m^2 square plots were randomly located within the stand and all trees within the plots were numbered and their stocking determined. Tree height was determined using a laser hypsometer (Impulse, LaserTech Inc., Englewood, CO, USA) and the DBH was measured using a forestry girthing tape. The stand characteristics are reported in Table 1. Ratio and regression estimators are usually estimated more efficiently if the population from which the samples are taken is stratified (Snowdon 1985, 1992). Such strata are usually based on some measure of tree size; therefore, ten trees, representative of the DBH distribution (Fig. 1), were selected for destructive sampling.

Tree sampling

Aboveground biomass

The sampling of this pool involved tree harvesting at ground level. Each harvested tree was then divided into various biomass components: namely, dead branches, live branches and stemwood. Dead branches were defined as branches without foliage and were removed prior to felling. As standing deadwood forms part of the dead organic pool (Penman et al. 2004) it was not included in calculations of aboveground biomass stock; however, the data was recorded. Following felling, the total stem height and crown height were measured. The crown was then divided into three sections of equal height. All the branches where removed from each section, stratified into nodal and internodal branches and their fresh weights (FW) recorded. Two sample nodal and internodal branches were randomly selected from each of the three crown sections, giving a total of 12 sample live branches per tree.

The total stem height and FW were measured and five cross sectional stem samples were collected between ground level and the timber height (the height of 7 cm diameter over bark). One further disc was taken at breast height. The diameter of each disc was measured.

Wood density

Basic density [t d.m. m^{-3} i.e. dry weight (DW) and wet volume] was estimated using a core method (Ilic et al. 2000). Cores were taken at breast height and immersed in water to determine the volume, then dried at 70°C until constant weight.

Volume

For each of the ten trees harvested, the volume was calculated in three ways, in order to estimate a level of uncertainty in the merchantable timber volume used in Eq. 2, for the development of C stock estimates. The stem volume of each harvested tree was calculated using the diameters of the sample discs taken along the stem and the formula for calculating the volume of a conical as in Eq. 3

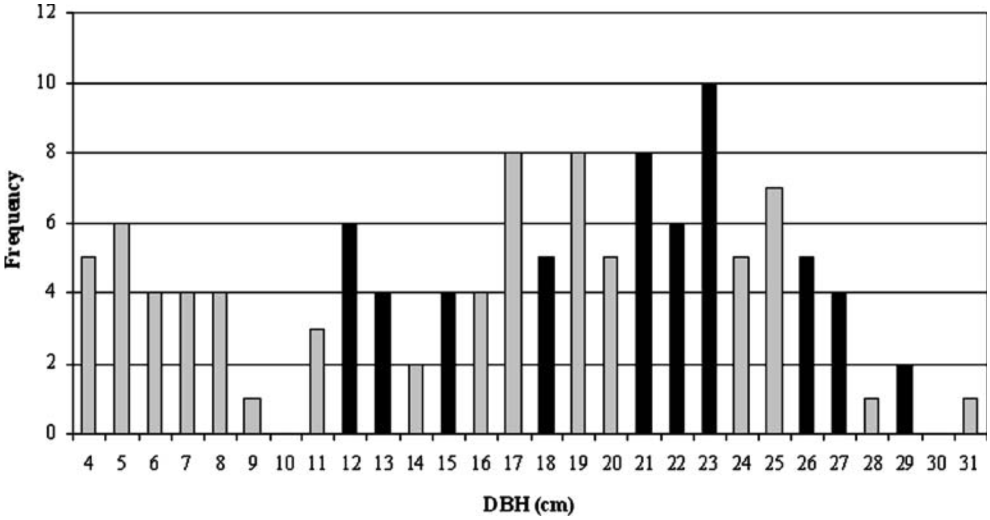

Fig. 1 Inventory DBH distribution and tree selection. DBH of trees selected for development of allometric relationships (*black*) and those for model verification (*hashed*)

Table 2 Default and literature values for coniferous species

	Irish national defaults values[a]	European average[a]	Great Britain values[b]	Improved Irish default values[c]
Biomass expansion factor	1.64	1.47	1.44	1.64
Wood density (t m^{-3})	0.37	0.49	0.35	0.35
Carbon concentration [C]	0.43	0.48	0.50	0.50

[a] Adapted from Lowe et al. (2000)

[b] Adapted from Levy et al. (2004)

[c] Adapted from Gallagher et al. (2004)

$$V_{\text{conical}} = \left(\frac{\pi l}{12}\right)\left(d_{\text{top}}^2 + \left(d_{\text{top}} + d_{\text{bottom}}\right) + d_{\text{bottom}}^2\right) \tag{3}$$

where V is the volume in cubic metres, l is the length in metres, d_{top} is the diameter of the top in metres, d_{bottom} is the diameter of the bottom in metres and π is 3.1459.

