CCAP

Comprehensive Carbon Assessment Program

Validating above-ground carbon estimates of eucalypt dominated forest in Victoria

Report to Victorian Centre for Climate Change Adaptation Research (VCCCAR) and the Department of Environment and Primary Industries (DEPI), June 2014

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Executive summary

Overview: This research, commissioned following a nationally legislated price for carbon, details the findings of the Comprehensive Carbon Assessment Program (CCAP) in improving: (1) the estimation of above-ground and below-ground biomass accumulation, and soil carbon in open eucalypt forest, and (2) the estimation of above-ground biomass accumulation in tall open eucalypt forest (see Appendix A; CCAP – Genesis and Evolution). The need to improve biomass estimates in these forest types came about as a consequence of former Department of Sustainability and Environment's LandCarbon project and the difficulties experienced with existing carbon modelling tools, which generated carbon estimates with significant uncertainty (see Appendix B; CCAP – Rationale).

Greater certainty in carbon estimation is required as part of mitigation and adaptation discussions and policy development around climate change. There has increasingly been an emphasis on developing more resilient terrestrial stocks of carbon that can adapt to climate change, play a role in mitigating atmospheric carbon dioxide, reduce risks associated with the management of carbon, and provide other ecosystem benefits such as biodiversity value. These stocks need to be quantifiable over time. CCAP was initiated to give greater certainty to carbon estimation for biodiverse ecosystems in Victoria.

Focus: While the primary focus of CCAP was on native open eucalypt forest on public land there was also a focus on private land, particularly where there was reforestation of this forest type. CCAP targeted this forest type because it covers a significant area of forested public land, has good biomass density with considerable above-ground carbon, and the majority of these forests are not well represented in previous carbon estimations. Additionally, these forests are found in the low to moderate rainfall zone (about 400-850 mm MAR), are often at the interface of public land and private land, and are therefore arguably the forest type that will be reforested under carbon reforestation initiatives such as the Commonwealth's Carbon Farming Initiative (CFI). Also, from an adaptation perspective, in the future this forest type is likely to be more impacted by disturbance associated with more frequent and extreme wildfire and drought as a consequence of climate change. Monitoring the resilience of these forests to disturbance and the extent of any carbon flux is likely to be an important management consideration. To do so will require using appropriate carbon estimation tools, with the preferred outcome being to develop an "improved FullCAM", which is capable of generating better estimates of biomass/carbon at the regional and project scale. Additionally, CCAP examined the influence of forest productivity on biomass/carbon estimation, using sites in the wetter tall open eucalypt forest (Mountain Ash dominated) type.

Above-ground biomass (AGB) in open eucalypt forest [Section (I)]: The ability to estimate the quantity of standing AGB/carbon in this forest type has been significantly improved, both for **native forests** and also for **reforested environmental plantings**. This has been achieved by developing two methodologies, destructive and non-destructive sampling, that allow more accurate determination of AGB.

A total of 337 trees across 8 native forest plots, with a maximum diameter of 143 cm (DBH), were destructively sampled (harvested), weighed and moisture-corrected. A total of 65 of these trees were used to parameterise and validate a non-destructive sampling approach using terrestrial laser scanning (TLS). When compared to the destructively-derived data the TLS approach showed an overestimation of about 10% in AGB compared to an underestimation of between 30 and 40% using existing allometric equations. Total AGB was derived for the 23 CCAP plots, averaging: Rushworth, 163 t ha^{-1}; Pyrenees, 234 t ha^{-1}; and Toombullups, 328 t ha^{-1} on a dry weight basis. Live AGB was compared to FullCAM predictions, with the current version (3.55) performing well for drier and less productive (Rushworth) sites (Δ4%) and significantly under predicting as sites became wetter and more productive (Pyrenees, Δ60%; Toombullups, Δ85%). For environmental plantings, destructive sampling (or 'direct measurement') in 3 of 11 Victorian sites was used as part of a larger data set to develop a range of allometric equations for providing regional estimates of above-ground biomass/carbon for a range of open eucalypt forest species. Recalibration of the FullCAM's yield curves (Tree Yield Formula) on the basis of planting geometry, spacing, and proportion of trees provided greatly improved predictions of biomass accumulation when compared to un-calibrated yield curves. This provided greater certainty in carbon estimation and, dependent on carbon price, should provide improved incentive for participation in schemes such as the Carbon Farming Initiative (CFI), which seek to financially reward landholders for "re-carbonising" their landscapes.

Below-ground biomass (BGB) in open eucalypt forest [Section (II)]: The ability to estimate the quantity of BGB/carbon has been significantly improved, for **native forests** and more particularly for **reforested environmental plantings**. This has been achieved by developing a destructive sampling methodology (whole plot excavation) for environmental plantings, which has allowed more accurate determination of BGB.

Three Victorian sites were used, as part of a larger data set, to develop root allometric equations for eucalypts (<52 cm DBH) and non-eucalypts (<40 cm DBH). Environmental planting data shows that root-to-shoot ratios can be high in water- and nutrient-limited environments. They ranged between 0.28 and 0.81 across 13 sites studied. Ratios were higher in tree-dominated sites, where the ratio tended to decline as productivity increased.

Soil carbon quantity and fractions (open eucalypt forest) [Section (III)]: The ability to estimate total organic carbon (TOC), particulate organic carbon (POC), humus organic carbon(HOC) and resistant organic carbon (ROC) of soils more cost-effectively has been demonstrated, using the MIR-PLSR calibration approach. Estimation of TOC has been demonstrated across a range of native forest sites, with varying soil texture, parent mineralogy, and dominant eucalypt species. It has also been demonstrated across a broad range ex-agricultural soils in which environmental plantings have been established. Additionally, for these soils the MIR spectroscopy methodology has also been able to predict the proportion of soil organic carbon with different classes of decomposability (ie. POC, HOC and ROC), providing a relatively cost-effective means for more completely describing the carbon sequestration ability of soils associated with reforestation. While this methodology has been demonstrated for the reforested environmental planting soils it is still being developed for native forest soils.

Above-ground biomass (AGB) in tall open forest (Mountain Ash) [Section (IV)]: The ability to estimate the quantity of standing AGB/carbon in this forest type has been significantly improved for native forests. This has been achieved by using a destructive sampling methodology.

A total of 98 mountain ash trees, with a diameter range of 17-121 cm (DBH), were destructively sampled (harvested), weighed and moisture-corrected. Allometric equations describing the relationship between live tree diameter (DBH) and tree fresh- and dry-weight of were developed. AGB of the mountain ash in these tall open forests were typically around 370 t ha-1 (on a dry weight basis), with additional AGB from understorey elements. Additional sampling is being conducted to expand the diameter range for Mountain Ash out to 160 cm (DBH).

Land management implications: In addition to any climate change policy implications, the research undertaken through CCAP has identified issues for land management. The key improvement is the development of new allometric equations, particularly using data representing the larger end of tree size class distributions. In the absence of appropriate allometric equations, the consequences for biomass estimation at the landscape scale can be significant. At this scale, bushfire can impact on a range of forest values, including carbon stocks, water resources, economic values, and biodiversity. Biomass/carbon estimation can be a critical tool in quantifying and evaluating associated consequences of this type of disturbance, or of lesser more localised disturbances such as harvesting. Overall, CCAP has provided a much improved capacity to estimate carbon in biodiverse ecosystems, which also has flow-on benefits to a range of ecosystem services. Additional knowledge will enhance this capacity and the ability of government to manage risk or to take opportunities as they develop in native forest environments.

