Predicting carbon for Douglas-fir†

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Abstract

A method was developed to estimate the total carbon in live Douglas-fir stands (ie stemwood, bark, crown, and roots). The weight of stemwood was estimated by a pre-existing volumetric model (DFNAT) combined with a measurement of basic density. Bark was estimated as a proportion of stemwood. The weight of the crowns, and the weight of roots, was linked to the oven-dry weight of stemwood plus bark. Elemental carbon was assumed to be half the dry weight. These equations were installed in a pre-existing delivery mechanism ("The Douglas-fir Calculator") that predicts the physical and financial outcomes from a single hectare of even-aged trees. The equations in this paper are an improvement on previous estimates that had used linear rather than non-linear relationships, as well as an intercept value that gave irrational results for very low levels of stem biomass.

Introduction

There is a need for a simple but reasonably accurate tool to predict carbon fixation by stands of Douglas-fir (Mirbel) Franco. Douglas-fir occupies approximately 6% of the New Zealand plantation estate (111,000 ha planted as at April 2008; MAF, 2009).

In a stand of trees, carbon is present in the stem (including bark), the crown (branches and needles), and the roots, including that part of the stump that is below ground. It is also present in dead standing trees, cones, the understorey, the mineral soil and litter- both fine litter, and coarse woody debris, especially that arising from thinning operations. In this exercise we are, at this stage at least, only concerned with the carbon fixed within the standing live trees.

Moore (2005) reviewed all available NZ data on biomass in plantation species, including the published data on Douglas-fir (Nordmeyer & Ledgard, 1993) and unpublished data. He reported that 22 Douglas-fir trees had been measured for biomass in five age classes on three sites, in the 10-20 year age range. The tallest tree was 13.5 m. Moore used this data to fit simple allometric functions of above ground biomass (t/ha) to diameter at breast height (DBH, cm) and height (m). At the stand level, the model AGB (above-ground biomass) = $-0.0068 + 0.2525DBH^2$ gave an r^2 of 0.91, compared to an r^2 0.93 for more complicated logarithmic forms, including the addition of stand height. Most of the measurements were located in relatively young stands on rather harsh sites. Clearly these functions should only be used with caution in stands taller than 13.5m. Moore's review referred mainly to New Zealand and Australian work, and did not cite the recent publications by French researchers (Ranger & Gelhaye, 2001; Ponette *et al*., 2001) or mention that numerous studies on Douglas-fir biomass have been completed throughout the world.

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† *This paper is dedicated to the late Leith Knowles*

The simple allometric approach used by Moore takes no account of tree stocking or wood density which must have a direct effect on stand biomass. In contrast, an alternative approach described here incorporates biomass into the Douglas-fir Calculator, to enable carbon prediction using expansion factors based on wood density and stem volume which can be accurately estimated using the existing mensurational models. Carbon estimates using the Douglas-fir Calculator should, therefore, be much more accurate than those obtained using a simple allometric approach.

The growth model that predicts Douglas-fir growth and yield New Zealand-wide is called DF NAT (which stands for Douglas-fir National Growth Model). This model has been developed over the past 12 years, and has been progressively improved and upgraded (Knowles & Hansen, 2004, Kimberley & Knowles, 2007, Hansen & Knowles, 2007). It operates at the stand level, and predicts total under-bark standing volume (TSV) as affected by site and silviculture, including pruning and thinning. It is included in the Douglas-fir Calculator, a Microsoft EXCEL-based application developed at Scion on behalf of the New Zealand Farm Forestry Association and the New Zealand Douglas-fir Research Cooperative (Knowles, *et al*., 2004). Copies of this software are available to members of the Farm Forestry Association and the Diversified Species Theme of the Future Forests Research.

The existing Calculator permits the user to enter breast-height outerwood density, either from actual measurements, or from a look-up table. This is then converted to whole stand-density, which is therefore readily available to convert TSV to wood biomass.

Prediction of carbon for Douglas-fir has been greatly aided by two key papers published by the French (Ponette *et al*., 2001, and Ranger & Gelhaye, 2001). These deal with above and below ground biomass prediction respectively, and included analysis of all available published biomass studies throughout the world in Douglas-fir. They reported that some 88 stands of Douglas-fir have been sampled for above-ground biomass, and 38 for above-ground biomass. Using all the studies, two linear regressions were fitted to predict stem biomass (wood + bark, r^2 =0.9963) and root biomass (r^2=0.994) from the total above-ground biomass at the hectare level. Both the linear regressions fitted include an intercept, resulting in a negative stem biomass of 9.6 t/ha when above-ground biomass is zero, and negative root biomass of 1.4 t/ha when above-ground biomass is zero.

