Forests **2015**, *6*, 3395-3411; doi:10.3390/f6103395

OPEN ACCESS

forests

ISSN 1999-4907

www.mdpi.com/journal/forests

Article

Empirical Estimates of Aboveground Carbon in Open *Eucalyptus* Forests of South-Eastern Australia and Its Potential Implication for National Carbon Accounting

Liubov Volkova [1,*], Huiquan Bi [2], Simon Murphy [1] and Christopher J Weston [1]

[1] School of Forest and Ecosystem Sciences, Faculty of Science, The University of Melbourne, Water Street, Creswick, Victoria 3363, Australia; E-Mails: murphys@unimelb.edu.au (S.M.); weston@unimelb.edu.au (C.J.W.)

[2] NSW Forest Science, Department of Primary Industries, Level 12, 10 Valentine Ave, Parramatta NSW 2150, Australia; E-Mail: huiquan.bi@dpi.nsw.gov.au

* Author to whom correspondence should be addressed; E-Mail: lubav@unimelb.edu.au; Tel.: +61-3-53-214-100; Fax: +61-3-53-214-166.

Academic Editors: Philip J. Polglase and Eric J. Jokela

Received: 14 August 2015 / Accepted: 15 September 2015 / Published: 24 September 2015

Abstract: The aboveground carbon (AGC) storage of open *Eucalyptus* forests is unknown yet they are estimated to account for almost 25% of all Australian forests and about 60% of forests in Victoria. In this study we provide the best possible estimates of total AGC including tree biomass derived from destructive biomass sampling across 23 study plots established in open *Eucalyptus* forests in Victoria. The field estimates of AGC were then used for calibration of Australia's National Carbon Accounting Model, FullCAM. The study aimed to develop a transparent and defendable method to estimate AGC for one of the most common Australian forests. Our calibrations showed that the 8.3 M ha of open *Eucalyptus* forests of SE Australia sequester at least 139 Mt C more than default FullCAM predictions. Because most of these forests are not subject to human-induced emission such as harvesting, only emissions and stock changes from a small area of these forests is reported in national inventories and international greenhouse emissions agreements. Concern for climate change and emission reduction will inevitably require land managers to come up with defendable methods of estimating forest carbon stocks and changes in all forest types; here we show how FullCAM can be further developed for this purpose.

Keywords: FullCAM; Litter; Coarse Woody Debris; allometric equations; understorey; fire emission

1. Introduction

Forests play a crucial role in the global carbon cycle so that maintaining and building forest carbon is central to limiting carbon emissions to the atmosphere from the biosphere. Developing transparent and accurate methods to estimate carbon stocks and changes is challenging because of the variability in forest carbon at a landscape scale, coupled with limited empirical forest biomass and soil carbon observations with which to build and to validate models.

In south-eastern (SE) Australia, medium open *Eucalyptus* forest (*i.e.*, crown cover >50%–80% and stand height >10–30 meters) extends over 8.3 M ha [1] and constitutes a significant and important carbon stock that is subject to change through altered wildland fire regimes, and forest management activities including timber extraction, prescribed fire and afforestation of previously cleared land [2]. Although separate estimates of forest carbon stock (e.g., [3,4]) and human-induced changes to carbon stock [5] have been published for the State of Victoria, there is no validation of these predictions with independently derived field observations.

A wide range of approaches to estimate forest carbon stocks and changes has been developed within national and state jurisdictions around the world. Australia's National Inventory System (NIS) uses several different methods to separately calculate forest carbon stocks and emissions for production forests, non-production forests, forest plantations and forest regrowth from land converted from crops or grassland [5]. Emission from forest fires (wild and prescribed) is estimated based on changes in fuel loads by forest type and State [6]. The Full Carbon Accounting Model (FullCAM [7]) integrates empirical sub-models that track the flow of carbon through biomass, debris, soil, products and the atmosphere [8]. Although the FullCAM tool allows for spatially explicit (Tier 3, tree yield formula) descriptions of forest carbon stocks and flows, it is applied by the Australian Government in a non-spatial (Tier 2, prescribed growth increments) mode for reporting human-induced emissions and removals from production forests using biomass increments tables adopted from [9]. A spatially explicit mode of FullCAM is used to estimate carbon stock changes due to the regrowth of forests following conversion from agriculture. However more than 90% of Australia's 125 M ha of forest is non-production forest where carbon stocks are derived from separate assumptions and modelling, not using FullCAM. This limited application of FullCAM in Australia's NIS recognizes that it requires further development before it can be implemented across Australia's broad range of non-production forests.

Despite the known limitations of FullCAM, and its restricted implementation by the Government, FullCAM is freely available and widely used by researchers to explore the impact of climate change and altered fire regimes or forest management on forest carbon stocks and emissions (e.g., [4,10]). Recent critical review of FullCAM shows that it systematically under-predicts aboveground forest carbon in medium open *Eucalyptus* forests (e.g., [11–13]). Therefore to realize the full potential of FullCAM its parameters should be tested for correlation with empirical measurements of forest carbon followed by independent validation as has been done for environmental plantings [14,15] and plantation forests [16,17].

To calculate aboveground biomass we applied recently developed allometric equations for eleven overstorey species derived from destructive sampling and weighing of whole trees [18], to forest inventory data collected across a broad range of open *Eucalyptus* forests that account for 60% of Victoria's forest estate. We aimed to compare and correlate these accurate biomass estimates with FullCAM predictions, and where necessary, to calibrate FullCAM by adjusting its parameters to improve aboveground biomass (AGB) estimates over larger areas of open eucalypt forest.