Significant challenges remaining: To further improve Victorian biomass/carbon estimation there are some key challenges remaining:

1. The AGB data set for native forests should be expanded using a combination of both destructive and non-destructive sampling techniques. Priority should be given to older/larger trees and increasing the range of eucalypt and non-eucalypt species.
2. BGB estimation, particularly in native forests with larger trees, is poorly developed in both the open and tall open eucalypt forests. An appropriate sampling methodology has been developed which could be used to meet this challenge.
3. Soils – the ability to cost-effectively estimate soil carbon fractions in forest soils should be further developed, as it would significantly enhance the ability to monitor and manage the sequestration of carbon in these forest environments.
4. The environmental planting measurements are for younger stands, and temporal change in longer-term stand dynamics in above- and below-ground biomass remains poorly understood. Repeated temporal measurements of growth or the selected measurement of older individuals is required to expand the data set, and hence expand the range of biomass/carbon estimation and the recalibration of FullCAM.

Introduction

The background and development of CCAP has been summarised in Appendix A (CCAP – Genesis and Evolution) together with the 11 Milestones that relate to the current Agreement between the State (Department of Environment and Primary Industry) and The University of Melbourne (through VCCCAR - Victorian Centre Climate Change Adaptation Research Centre). These have been grouped into 4 broad research areas for the purpose of clarity and utility, and are detailed in Appendix A - Table A.1. Additionally, the supporting rationale for CCAP and its activities is detailed in Appendix B (CCAP – Rationale).

Pursuant to the VCCCAR Agreement and the CCAP rationale, DEPI and The University of Melbourne embarked on a program of research with the expected outcome being that Victorian land managers and landowners would have better incentives to undertake biodiverse reforestation and revegetation projects associated in particular with Open Eucalypt Forest. A secondary expectation was that this would also extend to Tall Open (Mountain Ash) Forest. Additionally, there was an expectation that the National Carbon Assessment Scheme (NCAS) should better reflect the carbon potential of native forest systems in Victoria, in relation to both public and private lands. This research and its outcomes are captured under four broad areas of interest, namely:

Open eucalypt forest (including environmental planting)

I. Above-ground biomass (AGB) - Quantity of biomass stored above-ground, how to improve its estimation using an 'improved' FullCAM, and what would be the implications for carbon accounting.
II. Below-ground biomass (BGB) - Quantity of biomass stored below-ground, how to improve its estimation, and the relationship between below- and above-ground biomass.
III. Soil carbon quantity and fractions (SCF).

Tall open forests (Mountain Ash)

IV. Above-ground biomass (AGB) - Quantity of biomass carbon stored above-ground and the implications for carbon accounting.

VCCCAR has supervised the delivery of the CCAP Milestones via the University's Department of Forest and Ecosystem Science (DFES).

This report provides an overview of the CCAP research findings, and includes research where CCAP collaborated with other research agencies. Principally, with CSIRO's Division of Ecosystem Sciences, and Division of Land and Water, and the NSW Department of Primary Industry. In particular, Dr Huiquan Bi from NSW DPI as well being an author to this report has provided biometric services to the above-ground native forest component of CCAP that have assisted greatly in establishment, data collection, analysis and reporting.

The structure of this overview is based on the four research areas listed above. CCAP research is summarised with reference to journal publications, findings in preparation for publication, or unpublished reports.

CCAP publications

Publications that have resulted from CCAP funding, collaboration or both are listed below by research area, as follows:

Open eucalypt forest (including environmental planting)

(I) Above-ground biomass open forest

Calders *et al.* (2013). Estimating above ground biomass from terrestrial laser scanning in Australian eucalypt open forest. Silvi-Laser 2013, 9-11 Oct. 2013, Beijing, China.

Calders *et al.* (In Review) Non-destructive estimates of above ground biomass using terrestrial laser scanning. Methods in Ecology and Evolution.

Paul *et al*. 2013a. Improved estimation of biomass accumulation by environmental planting and mallee plantings using FullCAM. Report for Department of Climate Change and Energy Efficiency. CSIRO Sustainable Agriculture Flagship, Canberra, Australia.

Paul *et al*. 2013b. Development and testing of allometric equations for estimating above-ground biomass of mixed-species environmental plantings. Forest Ecol. Manage. 310, 483-494.

Paul *et al*. (In Review) Improved models for estimating temporal changes in carbon sequestration in above-ground biomass of mixed-species environmental plantings. Forest Ecol. Manage.

Volkova et al. (In Prep) Assessment of aboveground biomass in eucalypt open forests and implications for the national carbon accounting system.

Bi et al. (In Prep) Developing species – specific allometric equations for open eucalypt forest.

(II) Below-ground biomass open forest

Paul *et al*. 2013a. Improved estimation of biomass accumulation by environmental planting and mallee plantings using FullCAM. Report for Department of Climate Change and Energy Efficiency. CSIRO Sustainable Agriculture Flagship, Canberra, Australia.

Paul *et al.* 2014. Root biomass of carbon plantings in agricultural landscapes of southern Australia: Development and testing of allometrics. Forest Ecol. Manage. 318, 216-227.

(III) Soil carbon quantity and fractionations open forest.

Madhavan *et al*. (In Prep) Characterisation and estimation of soil organic carbon fractions in biodiverse environmental plantings, using mid-infrared spectroscopic techniques.

Krishnaraj *et al*. (In Prep) Prediction of soil organic carbon using Mid-Infra-Red Spectroscopy in contrasting soils of Victorian native forests.

(IV) Above-ground biomass in tall open forest (Mountain Ash)

Ximenes *et al.* (In Prep.). Carbon stocks and flows in native forests and harvested wood products in South-east Australia. Report to Forest and Wood Products Australia.

Above-ground biomass in open eucalypt forests

In researching the quantity of biomass stored above-ground biomass (AGB) in Open Eucalypt Forest, CCAP evaluated both Native forest sites (Section 1.1), and Environmental plantings (Section 1.2) associated with reforestation of this forest type. Given their significant differences in age and structure, and carbon biomass this report will outline methods and results separately, even though there are some common elements.

AGB – open eucalypt forests

Methodology

CCAP collected new data and collated existing data on native forest carbon biomass using Australian Greenhouse Office technical reports to guide this study, for example, Snowdon *et al*. (2002), Snowdon *et al.* (2000), Keith *et al*. (2000), and Ximenes *et al.* (2004). These together with Paul *et al.* (2011) and collaboration with CSIRO researchers were used to develop Commonwealth-CSIRO approved methodologies.

Site selection and characteristics

Eucalyptus Open Forest was targeted by CCAP because it covers a significant area of forested public land, has good biomass density with considerable above-ground carbon (Fig. 1.1), and the majority of these forests are not well represented in previous carbon estimations largely because they have low-commercial value. Additionally, these forests are found in the low to moderate rainfall zone (about 400-850 mm mean annual rainfall), are often at the interface of public land and private land, and are therefore arguably the forest type that will be reforested under carbon reforestation initiatives such as the Carbon Farming Initiative. As a National Vegetation Information System's Major Vegetation Group (MVG) it was also recognised nationally.