The measured volume was compared with that using the Huber formula, Eq. 4 and tariff tables (Hamilton 1975). Tariff tables are tables from which the volume of a single tree can be read if the DBH and height are known.

$$V = \frac{\pi d_{\text{m}}^2}{40,000} \times L \tag{4}$$

where V is the volume in cubic metres, L is the length in metres, d_{m} is mid-diameter in centimetres and π is 3.14159.

Belowground biomass

The sampling of belowground biomass was undertaken within a 2m × 2m square marked from the centre of the stump from which all roots over 2 mm were removed. Fine roots were not sampled. The roots were separated into three size classes based on diameter, namely coarse (> 50 mm), medium (10–50 mm) and small (2–10 mm). The depth of the coarse root fraction determined the depth to which the roots were excavated and varied between trees from 0.5 to 1.2 m. The FW of the collected roots was determined in the field and five samples from each size class were randomly selected.

All samples, both above- and belowground, were removed to the laboratory where the FW was immediately recorded on an electronic balance. The bark was removed from the stem samples and treated separately. Live branch, dead wood and bark samples were oven-dried at 70°C to constant weight. After drying, the foliage and branches were treated separately.

The stemwood samples were dried at 40°C for 5 days, to avoid the disintegration caused by rapid shrinkage, and then at 105°C to constant weight. The oven DW was recorded using an electronic balance. All the sample DW were considered to determine the DW:FW ratio for each component, which was then applied to the whole tree FW measured in the field to obtain the estimate of the whole tree biomass (Snowdon et al. 2002).

The component samples were then pooled by tree and ground using a hammer mill (screen size: 1.0 mm. Culatti model DFH48. Glen Creston Ltd., UK) for C determination using a total C analyser (Analitik Jena micro N/C Analyser).

Carbon stock estimates

Biomass functions between the biomass components and DBH or height were developed using regression analyses, with best-fit models being selected on the basis of the adjusted coefficient of determination (R^2). The selected biomass function was then solved for all surveyed trees to provide a weighted estimate of the plot biomass (Wang et al. 2000), which was then upscaled to estimate the biomass stock per hectare.

Comparisons were made with the estimate obtained from applying Eq. 2, using Ireland's national default values (Table 2) for BEF, wood density and C concentration and methods for determining stand volume. Additionally, the biomass functions published in the literature (Ter-Mikaelian and Korzukhin 1997) were compared with those developed in this study.

Table 3 Regression equations for predicting root biomass density

Equation	Intercept	*a*	*b*	*c*	*d*
A[a]	−1.0850	0.9256	–	–	–
B[b]	−1.3267	0.8877	0.1045	–	–
C[c]	−1.0587	0.8836	–	0.2840	0.1874

Adapted from Cairns et al. (1997). All equations are of the form $Y = \exp[\text{intercept} + a(\ln A) + b(\ln B) + c(C) + d(D)$ where B is age in years, C is 1 in temperate and 0 in boreal and D is 0 in tropical[a] Estimates RBD based on ABD only

[b] As A, but adds age

[c] As A, but adds latitudinal zone

Table 4 DW:FW ratios and biomass distribution between components

Component	N	Mean	% Uncertainty
Deadwood	50	0.55	3.6
Stemwood	60	0.35	2.2
Branchwood	120	0.43	3.4
Foliage	120	0.43	3.0
Bark	60	0.43	4.8
Small roots	50	0.43	2.6
Medium roots	50	0.42	2.7
Large roots	50	0.40	2.8

The methods for determining belowground biomass stocks are not as well established as those for aboveground biomass (Cairns et al. 1997). In this study, belowground biomass stocks are reported as a proportion of the aboveground biomass (i.e. R ratio), and our estimates are compared with the regression equations for predicting root biomass density based on aboveground biomass density developed by Cairns et al. (1997) (Table 3).

Applying the C concentration [C] conversion factor to the biomass stock estimates of each approach yields an estimate of stand C stock (t C ha^{-1}).