Forest aboveground biomass includes biomass of trees (overstorey and understorey) and debris (litter and woody material on the forest floor, [19]). Overstorey represents the biggest aboveground carbon pool in open *Eucalyptus* forests, accounting for 50%–70% of total AGB [20] and as such overstorey trees are usually the focus of destructively sampled biomass studies [21–23]. There are very few accurate estimates of other AGB components such as understorey, which make up between 8% and 33% of total AGB [20,24], and are an important carbon pool contributing to forest fire emissions [25]. Developing allometric equations from destructively sampled understorey trees is not well described in the literature and often surrogates are used to determine the carbon content of small trees [26], contributing to additional sources of uncertainty in estimation of carbon stock and greenhouse gases emission from temperate forests.

To improve estimates of forest carbon stocks the overall objectives of this study were: (1) to estimate total aboveground biomass of medium open *Eucalyptus* forest including destructively sampled biomass of overstorey and understorey trees and forest floor debris; (2) to develop a generic allometric equation for understorey trees that can be applied across medium open *Eucalyptus* forests of SE Australia; and (3) to calibrate the default tree yield formula of FullCAM based on our field biomass measurements.

2. Materials and Methods

2.1. Study Sites

Three distinct and separate areas of open *Eucalyptus* forests in central and eastern Victoria were selected for inventory and destructive sampling of aboveground biomass. The sites were chosen as representative of less-well studied non-managed forests of the drier inland slopes of central Victoria that are typical of large areas of open eucalypt forest in southern Australia

(Table 1, Figure 1). Common dominant tree species at the study sites included *Eucalyptus tricarpa* (Red Ironbark), *E. microcarpa* (Maiden) Maiden (Grey Box), *E. goniocalyx* F. Muell. ex Miq. (Long-leaved Box), *E. polyanthemos* Schauer (Red Box) and *E. macrorhyncha* F. Muell. ex Benth. (Red Stringybark). Soils across the sites vary from chromosols at Toombullup to sodosols at Pyrenees and Rushworth sites. These latter soils are highly weathered with generally poor water and nutrient retention, especially those typical of the Box Ironbark forest that have high quartz and gravel content. Mean annual rainfall ranges from around 526 mm at the Rushworth site to around 1166 mm in the herb-rich forests at Toombullup; average annual temperatures are 11 °C–15 °C (data derived from Bureau of Meteorology, http://www.bom.gov.au/climate/data, accessed on 1 February 2015).

Table 1. Details of the forest at each study site including overstorey species composition and stand characteristics.

#	Study Site/Forest Type	Dominant Species * (% Basal Area)	Stems (ha^{-1})	BA ($m^2 \cdot ha^{-1}$)	Dominant Height **(m)
Rushworth					
1	Box Ironbark Forest	RIB(100)	276	16.9	20.9
2	Box Ironbark Forest Mosaic	RIB(89), GB(11)	152	15.6	20.5
3	Box Ironbark Forest Mosaic	RIB(84), RB(16)	438	17.0	20.1
4	Box Ironbark Forest	GB(100)	495	10.2	22
5	Box Ironbark Forest	RB(39), GB(36), YG(24)	347	13.0	21.3
6	Box Ironbark Forest	RIB(27), GB(28), YG(45)	317	13.2	23.3
7	Box Ironbark Forest	RIB(43), GB(33), RB(23)	598	22.2	21
Toombullup					
1	Herb-rich Foothill Forest	NLP(66), MM(13), BG(13)	252	40.3	32.5
2	Herb-rich Foothill Forest	NLP(69), BG(22)	302	42.6	35.8
3	Heathy Dry Forest	YB(43), LLB(26), RSB(22)	437	24.8	31.4
4	Grassy Dry Forest	RSB(60), LLB(20), BLP(19)	529	36.2	26.3
5	Grassy Dry Forest	RSB(74), LLB(22)	485	32.2	20.9
6	Herb-rich Foothill Forest	RSB(89), BLP(8)	439	37.5	23.4
7	Herb-rich Foothill Forest	LLB(42), NLP(37), BLP(15)	549	42.0	26.4
8	Valley Grassy Forest	RSB(54), YB(21), LLB(9)	405	36.8	27.1

Table 1. *Cont.*

#	Study Site/Forest Type	Dominant Species * (% Basal Area)	Stems (ha^{-1})	BA ($m^2 \cdot ha^{-1}$)	Dominant Height **(m)
Pyrenees					
1	Box Ironbark Forest	RIB(95)	720	33.4	19.5
2	Box Ironbark Forest	RB(47), RSB(36), LLB(10)	554	25.6	15
3	Grassy Dry Forest	RSB(56), RB(37), YB(5)	627	31.4	21.5
4	Grassy Dry Forest	MM(56), BG(24), CB(9)	1,050	46.3	31.9
5	Grassy Dry Forest	MM(43), RSB(24), LLB(6)	702	46.5	23
6	Grassy Dry Forest	MM(54), CB(13), BLP(13)	539	38.5	25.8
7	Grassy Dry Forest	RSB(32), CB(31), YB(14)	390	25.8	20.6
8	Box Ironbark Forest	RSB(36), CB(35), YB(17)	334	19.2	18.1

Plot number within each study site/forest type. * YB, Yellow Box (*Eucalyptus melliodora* A. Cunn. ex Schauer); LLB, Long-leaved Box (*E. goniocalyx* F. Muell. ex Miq.); NLP, Narrow-leaved Peppermint (*E. radiata* Sieber ex DC); BG, Blue Gum (*E. bicostata* Maiden, Blakely & Simmons); MM, Messmate Stringybark (*E. obliqua* L'Hér.); RSB, Red Stringybark (*E. macrorhyncha* F. Meull. ex Benth.); RB, Red Box (*E. polyanthemos*); MA, Mountain Ash (*E. regnans*); RIB, Red Ironbark (*E. tricarpa*); YG, Yellow Gum (*E. leucoxylon* F. Meull.); CB, Candlebark (*E. rubida* Deane & Maiden); BLP, Broad-leaved Peppermint (*E. dives* Schauer); GB, Grey Box (*E. microcarpa* (Maiden) Maiden). ** Dominant height is a tree height of 3 largest trees of good health per plot.