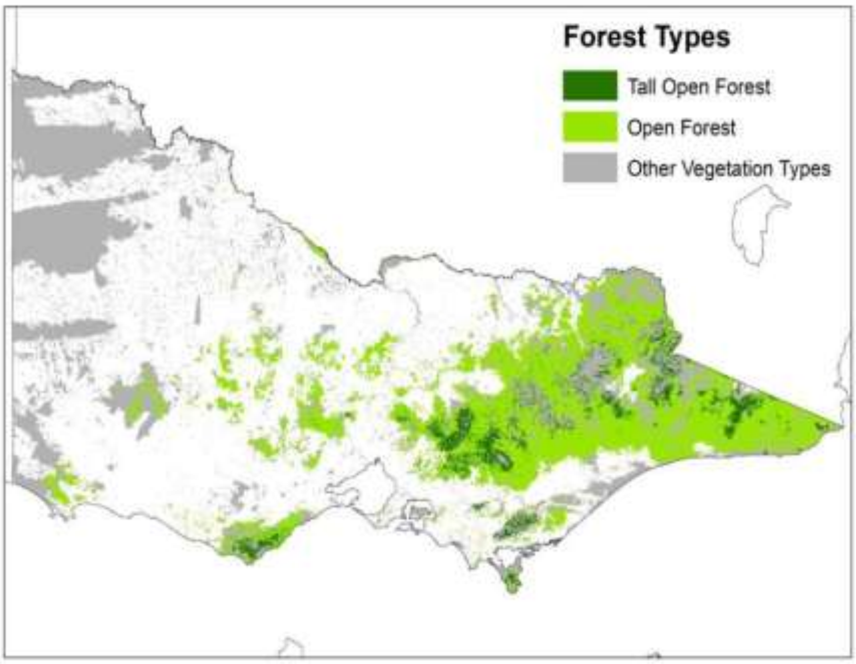

Figure 1.1: Eucalypt Open Forest and Tall Open Forest on publically managed land, Victoria 2010. Source, Fairman and Law, (2011).

Eucalyptus Open Forest are widespread in Victoria, except for the north-west and to some extent the west regions. There is significant variation in the range of species involved, equating largely to what has traditionally been referred to as low elevation mixed species forest type. These forests are often referred to by a number of 'common' names, usually based on climate, location or species, e.g. Dry and Lowland Sclerophyll, Foothill and Coastal Mixed Species, Box-Ironbark. When compared to the Tall Open Forests, these forests are typically located on warmer, drier sites occurring at low to mid elevations. The flora in these forests is often indicative of restricted nutrient availability, with nutrient levels increasing as the moisture gradient increases into damper forests (Connell and Raison 1996). Species composition in a particular place is determined by elevation, topography, aspect, rainfall, soil type, and disturbance history. This results in a mosaic of species associations, although pure stands of single species do occur.

Patches of State forest that were zoned for general harvest were targeted, and in particular forest that was in DEPI's Wood Utilisation Plans (DEPI, 2014). The scheduling of these areas for minor forest products harvesting meant that the destructive sampling required for CCAP could be undertaken as a component of routine forest operations, significantly reducing lead times for sampling. Following discussions with regional DEPI representatives, regarding access and scheduling of harvesting, 23 plots located across 3 sites were selected as potentially suitable, as detailed in Table 1.1. A range of fire and harvest disturbances were sought as part of site selection, as disturbance history was an important consideration and needed to be representative of the broader Open Forest type. Species composition was also a selection consideration because development of representative species-specific allometric equations was a preferred outcome of CCAP. A nominal 0.5 ha plot (80m diameter) was selected to collect area dependent stand parameters

Table 1.1: CCAP plots, location, EVC and disturbance history across 4 sites in Eucalypt Open Forest (MVG) on publically managed land, Victoria 2010. Source, Fairman and Law, (2011).

Plot Code	Easting	Northing	MVG	EVC	History (according to LandCarbon 3)
PYR 01	160427.5	5898018.6	Eucalypt Open Forests	Box Ironbark Forest	No identified events 1930-2010
PYR 02	160676.1	5897647.0	Eucalypt Open Forests	Box Ironbark Forest	No identified events 1930-2010
PYR 03	171174.3	5890587.3	Eucalypt Open Forests	Grassy Dry Forest	Wildfire 1982, Resprouter
PYR 04	168717.4	5890095.3	Eucalypt Open Forests	Herb-rich Foothill Forest	Wildfire 1982, Resprouter
PYR 05	167483.6	5891350.5	Eucalypt Open Forests	Grassy Dry Forest	Wildfire 1982, Resprouter
PYR 06	167552.8	5891313.0	Eucalypt Open Forests	Grassy Dry Forest	Wildfire 1982, Resprouter
PYR 07	162564.9	5887888.3	Eucalypt Open Forests	Grassy Dry Forest	No identified events 1930-2010
PYR 08	158715.5	5897015.2	Eucalypt Open Forests	Heathy Dry Forest	Prescribed Burn 1981, 2004
RUSH 02	317320.2	5937420.8	Eucalypt Open Forests	Box Ironbark Forest	Half of this site - STS Harvest 1981, 1997
RUSH 03	317894.2	5942473.4	Eucalypt Open Forests	Box Ironbark Forest	No identified events 1930-2010
RUSH 04	329433.5	5943623.4	Eucalypt Open Forests	Box Ironbark Forest	STS harvest 1987, Prescribe burn 2004
RUSH 05	332799.0	5941935.4	Eucalypt Open Forests	Box Ironbark Forest	Thin 1991
RUSH 06	322957.5	5929901.5	Eucalypt Open Forests	Box Ironbark Forest	No identified events 1930-2010
RUSH 07	322902.4	5930038.6	Eucalypt Open Forests	Box Ironbark Forest	No identified events 1930-2010
RUSH 08	319481.2	5932825.7	Eucalypt Open Forests	Box Ironbark Forest	STS Harvest 1991, Thin 2005
STRATH 01	404112.9	5926611.7	Eucalypt Open Forests	Grassy Dry Forest	No identified events 1930-2010
STRATH 02	406237.5	5911153.7	Eucalypt Open Forests	Herb-rich Foothill Forest	No identified events 1930-2010
STRATH 03	391778.7	5933773.9	Eucalypt Woodland	Grassy Dry Forest	No identified events 1930-2010
TOOM 01	427321.8	5928028.1	Eucalypt Open Forests	Herb-rich Foothill Forest	Prescribed burn 1986, 1988, 2004; Wildfire 1939, Resprouter
TOOM 02	427161.2	5927843.2	Eucalypt Open Forests	Herb-rich Foothill Forest	Wildfire 1939, Resprouter
TOOM 03	424663.5	5933604.4	Eucalypt Open Forests	Grassy Dry Forest	Wildfire 1939, Resprouter
TOOM 04	418934.4	5911211.0	Eucalypt Open Forests	Valley Grassy Forest	Prescribe Burn, 2009
TOOM 05	419103.4	5911325.0	Eucalypt Open Forests	Valley Grassy Forest	Prescribe Burn, 2009

From the CCAP plot inventory data the stand characteristics of the forest are detailed in Table 1.2 on the basis of dominant eucalypt species, number of trees by size class stocking and stems per hectare, basal area per hectare, and average height of the biggest trees with healthy crowns. Plots that were used for destructive sampling of above-ground biomass are shaded (Table 1.2).