Uncertainty

Uncertainties associated with each variable were reported as a confidence interval (expressed as a percentage) within which the underlying value of the uncertain quantity lies at a 95% probability (Penman et al. 2004). The percentage uncertainty is defined in Eq. 5 as half the 95% confidence interval width of the sampling distribution divided by the estimated value of the quantity, or otherwise twice the more commonly reported relative standard error (in %).

$$\%\ \text{uncertainty} = \frac{1}{2}\frac{(4\sigma)}{\mu} \times 100 = \frac{2\sigma}{\mu} \times 100 \qquad (5)$$

Uncertainty estimates of C stock where developed from the combined variable errors using Eq. 6

$$U_{\text{total}} = \sqrt{U_1^2 + U_2^2 + U_n^2} \qquad (6)$$

where U_{total} is the % uncertainty in the sum of the variables (half the 95% confidence interval divided by the total and expressed as a percentage) and U_i is the % of uncertainties associated with each of the variables.

Results

Descriptive statistics and ANOVA tests were conducted using the SPSS Version 11 (SPSS 2001).

Component DW:FW ratios and biomass distribution

All the samples were analysed using the component to determine a DW:FW ratio (Table 4), which was applied to the total FW of each component, as determined in the field to determine the component DW for each sample tree (Table 5).

Stemwood accounted for the majority of the aboveground biomass, with DW representing, on average, 43% of the total. Branchwood, foliage, bark and deadwood accounted for a further 16, 10, 7 and 6%, respectively. The remaining 18% was attributed to belowground biomass (i.e. small, medium and large roots).

Biomass functions

Biomass functions of the power form were compared on the basis of best fit (R^2) between aboveground tree component biomass and the independent variables DBH and height (Table 6). The best fit ($R^2 = 0.96$) was found between total aboveground live biomass (i.e. deadwood excluded) and DBH. The relationship between stemwood and DBH had an equivalent R^2. The relationships between biomass and height were also found to be strong.

Table 5 Component dry weight of each harvested tree

DBH (cm)	Deadwood (kg d.m.)	Stemwood (kg d.m.)	Branches (kg d.m.)	Foliage (kg d.m.)	Bark (kg d.m.)	Small roots (kg d.m.)	Medium roots (kg d.m.)	Large roots (kg d.m.)	Total (kg d.m.)
12	2.00	26.14	12.79	7.58	4.27	1.76	2.77	6.56	63.87
13	5.02	30.35	10.17	5.32	4.04	1.33	3.53	7.86	67.60
15	1.51	33.00	9.97	7.35	4.90	4.89	3.54	8.76	73.90
18	12.65	52.46	18.26	13.04	10.54	3.14	5.29	16.40	131.78
21	12.27	88.36	32.38	28.05	13.25	4.06	4.80	28.80	211.99
22	14.69	92.74	36.23	22.76	14.20	2.49	9.20	22.16	214.46
23	5.78	97.03	27.56	23.94	14.02	6.67	13.48	26.69	215.16
26	11.22	96.41	42.73	31.75	12.27	2.84	8.02	25.20	230.44
27	28.60	128.46	51.73	28.31	18.72	1.98	5.21	48.24	311.24
29	18.98	118.80	44.92	38.91	17.52	6.73	11.55	36.97	294.37

Table 6 Allometric relationships of tree component biomass with DBH and height

Component	DBH			Height		
	A	*B*	R^2	*a*	*b*	R^2
Aboveground[a]	0.3635	1.9382	0.96	0.0056	3.9057	0.85
Stemwood	0.2261	1.9030	0.96	0.0045	3.7682	0.83
Branchwood	0.0798	1.9182	0.89	0.0009	4.0055	0.86
Foliage	0.0241	2.2002	0.92	0.0002	4.4944	0.84
Bark	0.0449	1.8097	0.91	0.009	3.6443	0.81
Deadwood	0.0046	2.5015	0.66	0.00005	4.7280	0.51

[a] Includes living biomass components only (i.e. excludes deadwood)

Wood density

Wood density did not vary significantly with DBH and the measured mean of 0.38 tonnes d.m. m^{-3}, with an uncertainty of 6%, was found.

Volume

Comparisons of the three volume approaches determined that the Huber function, on an average, estimated the volume to within 7% of that measured, whereas applying tariff tables underestimated a single tree volume, on an average, by 24% (Fig. 2).