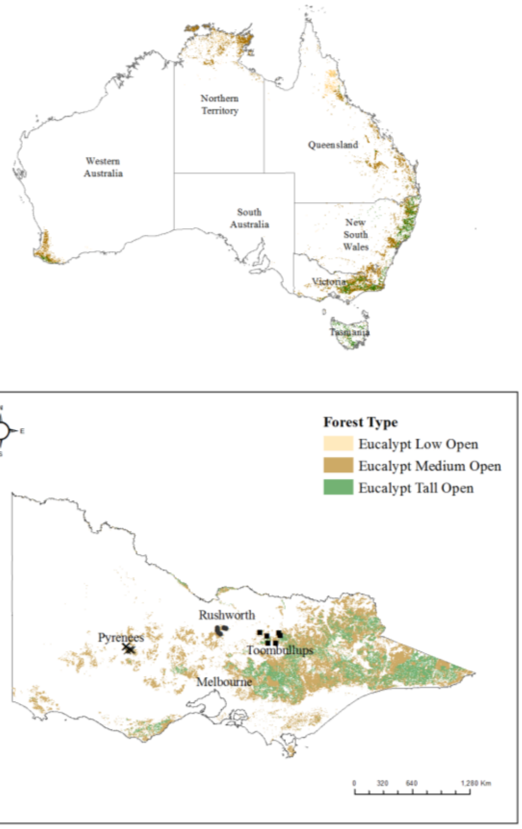

Figure 1. Study sites locations in *Eucalyptus* open forests of south-eastern (SE) Australia, where: × is Pyrenees, ● is Rushworth, and ■ is Toombullup.

2.2. Field Measurements of Overstorey and Understorey Trees

Live and dead trees in twenty-three inventory plots each of 0.5 ha (40 m radius circle) were identified, mapped and diameter at 1.3 m (diameter at breast height (DBH)) measured, prior to selecting a representative range of trees for biomass sampling. The five largest trees in each plot were measured for height to the nearest 0.1 m. The remaining trees were divided into diameter classes and for each class half of the trees were randomly chosen for height measurement. The total number of trees measured for height in each plot varied from 50 to 150 trees with a median of 70 trees among the 23 plots. For each plot, height and DBH equations were developed to predict the height of trees that were not measured.

Understorey trees of DBH between 1 cm and 10 cm were measured in each of four 5 m radius circular sub-plots in each quadrant of the inventory plot and species recorded.

2.3. Biomass of Overstorey, Small Trees, Coarse Woody Debris and Litter

Eleven *Eucalyptus* species occurred as major species in the three sites. Four sets of additive biomass equations for the estimation of stem, crown and total aboveground tree biomass of overstorey eucalypts have been developed [18]. The first two sets each consisted of 11 species-specific systems of additive biomass equations, with one set using the combined variable of DBH and tree height, D^2H, as the predictor and the other using DBH as the only predictor. The second two sets each had three site-specific systems of additive biomass equations, also with one set using the combined variable of DBH and tree height, D^2H, as the predictor and the other using DBH as the only predictor. These additive biomass equations were used to calculate the aboveground biomass of all overstorey trees with DBH greater than 10 cm in each plot.

Using the combined variable of DBH and tree height, D^2H, as the predictor, stem, crown and total aboveground tree biomass were estimated for all eucalypt trees with either measured or predicted tree height. For a small number of overstorey trees of unknown species without measured or estimated tree height, the site-specific systems of additive biomass equations with DBH as the predictor were used. The same was done for trees of minor eucalypt species for which species-specific biomass equations were not available. For dead standing trees, total aboveground biomass included only the stem component; crown biomass was excluded from the estimation. There were a total of 8 *Acacia dealbata* and *A. mearnsii* (De Wild) trees, but only three *A. dealbata* (A. Cunn.) were alive. For these trees, the additive biomass equations developed for *A. dealbata* [21] were used and crown biomass was also excluded from the calculation of total tree biomass for dead trees. Finally, the biomass of individual trees in each plot was summed up by two categories (*i.e.*, alive or dead) and converted to stand biomass on a per hectare basis.

To estimate understorey tree mass, 54 trees, mostly *Eucalyptus* and *Acacia* species, with DBH mostly below 10 cm were cut at ground level, weighed and a 2 cm–4 cm length section of stem sampled for oven dry weight (70 °C) to allow estimation of whole tree dry weight from the fresh weight. A generic nonlinear equation was developed to fit a curve to mass *versus* DBH for the 54 sample trees and estimate the total aboveground biomass of understorey trees.

Coarse woody debris (CWD) and litter were sampled along 100 m transects adjacent to each of the 8 plots selected for biomass sampling. Litter was sampled within 2 × 0.1 m^2 sampling rings along transect (20 m, 40 m, 60 m, 80 m); while mass of CWD was estimated following the methodology of [27]. The Rushworth site is dominated by Box Ironbark *Eucalyptus* species that are known for relatively high wood density, and to account for this representative cross sections of CWD of approximately 2–4 cm wide were sampled and measured in the laboratory for wood density by water displacement. The density of CWD at the Toombullup and Pyrenees sites was assumed to 464 $kg \cdot m^{-3}$ (sound) and 315 $kg \cdot m^{-3}$ (rotten) as these sites tend to be dominated by *Eucalyptus* species of medium to low wood density; these values are adopted from [28].

2.4. Deriving Plot Scale Biomass Estimates

Field estimated aboveground live biomass was used for validation and adjustment of FullCAM estimates as described below. A further step to calculate total aboveground biomass, including live and dead components, was calculated as the sum of the mass of live trees (overstorey and understorey), dead standing (overstorey and understorey) and debris (including CWD and litter).