Table 1.2. Forest stand characteristics at CCAP plot locations in open eucalypt forests. Shaded plots were to collect destructive sampling data for above-ground biomass.

#	**Plot location** (MGAz55) East.	North.	**Dominant species*** (% Basal Area)	**Stocking (0.5 ha plot) DBHOB class (cm)** *<10*	*10-20*	*20-40*	*40-60*	*60-80*	*>80*	**Stems** (/ha)	**BA.** (m^2/ ha)	**Ht.#** (m)
Rushworth												
2	160427.5	5898018.6	RIB(100)	*16*	*38*	*69*	*15*	*0*	*0*	276	16.9	20.9
3	160676.1	5897647.0	RIB(89), GB(11)	*0*	*15*	*36*	*24*	*1*	*0*	152	15.6	20.5
4	171174.3	5890587.3	RIB(84), RB(16)	*32*	*110*	*60*	*17*	*0*	*0*	438	17.0	20.1
5	168717.4	5890095.3	GB(100)	*111*	*97*	*28*	*10*	*1*	*0*	495	10.2	22
6	167483.6	5891350.5	RB(39), GB(36), YG(24)	*64*	*62*	*30*	*17*	*1*	*0*	347	13.0	21.3
7	167552.8	5891313.0	RIB(27), GB(28), YG(45)	*48*	*60*	*34*	*16*	*1*	*0*	317	13.2	23.3
8	162564.9	5887888.3	RIB(43), GB(33), RB(23)	*16*	*174*	*99*	*7*	*3*	*0*	598	22.2	21
Toombullups (and Strathbogies)												
1	427321.8	5928028.1	NLP(66), MM(13), BG(13)	*0*	*0*	*70*	*43*	*9*	*4*	252	40.3	32.5
2	427161.2	5927843.2	NLP(69), BG(22)	*16*	*16*	*65*	*27*	*22*	*5*	302	42.6	35.8
3	424663.5	5933604.4	YB(43), LLB(26), RSB(22)	*48*	*80*	*59*	*25*	*5*	*2*	437	24.8	31.4
4	418934.4	5911211.0	RSB(60), LLB(20), BLP(19)	*111*	*16*	*86*	*37*	*11*	*3*	529	36.2	26.3
5	419103.4	5911325.0	RSB(74), LLB(22)	*111*	*0*	*93*	*34*	*1*	*3*	485	32.2	20.9
6	404112.9	5926611.7	RSB(89), BLP(8)	*64*	*0*	*102*	*45*	*9*	*0*	439	37.5	23.4
7	406237.5	5911153.7	LLB(42), NLP(37), BLP(15)	*64*	*64*	*91*	*35*	*18*	*3*	549	42.0	26.4
8	391778.7	5933773.9	RSB(54), YB(21), LLB(9)	*32*	*64*	*53*	*37*	*15*	*2*	405	36.8	27.1
Pyrenees												
1	160427.5	5898018.6	RIB(95)	*16*	*181*	*140*	*22*	*1*	*0*	720	33.4	19.5
2	160676.1	5897647.0	RB(47), RSB(36), LLB(10)	*16*	*143*	*99*	*17*	*2*	*0*	554	25.6	15
3	171174.3	5890587.3	RSB(56), RB(37), YB(5)	*111*	*104*	*51*	*33*	*14*	*0*	627	31.4	21.5
4	168717.4	5890095.3	MM(56), BG(24), CB(9)	*207*	*127*	*129*	*52*	*9*	*1*	1050	46.3	31.9
5	167483.6	5891350.5	MM(43), RSB(24), LLB(6)	*95*	*80*	*113*	*50*	*11*	*2*	702	46.5	23
6	167552.8	5891313.0	MM(54), CB(13), BLP(13)	*80*	*48*	*92*	*40*	*8*	*2*	539	38.5	25.8
7	162564.9	5887888.3	RSB(32), CB(31), YB(14)	*16*	*69*	*79*	*21*	*8*	*2*	390	25.8	20.6
8	158715.5	5897015.2	RSB(36), CB(35), YB(17)	*32*	*54*	*59*	*14*	*8*	*0*	334	19.2	18.1

* YB, Yellow Box (*Eucalyptus.melliodora*); LLB, Long-leaved Box (*E.goniocalyx*); NPP, Narrow-leaved Peppermint (*E.radiata*); BG, Blue Gum (*E.bicostata*); MM, Messmate Stringybark (*E.obliqua*); RSB, Red Stringybark (*E.macrorhyncha*); RB, Red Box (*E.polyanthemos*); MA, Mountain Ash (*E.regnans*); RIB, Red Ironbark (*E.tricarpa*); YG, Yellow Gum (*E.leucoxylon*); CB, Candlebark (*E.rubida*); BPP, Broad-leaved Peppermint (*E.dives*); GB, Grey Box (*E.microcarpa*).
\# Height is expressed as the average height of trees in the biggest diameter class(es) that have good crown condition.

Coarse woody debris (CWD) and litter

Measurements of CWD, and litter were completed at harvested plots (shaded areas of Table 1.2.). Volkova et al. (In Prep) details the methodology used to collect and analyse data. In summary, measurement of intersected CWD along a 100 m transect was used to estimate loads of CWD, following the methodology of van Wager (1968). Representative biscuits of the CWD were used to obtain measurements of moisture content (OD 70ºC) and wood density (water displacement). Litter (and organic duff) were sampled at 4 points along the same transect using a 0.1m^2 sampling ring. All litter samples were oven dried at 40ºC, sub-sampled, sieved, ground to a fine powder (<0.1 mm) in a vibration mixer mill (Retsch MM301; Daigger, Vernon Hills, USA) before further analysis. Total organic carbon (TOC) and total nitrogen (TN) concentrations were determined by dry combustion elemental analyser (LECO CNS-2000).

Destructive sampling

Destructive sampling (harvesting) of trees was used to provide representative biomass data at the vegetation unit scale, and also at the dominant overstorey species scale. From the plot inventory data, trees were stratified by species, diameter class and height class. Trees were randomly selected from these classes, so that for each plot between 32 and 54 tree were selected for destructive sampling. The sampling involved the felling of the trees, cross-cutting into biomass categories (lower-stem, upper-stem, and canopy on the basis of over-bark diameter, and dead-attached), and bundling and weighing by biomass component at stump. On average 38% of these felled trees were additionally sampled systematically for moisture content. A total of 337 trees were felled across the 8 plots, as detailed in Table 1.5.

Table 1.5. Trees felled for destructive sampling by DBHOB class and sampling category; measurement of Fresh Weight only (FW) and, additionally, sampling for Moisture Content (MC).