A weighted volume was developed for the stand using a simple relationship, Eq. 7,

$$V = a(\mathrm{DBH})^b \qquad (7)$$

between the measured volume and the DBH of the harvested trees, where $a = 0.001$ and $b = 1.823$ ($R^2 = 0.93$), and was found to be 274 m^3 ha^{-1} based on the diameter distribution (Fig. 1). Forestry yield tables (Hamilton 1975) for estimating volume at the stand level, based on the highest yield class and no thinning, found the volume of the stand to be 208 m^3 ha^{-1}, 24% less than the measured quantity.

Carbon content

No significant difference in the C content was found between components and the mean of 0.52 tonnes C (tonnes d.m.)$^{-1}$, with an uncertainty of 1%, was applied.

Aboveground biomass stock

Biomass functions

Calculating the C stock, using biomass functions, resulted in an estimate of 143 tonnes d.m. ha^{-1}, with an uncertainty of 7%. Applying the measured C content value, the aboveground C stock per hectare was estimated to be 74 tonnes C ha^{-1}, with an uncertainty of 7%. This represents an average annual aboveground C stock increment of 3.9 tonnes C ha^{-1}.

Biomass expansion factors

Comparison with the BEF method and its associated default variables for Ireland, reported in Lowe et al. (2000), provided a mean biomass stock estimate of 103 tonnes d.m. ha^{-1}, with an uncertainty of 29%, equivalent to 44 tonnes C ha^{-1}, with an uncertainty of 29%. This represents an average annual aboveground C stock increment of 2.3 tonnes C ha^{-1}. This method of estimating aboveground C stock resulted in an underestimate of 40%, when compared to that measured, and had an associated uncertainty almost four times that reported using the developed biomass function. The volume estimate generated using yield

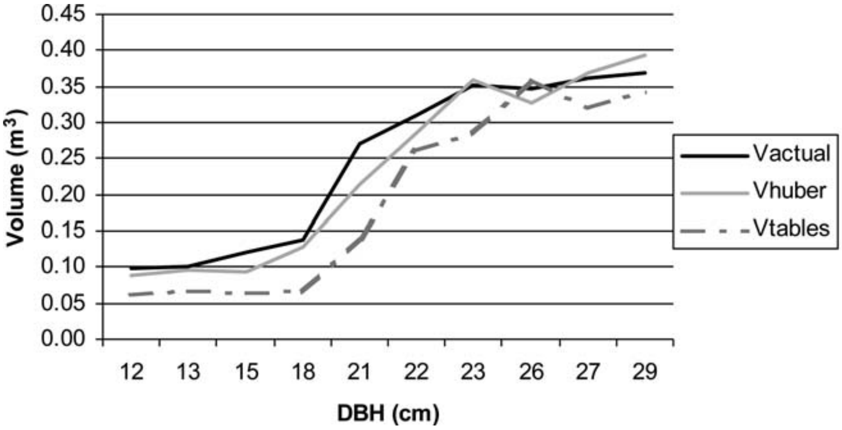

Fig. 2 Comparison of methods to estimate volume

models was the most significant source of uncertainty, in this instance, based on the results found in this study, and was followed by the C concentration and BEF value.

The recent publication of improved BEF and associated variables (Gallagher et al. 2004) yielded a mean biomass stock estimate of 119 tonnes d.m. ha^{-1}, with an uncertainty of 26%, equivalent to 60 tonnes C ha^{-1}, with an uncertainty of 26%. While it appears that these new values estimate C stock values that are more comparable with those developed using our functions, the BEF value reportedly includes belowground biomass.

The application of the mean BEF and associated variables, reported for Sitka spruce in the UK (Levy et al. 2004), resulted in a stock estimate of 105 t d.m. ha^{-1}, equivalent to 52 t C ha^{-1}.

Literature equations

The published equations for Sitka spruce biomass components were tested against those developed in this study at the stand level. For total aboveground biomass, these relationships yielded a total biomass stock estimate of 133 tonnes d.m. ha^{-1}, 7% less than that estimated with the developed relationships in this study and within the reported uncertainty. However, at the component level, the literature equations provided less reliable estimates of stemwood and branchwood, yielding an over estimate of 12% and an underestimate of 47%, respectively. The estimates of foliage were underestimated by 9%, when compared with those from functions developed in this study.