Materials and Methods

A summary of the key equations and assumptions involved in the Douglas-fir Calculator are as follows:

Equations:

- Wood density (t/m3) as entered in the Calculator for breast-height outerwood. The conversion of outerwood density from the age of measurement (Density of Outerwood 1, Age 1; or DO1, A1) to the age required for carbon reporting (DO2, A2) is given by the following equation (Knowles et al., 2004):

$$DO2 = \frac{DO1*(450.1 - 220.5^{(-0.0644*A2)})}{(450.1 - 220.5^{(-0.0644*A1)})} \quad [1]$$

- Stem wood biomass (t/ha) is TSV multiplied by the average basic density of the stand;
- Bark biomass (t/ha) is bark volume multiplied by bark density;
- Stem biomass (t/ha) is stem wood biomass added to bark biomass;
- Crown biomass (branches + needles; Y) is predicted using Equation [1] above

$Y=1.9057*X^{0.5496}$ (where X = stem+bark biomass) Equation [2];

- Total above-ground biomass is stem biomass added to crown biomass;
- Total live biomass (t/ha) is obtained by adding below-ground and above-ground biomass;
- Carbon content (t/ha) = biomass*0.50 (Matthews, 2006);
- Carbon dioxide equivalent (CO_2-e) is elemental carbon*3.667.

Assumptions:

- Factor for converting from breast-height outerwood density to under-bark stem density is 0.94 (Knowles *et al.*, 2003);
- Total under-bark stem volume (m^3/ha) as predicted by DF NAT within the Douglas-fir Calculator;
- Bark volume = 10% of TSV (McConnon & Knowles, 2004). Note that this is a conservative estimate, as Coastal Californian seed sources can have up to 14% bark;
- Bark density is assumed to be 0.35 t/m^3 in New Zealand (Harris & Nash, 1973), which is lower than the 0.40 t/m3 reported for Douglas-fir pulpwood in the US (Anon, 1975);
- Below-ground (root) biomass (t/ha) is 20% of above-ground biomass (Ranger & Gelhaye, 2001).

We hope that this information will be added as four new columns to the 'Stand History' sheet of the Calculator:

- CO_2 roots
- CO_2 stem+bark
- CO_2 crown (branches + needles)
- CO_2 total biomass

The columns dealing with biomass will be hidden to simplify the presentation of information.

Note that the existing 'root biomass' column in the Calculator utilises a biomass study from the Netherlands (Kuiper & Coutts, 1992). This will be converted to utilise the above regression, but will retain the decay function for decaying the stumps of thinnings and clear-felled stems as at present, as this is useful information for slope stability (Knowles, 2006). So the Calculator will display two root biomass columns- one labelled 'slope stability' giving total root biomass in kg/ha containing the decay function, and another labelled 'carbon' giving CO_2-equivalent content (t/ha) of the live roots, without the decay function.

Results

Fitting a new model to predict above-ground biomass

The paper by Ponette *et al.*, (2001) includes a summary of the data from the 88 studies of above-ground biomass, allowing a re-analysis of the data with a view to fitting a relationship utilising stem biomass as the predictive variable, and without an intercept. Initial examination showed that the relationship between crown biomass (branches and needles) and stem biomass (wood+bark) to be non-linear. Young stands have a much higher proportion of crown biomass relative to stem biomass compared to older stands. A non-linear regression predicting crown biomass from stem biomass, but without an intercept, was, therefore, fitted. (Figure 1).

Adding crown biomass to the stem biomass provides total above-ground biomass. The analysis showed this to be a superior approach, by eliminating the intercept, and resulting in a smaller residual mean square for prediction of above ground biomass of 10.24 t/ha compared to 10.68 t/ha using the equation of Ponette *et al*. (2001). The prediction of above-ground biomass for the 88 data sets using this new function is shown in Figure 2.