Plot ID	Dominant species* (% Basal Area)	Felled Trees by DBHOB Class (cm) & Sampling Category												Total Plot Trees felled		Total
		<10		10-20		20-40		40-60		60-80		>80				
		FW	MC	FW	MC	FW	MC	FW	MC	FW	MC	FW	MC	FW	MC	
Rushworth (96 trees)																
6	RB(39), GB(36), YG(24)	4	2	7	4	5	7	9	3	1	0	0	0	26	16	**42**
7	RIB(27), GB(28), YG(45)	9	5	10	3	8	5	10	3	0	1	0	0	37	17	**54**
Toombullups (134 trees)																
1	NLP(66), MM(13), BG(13)	10	7	0	0	11	4	5	4	3	3	2	0	31	18	**49**
2	NLP(69), BG(22)	0	0	5	2	10	2	6	2	6	2	1	2	28	10	**38**
3	YB(43), LLB(26), RSB(22)	10	9	0	0	7	8	4	6	1	0	0	2	22	25	**47**
Pyrenees (107 trees)																
1	RIB(95)	11	6	3	3	6	3	5	3	0	1	1	0	26	16	**42**
2	RB(47), RSB(36), LLB(10)	5	3	1	0	8	5	3	6	1	1	0	0	18	15	**33**
3	RSB(56), RB(37), YB(5)	5	4	3	2	4	2	5	2	3	2	0	0	20	12	**32**
	Total	**54**	**36**	**29**	**14**	**59**	**36**	**47**	**29**	**15**	**10**	**4**	**4**	**208**	**129**	**337**

* YB, Yellow Box (*Eucalyptus.melliodora*); LLB, Long-leaved Box (*E.goniocalyx*); NPP, Narrow-leaved Peppermint (*E.radiata*); BG, Blue Gum (*E.bicostata*); MM, Messmate Stringybark (*E.obliqua*); RSB, Red Stringybark (*E.macrorhyncha*); RB, Red Box (*E.polyanthemos*); MA, Mountain Ash (*E.regnans*); RIB, Red Ironbark (*E.tricarpa*); YG, Yellow Gum (*E.leucoxylon*); CB, Candlebark (*E.rubida*); BPP, Broad-leaved Peppermint (*E.dives*); GB, Grey Box (*E.microcarpa*).

Terrestrial laser scanning

In a collaborative project with CSIRO, terrestrial laser scanning (TLS) was used to explore the potential use of TLS data to non-destructively estimate above ground biomass at both the individual and tree and plot scale. TLS collected pre-harvest biometric data on all Rushworth, Toombullup and Strathbogies CCAP plots. It was also used to collect post-harvest data on the Rushworth 06 & 07, and Toombullups 01, 02 and 03 plots.

Calders *et al.* (2013) and Calders *et al.* (In Review) detail the methodology used to collect and analyse data. In summary, individual trees on the plot were characterised by 'point clouds', which were used to reconstruct the trees using segmentation and surface reconstruction techniques. Tree volume (over bark) was directly inferred from tree models reconstructed from the TLS data. These modelled trees could be matched with actual trees on the plot using their digitised positions. Tree density and moisture content estimates from the destructive sampling enabled conversion of these volume estimates to biomass estimates (i.e. using conversion from fresh weight (FW) to dry weight (DW) equivalents).

For the two Rushworth plots, the DW:FW ratios from the destructive sampling were used to describe moisture content (MC) as a function of DBH (Diameter at Breast Height over bark) for each tree species (DW:FW = a + b*DBH). The reference dry weight of single trees (i.e. AGB), was derived from the measured fresh weights in combination with the inverse DW:FW ratios. Basic densities were determined using DBH sample discs from the destructive sampling.

Data from the destructively harvested (reference) trees on above-ground biomass, DBH, and tree height was compared with the TLS derived data, using up to 65 trees, as outlined in Table 1.3.

Table 1.3. Rushworth plot trees, felled and sampled trees, and trees used in analyses. Source, Calders *et al.* (In Review).

Tree Categories	Rushworth Plot ID		Total
	06	07	
Live Plot Tress (0.5 ha plot)	110	107	217
Felled and sampled Plot Trees (FPT)	36	39	75
FPT –AGB analysis	34	31	65
FPT – DBHOB analysis	34	31	65
FPT – Height analysis	33	28	61

Above-ground biomass derived estimates from species-specific and generic allometric equations from Paul et al. (2013a, b), as outlined in Table 1.4, were also compared with the TLS derived and the reference estimates.

Table 1.4: Summary of parameters a, b and CF from existing allometric equations (Paul *et al*. 2013a, b). N gives the number of individual trees and maximum DBHOB indicates the upper limit of the calibration data used to develop the allometric equations. Source, Calders *et al*. (In Review).

Allometric equation	N	Max. DBHOB [cm]	a	b	CF
Species - E. leucoxylon	28	25	-1.37	2.07	1.04
Species - E. microcarpa	30	110	-1.92	2.36	1.17
Species - E. tricarpa	54	60	-2.39	2.40	1.10
Generic-eucalypt	2640	100	-1.71	2.21	1.29

Results and Discussion

Terrestrial Laser Scanning Biomass Estimation

Calders *et al.* (2013) reported on a 'proof of concept' approach to estimating above-ground biomass (AGB) from terrestrial laser scanning (TLS) in Eucalypt Open Forest. The scope of the estimation was limited to six trees (two species) from CCAP plots, Rushworth 06 and 07.Calders *et al*. (In Review) details analyses using additional felled and sampled trees (up to 65 trees in total), as outlined in Table 1.3.

Above-ground biomass estimates derived from TLS showed a high agreement with the reference biomass values from destructive sampling, with a concordance correlation coefficient (CCC) of 0.98 (Fig. 1.2). The agreement between above-ground biomass estimates from allometric equations and the reference biomass is lower (CCC = 0.68 to 0.78, Fig. 1.3).

The total above-ground biomass of the 65 trees analysed was 69.02 t for the directly weighed reference, 43.78 t for the Generic-eucalypt estimate, 48.42 t for the Species-specific estimate, and 75.70 t for the TLS-derived estimate. Hence, when compared to the reference value the TLS approach used by Calders *et al.* (in review) showed an overestimation of 9.68% compared to an underestimation of 36.57% to 29.85% for the allometric equations. It is likely that poor modelling of the canopy is a major reason for the overestimation by the TLS-derived estimate. Using cylinders is not a good approximation for the geometric structure of leaves. The underestimation by the allometric equations of total AGB by 29.85% to 36.57% is not unexpected, and indeed, the AGB data suggests that the absolute error increases with increasing DBH of trees. This is likely to be because large trees have rarely been harvested and measured to calibrate allometric equations and also because large trees are more likely to have greater variation in biomass (e.g. Stephenson et al., 2014 and Paul *et. a*l 2013a).

Using 3D TLS data also enables the height distribution of above-ground biomass to be better understood. In the Rushworth plots the TLS data, on average, showed that 80% of the above-ground biomass was found below 60% of the canopy (tree) height (Fig. 1.4).