Belowground biomass

The average ratio of above- to belowground biomass was found to be 0.23, with an uncertainty of 10%. Belowground biomass was then estimated from the aboveground biomass stock, generated using the biomass function method, and was found to be 32.7 t d.m. ha^{-1}, with an uncertainty of 12%, equivalent to 17.0 t C ha^{-1}, with an uncertainty of 12%. This corresponds to an average annual belowground C stock increment of 0.89 t C ha^{-1} year^{-1}. The R value in our study (0.23) did not compare well with recently reported values in the UK (0.41) (Levy et al. 2004); however, comparisons made between above- and belowground biomass at the stand level, with those estimated using the relationships developed by Cairns et al. (1997), found a good correlation between the stock estimates. The equation for estimating root biomass density, only from aboveground biomass density (i.e. Equation A from Table 3), underestimated the stock by 2%. Incorporating the latitude or stand age into the equation lead to an overestimation of the root biomass stock by 10 and 12%, respectively.

Discussion

Components

Stemwood accounted for the largest proportion of the total aboveground biomass by weight (43%) and was approximately 10% lower than what was reported in another study of biomass distribution in Sitka spruce grown in Ireland (Carey and O'Brien 1979). Branchwood and the proportion of foliage were found to be higher. The proportion of roots (18%) was found to be similar to the estimate (16%) of Carey and O'Brien (1979). Differences in site conditions, stocking and management would account for these slight variations in the biomass distribution between these two studies.

Comparison with other models

Aboveground

In the absence of biomass functions specific to the Irish forestry conditions, the relationships developed in other countries would have to be applied for ecosystem modelling and developing C inventories for reporting to the UNFCCC. Calculations based on published equations (Ter-Mikaelian and Korzukhin 1997) yielded good total aboveground biomass stock estimates; however, estimates of the individual components are less reliable. National or even local growing conditions may be having an influence on the form of the tree, which further supports the need for nationally specific information for the development of representative biomass stock estimates.

Belowground biomass

In a review of the literature, Cairns et al. (1997) reported a mean R ratio of 0.26, which is comparable to our mean R ratio of 0.23. Comparisons with models of the relationship between above- and belowground biomass stock (Cairns et al. 1997) provided good estimates of belowground biomass, based on the measured aboveground biomass and stand age. The use of literature models for estimating belowground biomass provided estimates to within a measured uncertainty of our measured stock value (i.e. 12%).

The root excavation area chosen for this site could have resulted in a slight underestimation of the root stock and, therefore, lead to a lower reported R ratio. Ideally, the area excavated should represent the area occupied by the tree, which would be equivalent to tree spacing within the stand. The trees were spaced at 2.3 m in the study site, slightly wider than the recommended spacing of 2 m (Anon 2000), and the excavation of roots in a 2.3 m×2.3 m square would have been more appropriate. A study of Sitka spruce root production in Scotland (Deans 1981) found that the root diameter decreased rapidly in the first 1 m from the tree stumps and that almost 80% of the total root biomass (i.e. roots > 5 mm) was no more than 1 m from the tree stem. As this study suggests that root biomass stock would appear to reduce exponentially with the distance from the tree stump, the error associated with the chosen excavation area was considered to be relatively small.

According to the IPCC GPG (Penman et al. 2004), the mean default value of R, for conifer plantations with an aboveground biomass stock of 50–150 tonnes d.m. ha^{-1}, is 0.32 with a range of 0.24–0.50. According to default values, the R ratio decreases with an increasing aboveground biomass. Our work suggests that the R values in this stand are in the lower range of suggested default values, as would be expected since the aboveground biomass stock measured in the study site was at the higher end of the range (143 t d.m. ha^{-1}). For stands with over 150 t d.m. ha^{-1}, the mean R default value for reporting reduces to 0.23, the same value that was measured in our study.

Wood density

The basic density of wood can be influenced by a number of factors such as climate, growing medium and nutrition. In the reporting of forestry related biomass stock in Irelands national GHG inventory to the UNFCCC, a density value of 0.37 tonnes d.m. m^{-3} for coniferous species is used (Anon 1996b). This value is published by the British Forestry Commission (Hamilton 1975). Our measured value of 0.38 tonnes d.m. m^{-3}, with an uncertainty of 6%, corresponded very closely with this value.

Volume

Forest mensuration and management yield models developed in Britain (Hamilton and Christie 1971; Hamilton 1975) are commonly used in Irish conditions, in the absence of equivalent national information (Joyce and O'Carroll 2002).

However, the experience in Ireland has shown that recorded growth rates can be considerably in excess of the highest level covered by the tables (Joyce and O'Carroll 2002). The growth rate experienced at the study site was classified as in excess of Yield Class 24, the highest growth rate covered by the tables; this would account for the uncertainty in the stand volume estimate using the models.