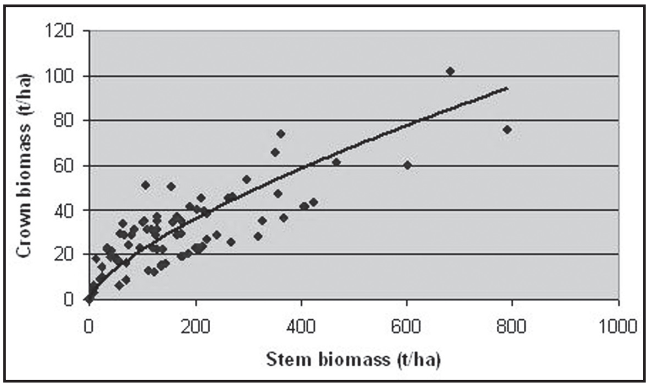

Figure 1: Relationship between crown (branches+needles) and stem (wood+bark) biomass (n=88).

A re-fitting of the equation by Ranger & Gelhaye (2001) to predict below-ground biomass without an intercept is not readily possible as a summary of the 38 studies is not provided. Also, a negative intercept of just 1.4 t/ha means that only very young stands are affected by the presence of the intercept. Below-ground biomass is, therefore, predicted from total above-ground biomass using the slope coefficient (0.20) given in the equation of Ranger & Gelhaye (2001).

Validation using New Zealand Data

Validation of the above regressions and assumptions against New Zealand stands is desirable. A study by Nordmeyer & Ledgard (1993) in a 15 year old stand at Craigieburn is the only published source of biomass information in New Zealand Douglas-fir. This study is not referenced by Ponette *et al*. (2001) in their world-wide review. When the regression developed by Ponette *et al*. (2001) was reversed to predict total biomass from stem biomass, it predicted an above-ground biomass of 90.9 t/ha for the Craigieburn stand compared to the actual total above-ground biomass 109.3 t/ha. The improved function reported here predicts 92.8 t/ha. We understand that further data from a later age at the same Craigieburn site, and for two age classes at Ribbonwood (Omarama) will be made available for further validation (A Nordmeyer, pers comm.).

Additional work

The two missing components in the above approach for carbon prediction in Douglas-fir stands are coarse woody debris, and fine litter. It should be straightforward to be able to add some key elements of coarse woody debris to the carbon section of the Douglas-fir Calculator. Tree mortality in New Zealand Douglas-fir stands is already predicted within the Calculator using a recently updated function based on a modified version of Reineke's 3/2 power rule, based on analysis of more than 1300 permanent sample plots (Kimberley & Knowles, 2007). Thinning volume is also predicted. The derivation and provision of suitable decay functions for these two components, especially where thinning is to waste, would permit these major sources of

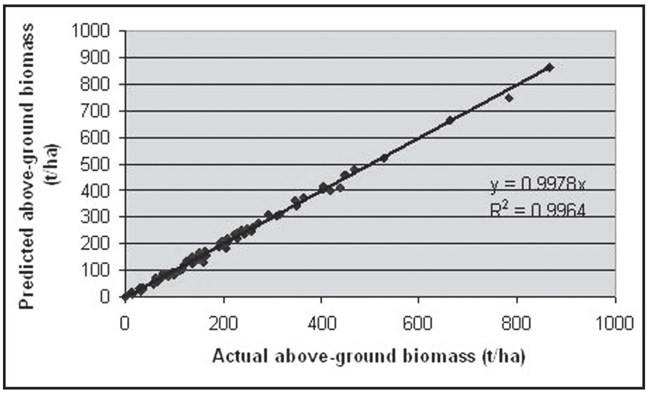

Figure 2: Relationship between predicted above ground biomass, utilising stem biomass and predicted crown biomass, compared to actual measurements (n=88).

coarse woody debris to be included. Douglas-fir is seldom pruned so there should be little need to include estimation of pruned branches, and their decay. Examination of the debris remaining following thinning to waste indicates the temporary nature of the coarse woody debris component. Ten-twelve years following thinning, little debris remains. The validity of using the existing decay function for roots would also have to be explored.

Once stands reach canopy closure, fine litter (t/ha) can be expected to stabilise through decomposition, and as the stem biomass continues to expand, to contribute a decreasing proportion of the total biomass. In a typical mature stand of *Pinus radiata* D.Don for example, fine litter contributes only 3-4% of the total biomass. Douglas-fir could be expected to follow a similar pattern, but actual measurements will be necessary to confirm this.

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