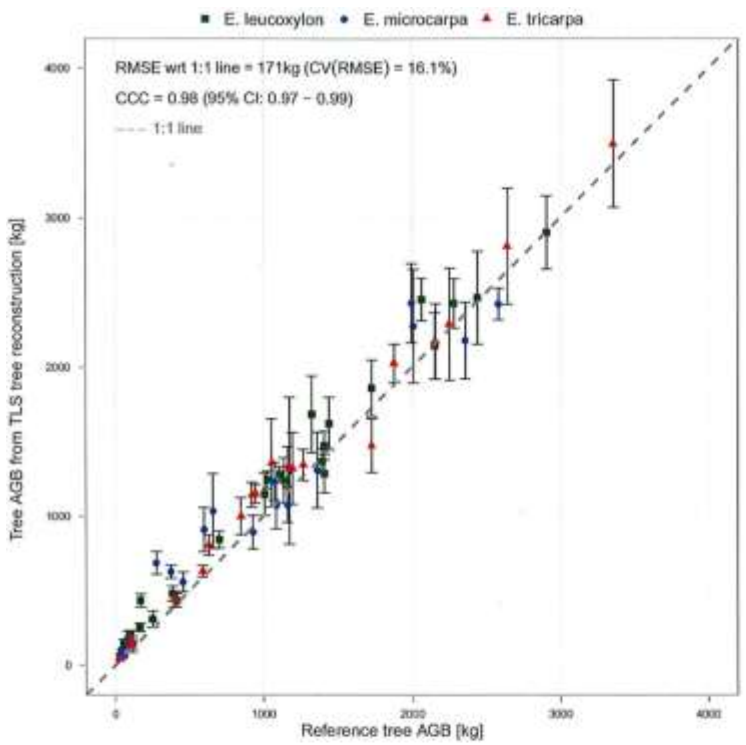

Figure 1.2. Rushworth Plots 6 & 7, comparison of reference tree AGB (destructively sampled) with TLS-derived AGB estimates, using tree reconstruction and basic density information. Error bars indicate the 95% confidence interval around the mean of 10 reconstructions. Source Calders *et al.* (In Review).

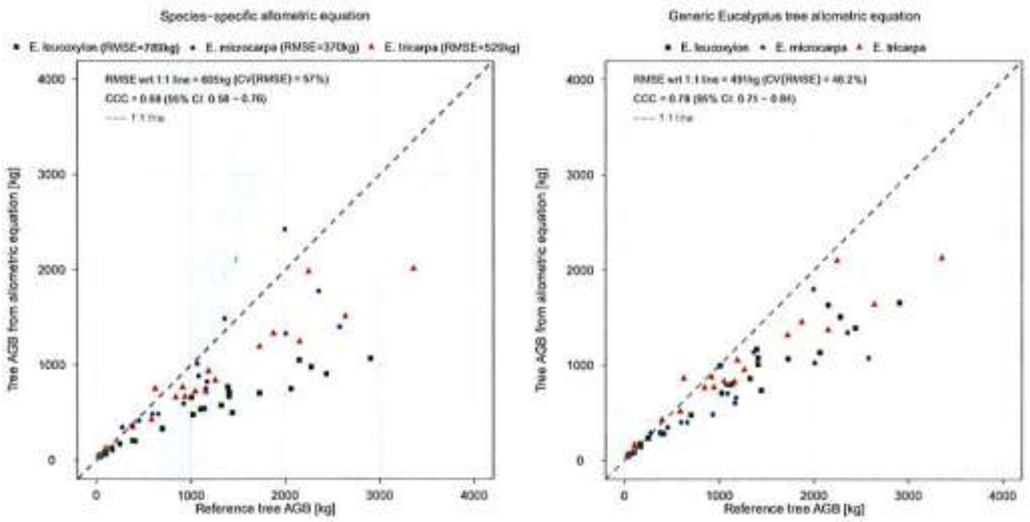

Figure 1.3. Rushworth Plots 6 & 7, comparison of reference tree AGB (destructively sampled) with AGB derived from allometric equations. (left) Species-specific estimates, and; (right) Generic Eucalypt estimates. Source, Calders *et al.* (In Review).

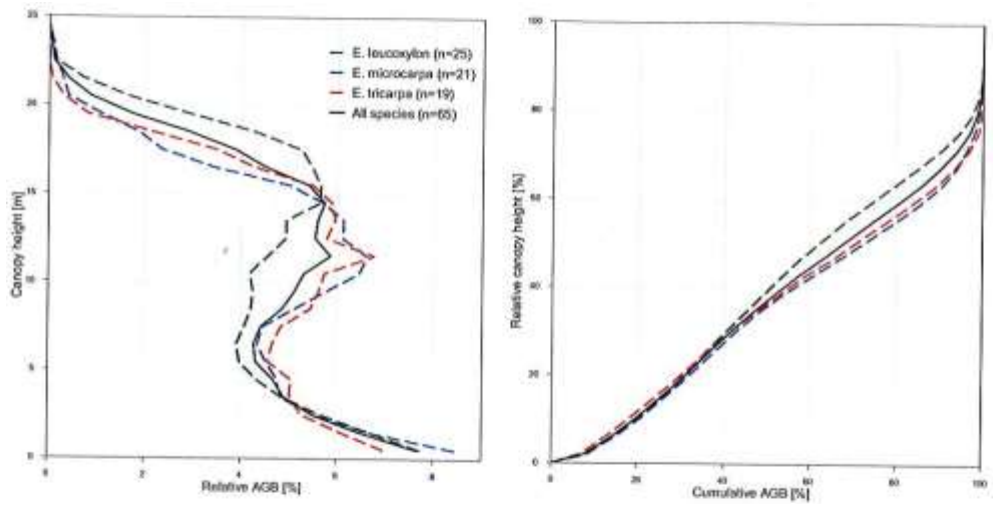

Figure 1.4. Rushworth Plots 6 & 7, distribution of above-ground biomass derived from TLS (LiDAR) as a function of canopy (tree) height, using height bins of 1 m. Source, Calders *et al.* (In Review).

Biomass Carbon and FullCAM

The Full Carbon Accounting Model (FullCAM version 3.55) was used to estimate biomass of above-ground tree biomass (AGB, t/ha), accounting for site level disturbance as derived from the DSE's LandCarbon data. CCAP plot derived and FullCAM predicted AGB estimates were compared by plotting against a 1:1 line to indicate the distribution of residuals and display any bias. FullCAM's species multiplier, *r*, reflecting site maximum AGB was used to explore possible adjustments of FullCAM (see Paul *et al.* 2013). Because FullCAM uses component specific biomass-carbon conversions (range 52% - 47%) rather than a single generic conversion (47%) as recommended by IPCC (2003), data presented here is on a biomass basis (tonnes dry weight per hectare, t ha^{-1}).

Above-ground biomass

Derived AGB (t ha^{-1}) across the three CCAP sites (23 plots) is detailed in Table 1.5, on the basis of biomass component (Note: the CWD, ground cover and litter data reflects only the 8 destructively sampled plots). An average AGB of 242 t ha^{-1} was estimated across all sites, with a range of 163 – 328 t ha^{-1}. On a component basis, 72% was live trees, 10% dead trees, 12% CWD, 2% litter and 4% live ground cover. Table 1.6 details average tree mortality and CWD as a percentage of AGB for the three sites, and across sites. The data indicates a relationship between dead tree biomass and CWD biomass, and possibly between increasing biomass of dead trees and CWD with increasing productivity.

Table 1.5. Average above-ground biomass (t ha^{-1}) on a component basis, CCAP sites.

Site	Live trees		Dead trees		CWD*	Ground cover	Litter	AGB
	Overstorey	Small trees	Overstorey	Small trees				
Rushworth	114±5.7	1.7±0.6	4.4±4.0	0.2±0	4.1±1.4	2.9±0	5.7±0.5	163
Toombullups	225±23.6	5.1±1.2	35.6±6.9	3.0±0.7	45.5±16.1	5.2±2.8	8.1±1.2	328
Pyrenees	160±19.2	8.1±3.1	21.6±3.7	4.0±1.5	32.2±1.9	2.2±1.0	5.8±0.4	234
Average	**169±14.0**	**5.4±1.4**	**22.8±4.0**	**3.3±0.8**	**30.1±8.1**	**3.6±1.3**	**6.6±0.6**	**242**
%	**70**	**2**	**9**	**1**	**12**	**2**	**4**	**100**

*CWD at a density of 952 kg m^{-3}

Table 1.6. Tree mortality and CWD biomass as a percentage of AGB, CCAP sites.