Carbon concentration

In this study, the uncertainty associated with the mean C concentration (0.52 ± 1%) was low. When compared to the previous reported default value (0.43) (Lowe et al. 2000), it suggests a 17% variation. The value for C concentration is widely accepted to be 0.5 for C reporting and accounting (Penman et al. 2004). Our study suggests that the recent changes to this value, as reported by Gallagher et al. (2004), are justified.

Stock estimates

This study suggests that the annual C stock increment in Sitka spruce plantations in Ireland could be in the region of 3.90 tonnes C ha^{-1} $year^{-1}$ aboveground and 0.89 tonnes C ha^{-1} $year^{-1}$ belowground. Previous estimates of C stock increments (inclusive of forest and soil C) in Ireland have been reported as 3.36 tonnes C ha^{-1} $year^{-1}$ (Kilbride et al. 1999). Our study suggests that forests could store 13% more than this value in the aboveground C pool alone. This deviation can largely be attributed to conservative estimates of the BEF (1.3) and C concentration (0.43) (see Table 1). This study also indicates that the use of non-nationally specific variables, in the calculation of C stocks in Ireland, could result in significant underestimation of the aboveground component.

Uncertainty

Currently, there is no agreed precision at which C stocks should be measured and reported to the KP; however, the GPG (Penman et al. 2004) provided guidance to ensure that uncertainty estimates are reported in a consistent manner. As a result uncertainty estimates are twice the relative standard error (in %), the most commonly used statistical estimate of relative uncertainty.

Our study found that the direct measurement of aboveground biomass is subject to lower uncertainty than that of belowground biomass. The estimation of aboveground biomass, using biomass functions, may be subject to lower uncertainty, since the method is reliant on fewer variables, when compared with the application of the BEF approach, and is evident in the uncertainty estimates within the comparisons made in this study. Of the variables used in this method, the BEF had the largest associated uncertainty, estimated at 13%, based on the data gathered in this study. Stand level volume estimates generated from tables had the second highest uncertainty. Previous estimates of C stocks in Irish forests, using the BEF method, were subject to high uncertainty in the value used for C concentration; however, improved default values for reporting based on recent research undertaken on existing data in Ireland (Black et al. 2004; Gallagher et al. 2004) have now reduced this, but highlight the need for more field research in Irish conditions to improve the estimates for reporting and accounting requirements.

Relatively few studies have quantified the uncertainty associated with the development of stock estimates from biomass functions. The higher uncertainties reported here, compared with those reported in other studies (Lehtonen et al. 2004; Wirth et al. 2004), could be attributed to the rather small sample size, as the standard error of the mean decreases with increasing sample size.

Conclusion

Comparisons made between aboveground C stocks, estimated using the developed biomass functions, and the BEF approach, using the most recent updated variables, underestimated the C stock by 20% within the study site. More significantly, however, is the fact that the associated uncertainty with the BEF approach was up to four times that associated with the biomass function approach. This increased uncertainty was largely attributed to estimating the stand volume and the values used for C concentration and BEF. This study supported the increase of the value for the C concentration, to the widely accepted 0.5, leading directly to reduced uncertainty in the estimates. The use of British Forestry Commission Yield Models, for estimating the stand volume, had an impact on the uncertainty. The ongoing development of Irish models and forestry statistics, which will become available with the completion of the new NFI, will contribute to improved estimates of standing tree volume and reduced associated uncertainty in future reporting periods. Additionally, the important statistics from the NFI will provide species diameter distributions to enable the use of biomass functions in C stock estimates. Within our study site, C stock estimates developed using biomass functions were subject to reduced uncertainty when compared with the current BEF approach, suggesting this to be the preferred approach. More data, both from destructive tree sampling and the NFI, would be required to test this at the national level.

This study provides nationally specific information that can be used in the development of C stock estimates for reporting to the UNFCCC. Although Sitka spruce is a major tree species found in Irish forestry, conifer species such as Lodgepole pine (*P. contorta*), Norway spruce (*Picea abies*) and Japanese Larch (*Larix kaempferi*), as well as broadleaves such as Ash (*Fraxinus excelsior*), Alder (*Alnus spp.*) and Oak (*Quercus petraea*), are increasingly becoming significant species in the move to a more diverse national forest resource. With the provision of national data on these species, increased transparency and verifiability in the reporting of C stock estimates to the UNFCCC for forest land in Ireland will result.

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