2.5. Estimating Tree Biomass Using FullCAM

The Full Carbon Accounting Model (FullCAM Version 3.55) was used in Tier 3 spatially explicit mode (Tree growth based on Tree Yield Formula) with all parameters set to default values. Estimates of aboveground live biomass (AGB live) for each of the 23 study plots were computed in tonnes dry matter per hectare ($t \cdot dm \cdot ha^{-1}$) and converted to carbon mass by multiplying by 0.5. The spatially explicit mode of FullCAM implements a Tree Yield Formula (TYF) to estimate aboveground tree biomass at any given stand age using Equation (1) (for details see http://www.fullcam.com):

$$T(A) = r \times M \times y \times \exp(-\frac{k}{d}) \quad (1)$$

where: *T*—Aboveground stand biomass ($t \cdot dm \cdot ha^{-1}$); *A*—stand Age (years); *M*—Maximum aboveground biomass of trees (t ha^{-1}); *r*—Maximum aboveground biomass multiplier; *y*—Tree yield multiplier; $k = 2 \times G - 1.25$; and *G*—Tree age of maximum growth (years), *d*—adjusted age of the trees (years).

To generate maximum aboveground biomass of trees (*M*) in TYF mode, FullCAM relies on a dimensionless measure of site productivity—Forest Productivity Index (FPI). The FPI is calculated from national databases of site biophysical attributes such as rainfall, soil type, radiation, and vapor pressure deficit [29]. Estimates of both the annual FPI and long-term average FPI vary temporally and spatially and are available from the FullCAM database [30]. To overcome issues of either over– or under–estimating tree biomass in mature native forests, a maximum aboveground biomass multiplier (*r*) was introduced in FullCAM to allow adjustment of model predictions to real conditions. For example, this feature of FullCAM allowed improvement in the TYF by modifying *r* and *G* to better estimate AGB in mixed-species environmental plantings [31]. Similarly, in this study of open *Eucalyptus* forests we calibrated the *r* of the TYF, located in "Growth" of the "Trees" tab of FullCAM.

2.6. Calibrating the Tree Yield Formula of FullCAM

The Tree Yield Formula was used to calculate tree growth (Equation 1). Because stand age in the study sites was not known and the forests were of two or more age cohorts, the parameters relating to growth rate, *G* and *y*, were not appropriate for modifying FullCAM biomass estimates and remained default throughout calculations. Rather, the maximum AGB multiplier parameter, *r*, was used to adjust the maximum AGB of live trees (M). This provided an approach to explore better aligning observed and predicted estimates, with the underlying assumption being that these plots represented stands that were close to their maximum AGB. To estimate tree biomass in FullCAM the simulation period was set to 1900–2011, species was selected as *Eucalyptus* Open Forest and default settings adopted for tree age of maximum growth (*G*) = 10 and Tree yield multiplier (*y*) = 1.

For each of the 23 study plots, the observed (field measured) and predicted (FullCAM) estimates of aboveground tree biomass were plotted, with a 1:1 line used to indicate the distribution of estimates and to display any bias. Initially the FullCAM predictions were made with the value of *r* set to 1; then different values of *r* (range 0.8–7) were applied for each plot to reach zero difference in observed and predicted biomass estimates. This was achieved by finding a point of intersection between observed and predicted biomass using the slope and intersect function of two lines (before and after intersection). In this way the maximum aboveground biomass multiplier *(r)* for each plot was estimated as following:

$$r = (observed\ biomass - intercept)/slope. \tag{2}$$

For each plot, after determining the new *r*, FullCAM was re-run to confirm that predicted biomass matched the observed. The new calibrated *r* values were investigated for consistent relationships with forest productivity to identify transparent and defensible ways to adjust the tree yield formula in FullCAM and to achieve more accurate forest carbon predictions for multi-aged open *Eucalyptus* forests.

3. Results

3.1. Study Sites

The 23 study plots cover a range of ecological vegetation classes that fall into open forest formation (Table 1, Figure 1). The Rushworth study site is dominated by Box Ironbark forest of *E. tricarpa* and *E. microcarpa* with basal area (BA) from 10 to 33 $m^2 \cdot ha^{-1}$ (Table 1). These Box Ironbark forests are notable for their sparse understorey and generally low productivity relative to the other forests in this study and to open forests in general. The Toombullup site is dominated by herb-rich and grassy dry forests, with an average basal area of 37 $m^2 \cdot ha^{-1}$ and with tall open forest (to 35 m height) in some plots. The Pyrenees site is a mix of Box Ironbark and grassy dry forest types with a higher overstorey density (average 615 stems ha^{-1}) than the other sites (Table 1).

3.2. Biomass Equation for Understorey Trees with DBH Less Than 10 cm

The total aboveground biomass of understorey trees was estimated from a curve fitted to mass *versus* DBH as shown in Figure 2. The equation was fitted through nonlinear least squares and had a generalized r^2 of 0.91 (Equation (3), Figure 2):

$$Mass = e^{-2.3243} \times D^{2.4891} \quad (3)$$

where: *Mass* is the total aboveground tree biomass of understorey trees with DBH < 10 cm (kg) and D is diameter at breast height overbark (cm).

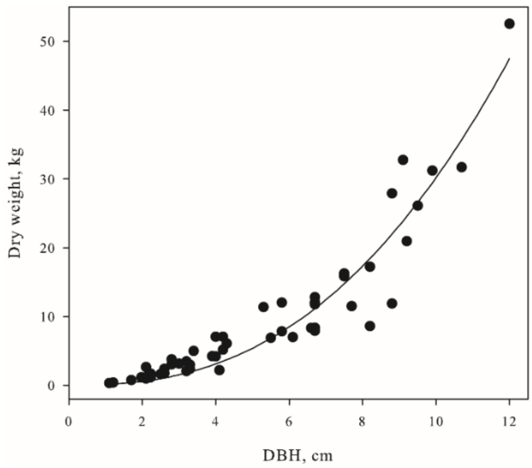

Figure 2. Relationship between total aboveground dry weight of understorey trees (DBH < 10 cm) and diameter at breast height (1.3 m) overbark fitted to nonlinear curve. DBH: diameter at breast height.