Site	% Dead Trees	% CWD
Rushworth	3.5%	3.1%
Toombullups	11.8%	13.9%
Pyrenees	11.0%	13.8%
Average	10.8%	12.5%

Predicted vs. observed measurements of AGB

As shown in Figure 1.7, FullCAM predicted tree AGB well for the less productive Rushworth sites (Δ4%), but predicted more poorly for the Pyrenees (Δ60%), and Toombullups (Δ85%) sites. Indicating that FullCAM increasingly underestimates tree AGB as site productivity increases. Overall, FullCAM underestimated tree biomass on average 52%, with residuals skewed below 1:1 line (Fig 1.7A). Calibration of the tree yield formula by increasing the species multiplier of maximum AGB (*r*) from 1 to 1.95, has improved the model performance slightly (r^2= 0.558, Fig 1.7B).

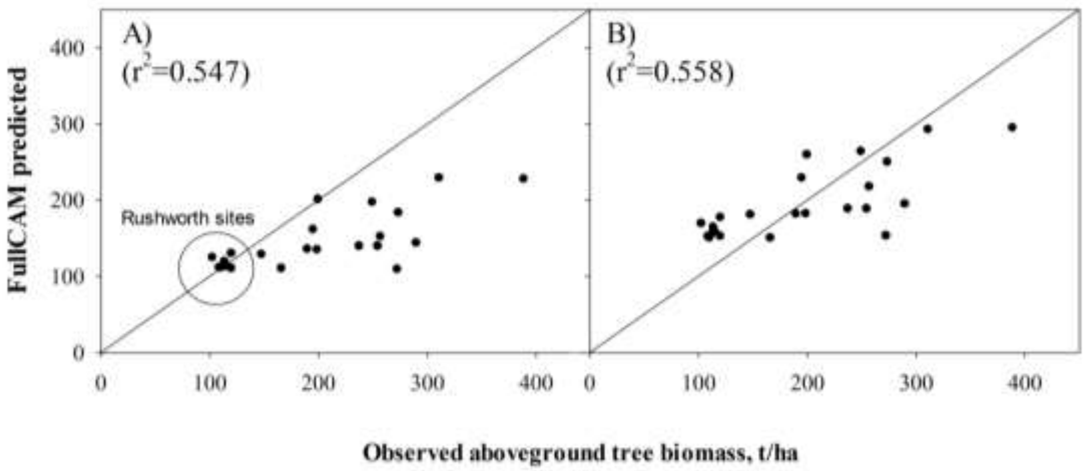

Figure 1.7. FullCAM-predicted estimates vs. Observed estimates of tree AGB across CCAP sites; A)Using default species multiplier for maximum AGB, *r* (r=1) and B) Using modified *r* (1.95).

The FullCAM parameter *r* has been calibrated based on 23 estimates of biomass accumulation. Though the overall efficiency of model remained low (r^2=0.558 vs. 0.547, calibrated vs. default respectively), there was not apparent bias in model prediction (Fig. 1.7).

AGB - Environmental plantings

The environmental plantings component of CCAP was conducted as part of a CSIRO lead nationally-collaborative research project to improve the estimation of biomass accumulation by mixed-species environmental plantings and mallee eucalypt plantings. While this collaborative research project also addressed tropical and mallee environmental plantings, temperate mixed-species environmental plantings throughout the non-arid (>300 mm mean annual rainfall) regions of Australia were the main area of interest to CCAP.

In addition to consolidating data from previous work, Australia-wide, 50 new site estimates of biomass carbon were obtained as part of this national-collaboration. In Victoria, CCAP and CSIRO selected 11 of these sites at 7 locations. A full report of this research program is given in Paul *et al*. (2013a). On the 11 Victorian environmental planting sites, CCAP provided funds and collaboration on site selection, site measurement and data collection, and report preparation for both above- and below-ground biomass estimation and soil carbon determination. Paul *et al*. (2013a), was prepared specifically for the primary client, the Commonwealth's Department of the Environment. Numerous journal publications have also resulted from this national collaboration and have been listed previously under *CCAP Publications*.

To quantify the benefits that environmental plantings (i.e. mixed-species of indigenous trees and shrubs) have on sequestration of carbon and other commercial or environmental benefits, accurate (precise and non-biased) estimates of biomass were required. Given these plantings comprise multiple species, estimation of biomass and carbon through the development and application of allometric relationships is a challenge. To address this challenge, a large database on growth and biomass accumulation was developed across a wide range of planting types, comprising 1,480 site-based observations, 183,675 stem diameter measures (36% from new sites) and 8,288 measures of tree or shrub above- and below-ground biomass (40% from new sites). These data were analysed to identify the key factors affecting the growth of plantings, resulting in 26 statistically-different categories of plantings. Modifiers that account for large variations in growth of these categories of plantings have been developed for use in FullCAM.

Methodology

Methods are detailed in Paul *et al.* (2013a) and summarised here with specific reference to the 11 Victorian sites. These sites were selected as representative of Open Eucalypt Forest reforestation, and additionally, plantings (includes sowing) needed to have the following:

1. Species native to the local area, but not include natural regeneration.
2. A mix of trees, shrubs, and understorey species reflecting local native vegetation.
3. Representative of other plantings with 'typical' management regimes.

Plantings ranged from 8 to 16 years, as detailed and characterised in Table 1.7.

Table 1.7. Summary of site characteristics, including location (latitude, longitude, in decimal degrees), mean annual rainfall (MAR), planting type (block or linear plantings), planting method, year of establishment, age of planting, and the main species which were present at measurement. Compiled from Paul *et al.* (2013a).

Site	Location	MAR (mm)	Plant. type	Plant. method	Year planted	Age (yrs.)	Species present
				'Direct measurement' plantings			
Jenharwill	-36.3958, 144.4304	406	Linear	Tubestock	1999	12	*A. calamifolia, A. hakeoides, A. pycnantha, E. leucoxylon*
Gumbinnen	-36.2447, 141.8148	347	Block	Tube & seeded	2001	10	*A. pycnantha, A. trineura, E. largiflorens, Melaleuca*
Leos	-37.8381, 147.7582	626	Linear	Tubestock	1996	16	*A penninervis, C. cunninghamian, E. kitsoniana , E melliodora, M. armillaris*
				'Indirect estimates' plantings			
Gunbower 1	-35.9800, 144.3847	345	Block	Tubestock	2002	9	*A. salicina, A. stenophylla, E. occidentalis, E. camaldulensis, E. largiflorens*
Gunbower 2	-35.9828, 144.3833	367	Block	Tubestock	2003	8	*A. salicina, A. stenophylla, E. occidentalis, E. camaldulensis, E. largiflorens*
Lynvale	-37.8987,	678	Block	Direct	2003	8	*A. mearnsii, A. melanoxylon, A. pycnan-*

	141.6380			seeded			*tha, E. viminalis*
Batterns 1	-38.6674, 145.9886	869	Linear	Broadcast	2001	11	*A. melanoxylon, E kitsoniana, E. ovata, E. viminalis, M. ericifolia*
Batterns 2	-38.6686, 145.9925	870	Linear	Broadcast	2000	12	*A. melanoxylon, E kitsoniana, E. ovata, E. viminalis, M. ericifolia*
Batterns 3	-38.6714, 145.9894	860	Linear	Broadcast	2003	9	*A. melanoxylon, E kitsoniana, E. ovata, E. viminalis, M. ericifolia*
Batterns 4	-38.6674, 145.9886	864	Linear	Broadcast	2001	11	*M. ericifolia*
Suttons	-38.3998, 145.8996	1050	Block	Tubestock	2004	8	*E. globulus, E. regnans, Olearia argophylla, Pomaderris aspera*

At these sites representative plots were selected using different approaches. Plot characteristics together with the method of plot selection are summarised in Table 1.8.