3.3. Field Measured Aboveground Biomass in Medium Open Eucalyptus Forests

In these open *Eucalyptus* forests overstorey trees accounted for about 80.5% of total aboveground biomass (AGB), with 167 $t \cdot dm \cdot ha^{-1}$ in live trees averaged over all three study areas (Table 2). The Toombullup forests are the most productive in the study, with almost double the live overstorey biomass (225 $t \cdot dm \cdot ha^{-1}$) compared with Box Ironbark forests of the Rushworth sites, which were the lowest productivity forests in the study area (115 $t \cdot dm \cdot ha^{-1}$ Table 2). On average, understorey trees accounted for two percent of total AGB (4.8 $t \cdot dm \cdot ha^{-1}$), and ranged from 1 to 8 $t \cdot dm \cdot ha^{-1}$ among sites (Table 2).

Table 2. Aboveground biomass (AGB, t·dm·ha^{-1}) in medium open *Eucalyptus* forests of south-eastern Australia.

Site	AGB Live		Dead Standing		Debris		AGB Total
	Ov	Un	Ov	Un	CWD	Litter	
Rushworth	115 ± 13.9	1.2 ± 0.6	3.2 ± 2.7	0.03 ± 0.2	1.9 ± 0.4	5.7 ± 2.2	126 ± 8.0
Pyrenees	160 ± 18.1	8.1 ± 2.9	21.6 ± 3.5	3.5 ± 1.3	4.2 ± 1.1	5.8 ± 0.4	204 ± 22.7
Toombullup	225 ± 23.6	5.1 ± 1.8	35.5 ± 6.9	2.7 ± 0.7	10.4 ± 5.1	8.1 ± 1.2	286 ± 21.9
Average	**167 ± 32**	**4.8 ± 2.0**	**20.1 ± 9.4**	**2.1 ± 1.1**	**5.5 ± 2.5**	**6.5 ± 0.8**	**206 ± 46.1**
%	81	2	10	1	3	3	100

Values are mean ± S.E. (Standard Error); Ov = Overstorey, Un = Understorey. CWD = coarse woody debris.

Dead overstorey trees accounted for 10% of total AGB or 20 t·dm·ha^{-1}, dead understorey trees contributed only 1% to total AGB (2.1 t·dm·ha^{-1}). Litter (6.5 t·dm·ha^{-1}) and CWD (5.5 t·dm·ha^{-1}) each contributed to about 3% of total AGB (Table 2). *E. tricarpa* (and *E. microcarpa, E. leucoxylon*) has high CWD density of 952 kg·m^{-3}, almost twice that of other species in the study (464 kg·m^{-3}), yet CWD loads in the pure Box Ironbark forests of the Rushworth site were relatively low, probably reflecting fire wood removal allowed at the study site.

3.4. Biomass Estimates: FullCAM vs. Field Measurements

Empirically estimated (observed) aboveground live tree biomass (AGB live) was compared against FullCAM predictions for the same sites at the default parameters (r = 1) (Figure 3). FullCAM predictions at default r were within the observed range of AGB for the low productivity Box Ironbark forests at the Rushworth, and about 30% lower than field-measured AGB live above 125 t·dm·ha^{-1} (Figure 3).

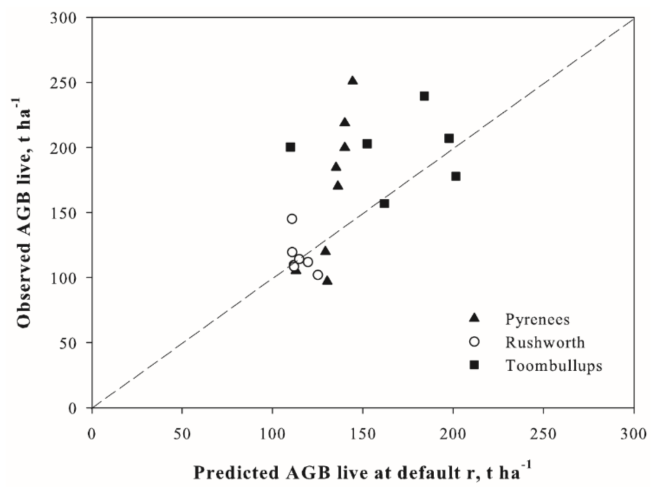

Figure 3. Observed *vs.* Full Carbon Accounting Model predicted aboveground live biomass in *Eucalyptus* open forests of SE Australia at default *r*.

Calibrated the maximum aboveground multiplier *r* was strongly correlated with aboveground live biomass and tended to increase with increase in AGB live (Figure 4).

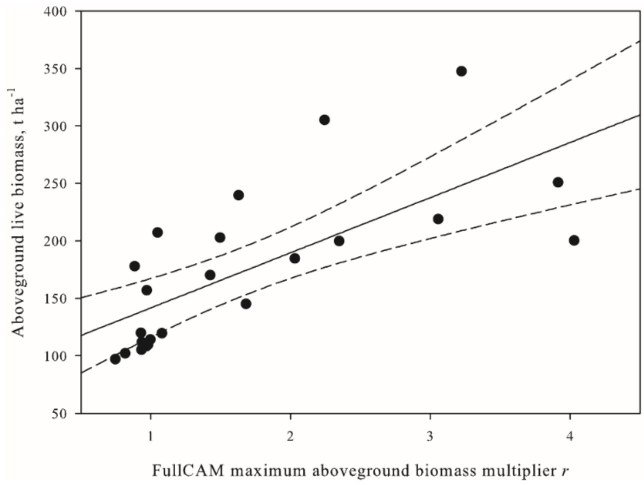

Figure 4. Maximum aboveground biomass multiplier (*r*) fitted to aboveground biomass (AGB) live using linear regression function. Dash lines are 95% confidence interval; Pearson correlation coefficient $r = 0.712$, $p < 0.001$.

Calibration of *r* did not improve FullCAM predictions in total aboveground carbon. The aboveground debris pool (litter and CWD) remained significantly lower than the observed values and dead standing trees were not accounted in default settings of FullCAM (Figure 5).

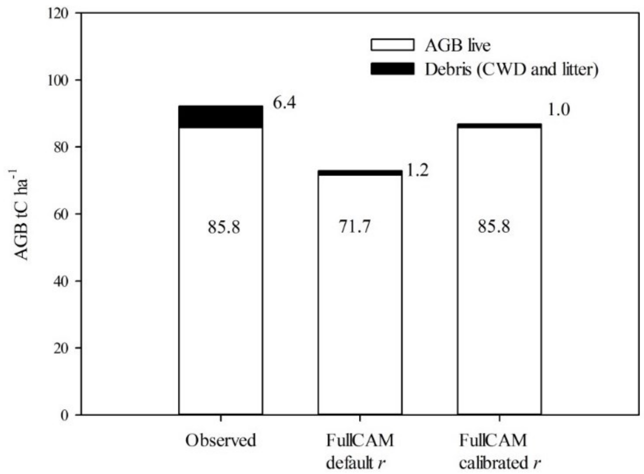

Figure 5. Observed and Full Carbon Accounting Model predicted (before and after calibration) aboveground biomass (AGB) and debris pools (tonnes carbon per hectare).

4. Discussion

4.1. Implications for Land Management Policy

The revised calibration of FullCAM increases estimated forest carbon in open *Eucalyptus* forests of south-eastern Australia over default FullCAM estimates, especially for higher productivity forests. Medium open *Eucalyptus* forests occupy around 3.1 M ha in Victoria and around 8.3 M ha in south-eastern Australia (including Victoria, Tasmania, NSW, South Australia and ACT, Figure 1). The AGB sampled in this study ranges from 48 $t \cdot dm \cdot ha^{-1}$ to 183 $t \cdot dm \cdot ha^{-1}$, covering from low to medium range for aboveground tree biomass in open *Eucalyptus* forest of Victoria (e.g., 75–239 $t \cdot dm \cdot ha^{-1}$ [3]). If we apply the re-calibrated FullCAM to the median AGB in our dataset (170 $t \cdot dm \cdot ha^{-1}$; $r = 1.4$), the open forest carbon stock estimate increases by an average 34 $t \cdot dm \cdot ha^{-1}$, equivalent to an increase of almost 53 Mt C currently not accounted in Victoria's forests, or 139 Mt C ha for SE Australian forests. This revised estimate also has implications for evaluating management impacts on forest carbon, including human-induced changes to forest stocks that are currently accounted in the national inventory.

4.2. FullCAM

For the range of forests in this study the FullCAM tool in default settings accurately predicted aboveground biomass for the lower productivity forests with 90 to 125 $t \cdot dm \cdot ha^{-1}$ stored in AGB live. As biomass increased beyond 125 $t \cdot dm \cdot ha^{-1}$ FullCAM increasingly underestimated biomass, revealing a strong trend for under prediction of forest carbon in higher productivity forests. This trend supports the findings by other studies where FullCAM predictions were analyzed against a dataset of 221 estimates of AGB live [32] concluding that FullCAM systematically under-predicted native vegetation biomass in those sites where vegetation carbon is greater than approximately 100 $t \cdot C \cdot ha^{-1}$ [11].

The calibration of FullCAM presented here involves simple adjustment of the *r* term in the tree yield formula (in FullCAM under the trees tab > growth tab) before running the model, to improve prediction of aboveground tree biomass for medium open *Eucalyptus* forests of SE Australia. Although forests vary in understorey characteristics and structure, because AGB is dominated by overstorey trees (80%, this study), calibrating the "*r*", that ignores species composition, is reasonable. The calibration of the maximum aboveground biomass multiplier *r* was based on 23 plot-level estimates of biomass derived from destructive sampling of 337 overstorey trees of variable age, height and diameter classes. This is the most detailed study of aboveground tree biomass available for medium open *Eucalyptus* forests of SE Australia. This calibration of FullCAM provides improved regional aboveground biomass estimates and will benefit from further verification with field measurements from a broader range of open forests in SE Australia.

4.3. FullCAM Does Not Adequately Predict Dead Standing and Forest Debris Pools

The FullCAM tool run in default mode does not accurately predict CWD and litter of aboveground carbon. Field observations clearly showed that forest floor debris (CWD and litter) contribute around 6% to total AGB (Table 2). Notably, CWD loads in our study were lower than reported for similar forest type [33], most likely as a result of firewood fuel removal from the study sites in the past. Yet even following calibration of the TYF to improve AGB estimates, FullCAM under estimates CWD and litter by 6 times (mean 1 t·dm·C·ha^{-1} in both default and calibrated FullCAM *vs.* 6 t·dm·C·ha^{-1} observed, Figure 5). Other studies also observed disconnection between growth dynamics of the living vegetation pools and litter in the Tree Yield Formula, hence "the living plant turnover percentages can be altered to increase or decrease the stock of litter carbon, but modifying these parameters does not affect the biomass pools themselves" [11]. Furthermore the dead standing trees component is not created in the default FullCAM settings so that about 11% of AGC is not accounted (Table 2). This shows that FullCAM input parameters need further calibration to adequately represent dead standing and forest floor debris pools. Because these dead standing and debris pools make up the majority of biomass consumed in fire, e.g., [25,34] we do not recommend using FullCAM to model greenhouse gas emissions from forest fires.

4.4. Importance of Allometric Equations for Small Trees

This work resulted in the development of a generic allometric equation to estimate biomass for small, understorey trees, with DBH < 10 cm in the medium open *Eucalyptus* forests of SE Australia. While understorey accounted for a minor proportion of AGC in studied forests (about 3%), it is an important carbon pool that can contribute between 2% and 28% to forest fire emissions [20,25]. The developed allometric equation for understorey trees will contribute to more accurate estimates of this small but significant carbon pool and improve our understanding of understorey contribution to forest carbon cycling and ecosystem productivity [35].

5. Conclusions

We provided one of the most accurate estimates of AGB for medium open *Eucalyptus* forests currently available in the literature. Our biomass measurements, based on whole-tree weighing, were applied to calibrate the carbon accounting model, FullCAM, broadly used in Australia. We demonstrated that with simple adjustment of the tree yield formula parameter *r*, FullCAM produces reliable predictions of aboveground live carbon stock in medium open *Eucalyptus* forests. It is believed that the observed relationship between *r* and AGB live (Figure 4) can be a useful tool in adjusting FullCAM predictions without complex and expensive field measurements, and the FullCAM developers could use this simple approach in revisions to improve the model, or as a guide to improving the underlying components of the TYF. We caution that any improvements in estimation of AGB live do not automatically improve estimates of the debris pool and dead standing biomass, as these are derived from look up tables in the initial settings tab, and must be adjusted from default to achieve better estimates. Consequently at present FullCAM is not reliable for estimates of forest fire emissions from medium open forests.

With growing interest in managing native vegetation for greenhouse benefit, a uniform system has to be adopted to produce transparent and reliable estimates of the carbon stock in native forests of Australia. Now is the time to start applying and evaluating FullCAM across a broader range of native ecosystems.

Acknowledgments

Authors would like to acknowledge funds provided by Victorian Department of Environment and Primary Industries as a part of Comprehensive Carbon Accounting Program (CCAP) project and the in-kind support of NSW Department of Primary Industries for this project. Comments from the Department of Environment on applicability of FullCAM in the National Inventory System are greatly appreciated.

Author Contributions

Liubov Volkova wrote the main body of the paper and worked on calibration of the FullCAM component. Huiquan Bi and Simon Murphy conceived and designed the field experiment and managed destructive sampling of tree biomass; Huiquan Bi developed allometric equations for understorey trees and estimated overall tree biomass. Christopher J Weston designed sampling of forest floor components, sampled data, analysed the data and significantly contributed to writing of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. The Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). *Australia's State of the Forests Report, Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee*; Australian Government, Department of Agriculture: Canberra, Australia, 2013.
2. Adams, M.; Attiwill, P. *Burning Issues: Sustainability and Management of Australia's Southern Forests*; CSIRO Publishing: Clayton, Victoria, Australia, 2011; pp. 1–144.
3. Grierson, P.F.; Adams, M.A.; Attiwill, P.M. Estimates of carbon storage in the aboveground biomass of Victoria's forests. *Aust. J. Bot.* **1992**, *40*, 631–640.
4. Norris, J.; Arnold, S.; Fairman, T. An indicative estimate of carbon stocks on Victoria's publicly managed land using the Full Carbon Accounting Model. *Aust. For.* **2010**, *73*, 209–219.

5. Commonwealth of Australia. *National Inventory Report (NIR)*; Commonwealth of Australia 2015: Canberra, Australia, 2013; Volume 2.
6. Roxburgh, S.H.; Volkova, L.; Surawski, N.; Meyer, M.; Weston, C.J. *Review of Fuel Loads, Burn Efficiencies, Emissions Factors and Recovery Functions Used to Estimate Greenhouse Gas Emissions and Removals Associated with Wildfire on Temperate Forested Lands*; Report for the Department of the Environment; CSIRO: Canberra, Australia, 2015, p. 35.
7. Richards, G.P.; Evans, D.M.W. Full Carbon Accounting Model (FullCAM). In *National Carbon Accounting System*; Australian Greenhouse Office: Canberra, Australia, 2000.
8. Paul, K.I.; Polglase, P.J. Prediction of decomposition of litter under eucalypts and pines using the FullCAM model. *For. Ecol. Manag.* **2004**, *191*, 73–92.
9. Lucas, R.M.; King, S.; Davis, S.; Whiteley, S. *The Role of Australia's Native Forests in Carbon Sequestration: Tasmania as a Case Study*; Report to the Department of Environment, Sports and Territories; Bureau of Resource Sciences: Canberra, Australia, 1997.
10. King, K.J.; de Ligt, R.M.; Cary, G.J. Fire and carbon dynamics under climate change in south-eastern Australia: Insights from FullCAM and firescape modelling. *Int. J. Wildl. Fire* **2011**, *20*, 563–577.
11. Roxburgh, S.; England, J.; Paul, K. *Developing Capability to Predict Biomass Carbon in Biodiverse Plantings and Native Forest Ecosystems*; CSIRO for the Department of Sustainability & Environment: Victoria, Australia, 2010.
12. Preece, N.D.; Crowley, G.M.; Lawes, M.J.; van Oosterzee, P. Comparing above-ground biomass among forest types in the wet tropics: Small stems and plantation types matter in carbon accounting. *For. Ecol. Manag.* **2012**, *264*, 228–237.
13. Fensham, R.J.; Fairfax, R.J.; Dwyer, J.M. Potential aboveground biomass in drought-prone forest used for rangeland pastoralism. *Ecol. Appl.* **2012**, *22*, 894–908.
14. Paul, K.; Polglase, P.; Snowdon, P.; Theiveyanathan, T.; Raison, J.; Grove, T.; Rance, S. Calibration and uncertainty analysis of a carbon accounting model to stem wood density and partitioning of biomass for *Eucalyptus Globulus* and *Pinus Radiata*. *New For.* **2006**, *31*, 513–533.
15. Paul, K.I.; Roxburgh, S.H.; England, J.R.; de Ligt, R.; Larmour, J.S.; Brooksbank, K.; Murphy, S.; Ritson, P.; Hobbs, T.; Lewis, T.; *et al.* Improved models for estimating temporal changes in carbon sequestration in above-ground biomass of mixed-species environmental plantings. *For. Ecol. Manag.* **2015**, *338*, 208–218.
16. Waterworth, R.M.; Richards, G.P.; Brack, C.L.; Evans, D.M.W. A generalised hybrid process-empirical model for predicting plantation forest growth. *For. Ecol. Manag.* **2007**, *238*, 231–243.
17. Waterworth, R.M.; Richards, G.P. Implementing Australian forest management practices into a Full Carbon Accounting Model. *For. Ecol. Manag.* **2008**, *255*, 2434–2443.

18. Bi, H.; Murphy, S.; Volkova, L.; Weston, C.; Fairman, T.; Li, Y.; Law, R.; Norris, J.; Lei, X.; Caccamo, G. Additive biomass equations based on complete weighing of sample trees for open eucalypt forest species in south-eastern Australia. *For. Ecol. Manag.* **2015**, *349*, 106–121.
19. The Intergovernmental Panel on Climate Change (IPCC). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*; Penman, J., Gytarsky, M., Eds.; Institute for Global Environmental Strategies (IGES) for IPCC: Kanagawa, Japan, 2003.
20. Volkova, L.; Weston, C.J. Carbon loss from planned fires in southeastern Australian dry eucalyptus forests. *For. Ecol. Manag.* **2015**, *336*, 91–98.
21. Bi, H.; Turner, J.; Lambert, M.J. Additive biomass equations for native eucalypt forest trees of temperate Australia. *Trees Struct. Funct.* **2004**, *18*, 467–479.
22. Bi, H.; Long, Y.S.; Turner, J.; Lei, Y.C.; Snowdon, P.; Li, Y.; Harper, R.; Zerihun, A.; Ximenes, F. Additive prediction of aboveground biomass for *Pinus radiata* (D. Don) plantations. *For. Ecol. Manag.* **2010**, *259*, 2301–2314.
23. Hamilton, S.D.; Brodie, G.; O'Dwyer, C. Allometric relationships for estimating biomass in grey box (*Eucalyptus microcarpa*). *Aust. For.* **2005**, *68*, 267–273.
24. Fedrigo, M.; Kasel, S.; Bennett, L.T.; Roxburgh, S.H.; Nitschke, C.R. Carbon stocks in temperate forests of south-eastern Australia reflect large tree distribution and edaphic conditions. *For. Ecol. Manag.* **2014**, *334*, 129–143.
25. Volkova, L.; Meyer, C.P.; Murphy, S.; Fairman, T.; Reisen, F.; Weston, C.J. Fuel reduction burning mitigates wildfire effects on forest carbon and greenhouse gas emission. *Int. J. Wildl. Fire* **2014**, *23*, 771–780.
26. Dean, C.; Fitzgerald, N.B.; Wardell-Johnson, G.W. Pre-logging carbon accounts in old-growth forests, via allometry: An example of mixed-forest in Tasmania, Australia. *Plant Biosyst.* **2012**, *146*, 223–236.
27. Van Wagner, C.E. Line intersect method in forest fuel sampling. *For. Sci.* **1968**, *14*, 20–26.
28. Volkova, L.; Weston, C.J. Redistribution and emission of forest carbon by planned burning in *Eucalyptus obliqua* (L. Hérit.) forest of south-eastern Australia. *For. Ecol. Manag.* **2013**, *304*, 383–390.
29. Landsberg, J.J.; Waring, R.H. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manag.* **1997**, *95*, 209–228.
30. Kesteven, J.; Landsberg, J.; URS Australia. *Developing a National Forest Productivity Model. National Carbon Accounting System*; Technical Report 23; Commonwealth of Australia, Australian Greenhouse Office: Canberra, Australia, 2004.
31. Paul, K.I.; Roxburgh, S.H.; de Ligt, R.; Ritson, P.; Brooksbank, K.; Peck, A.; Wildy, D.T.; Mendham, D.; Bennett, R.; Bartle, J.; *et al.* Estimating temporal changes in carbon sequestration in plantings of mallee eucalypts: Modelling improvements. *For. Ecol. Manag.* **2015**, *335*, 166–175.

32. Raison, J.; Keith, H.; Barrett, D.; Burrows, B.; Grierson, P. *Spatial Estimates of Biomass in "Mature" Native Vegetation;* Technical Report 44; Commonwealth of Australia, Australian Greenhouse Office: Canberra, Australia, 2003.
33. Woldendorp, G.; Keenan, R.J.; Barry, S.; Spencer, R.D. Analysis of sampling methods for coarse woody debris. *For. Ecol. Manag.* **2004**, *198*, 133–148.
34. Bennett, L.T.; Aponte, C.; Baker, T.G.; Tolhurst, K.G. Evaluating long-term effects of prescribed fire regimes on carbon stocks in a temperate eucalypt forest. *For. Ecol. Manag.* **2014**, *328*, 219–228.
35. Preece, N.D.; Lawes, M.J.; Rossman, A.K.; Curran, T.J.; van Oosterzee, P. Modelling the growth of young rainforest trees for biomass estimates and carbon sequestration accounting. *For. Ecol. Manag.* **2015**, *351*, 57–66.

© 2015 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).