Table 1.8. Plot Summary: method of selection (E=Entire area sampled; F-PS=Full site survey and precision sampling; G-PS= Generalised Random Tesselation Stratified Sampling to select a large number of plots from which precision sampling was based; SYS=Systematic sampling, SRS=Simple random sampling); planting size (ha), number of trees measured for stem diameters in the inventory (and number of measurement plots), number of trees harvested (and the number of harvest plots), height at which stem diameters were measured, the total area across all plots, stocking (stems per hectares), Basal area (BA), and Proportion of Trees. Compiled from Paul *et al.* (2013a).

Site	Selection method	Size (ha)	No. Trees (plots)	Harv. Trees (plots)	Diam. Point (cm)	Total Plot Area	Stock. (sph)	BA (m^2ha^{-1})	Prop. Trees
				'Direct measurement' plantings					
Jenharwill	F-PS	1.52	3108(62)	344(6)	130, 10	0.05	6456	16.9	0.04
Gumbinnen	G-PS	18.4	3034(38)	504(6)	130, 10	0.22	2282	4.4	0.10
Leos	SYS	1.67	470(51)	96(10)	130	0.11	845	26.6	0.4
				'Indirect estimates' plantings					
Gunbower 1	E	2.45	2538(0)	97	50, 10	2.45	1036	5.7	0.34
Gunbower 2	E	3.2	2079(0)	97	50, 10	3.20	650	3.4	0.34
Lynvale	G-PS	3.31	1604(20)	80	130	0.74	869	14.4	0.17
Batterns 1	SRS	0.32	378(8)	109	130	0.08	4638	35.9	0.82
Batterns 2	SRS	0.43	512(7)	21	130	0.14	3652	27.1	0.21
Batterns 3	SRS	0.60	1253(7)	24	130	0.13	7009	38.1	0.81
Batterns 4	SRS	0.10	251(1)	NA	130	0.02	13971	10.0	0
Suttons	E	0.75	1043	88	130	0.67	1428	17.9	0.27

Within each selected plot, stem diameters of all individuals were measured. Height at which diameters were measured varied between plantings based on the heights of the trees and the average height at which they branched into multiple stems. As a general rule, the diameters were measured as high as possible (up to 130 cm height (DBH)), but below the height at which the stem became multi-stemmed. This was to decrease measurement errors. Generally for all shrub species, diameters were measured at 10 cm height (i.e. D10). Species, or at least life form, was also recorded with each diameter measurement.

Three of these sites were 'direct measurement' sites, where all individual trees (and shrubs) within 10 x 10 m sub-plots were harvested and roots were excavated. At the other 8 sites, biomass estimates were obtained indirectly through the development of site-and-species specific allometrics from selective harvesting of trees and shrubs.

Generally for each key species, at least three representative individuals were selected for obtaining moisture content sub-samples. Each selected tree or shrub was divided into crown (all foliage and twigs less than about 5 mm diameter) and the remaining bole (stem and branches) as appropriate. The fresh weights of these two components were measured in the field, and then sub-samples were taken, weighed and transported back to the laboratory and dried (at 70°C) until the dry weights stabilised. Dry weight equivalents of material weighed in the field was then calculated.

For the development and testing of allometric equations for estimating above-ground biomass of mixed-species environmental plantings, detailed methods are described in Paul *et al.* (2013b). In summary, four types of allometric equations were developed: (i) site-and-species specific, (ii) generic species, or species-specific but applicable across sites, (iii) generic genus and growth-habit based, and (iv) generic universal growth habit, including all trees and shrubs for all genera and species. Growth-habit was defined around grouping into different genera of trees and shrub forms which were found to either have statistically different allometry, or had such unique form that they were categorised into a separate growth-habit category.

Results and Discussion

The results relevant to mixed-species environmental plantings in temperate regions (includes the 11 Victorian sites) are summarised below from Paul *et al*. (2013a, b and Paul *et al*. In Review)

Allometric Equations

In developing generic allometric equations analysis consistently demonstrated that allometry was not significantly influenced by site-factors, and that pooling of datasets from across multiple sites to develop generic species-specific allometric equations, was valid.

Three types of generalised or generic allometrics were developed based on different categories of species across multiple sites: (i) species-specific, (ii) genus and growth-habit, and (iii) universal growth habit irrespective of genus. For the two most generalised allometric equations, plots of universal growth habit (Fig. 1.8a) and genus and growth-habit (Fig. 1.8b) allometry are provided.

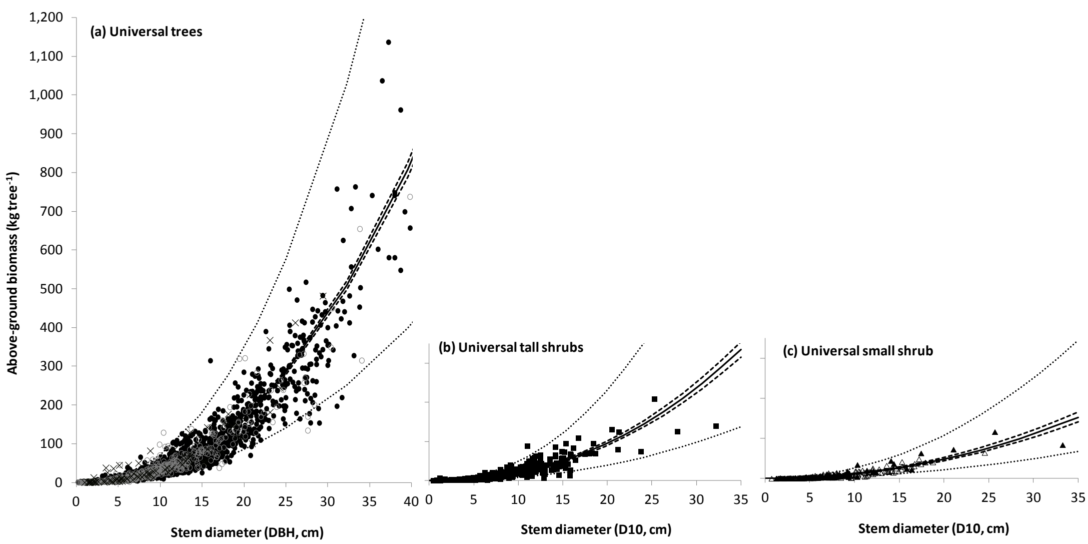

Figure 1.8a. Generic universal growth habit allometrics for above-ground biomass of: (a) trees, (b) tall shrubs, and (c) small shrubs found in environmental plantings. The universal relationships for trees include: *Eucalyptus* (●), *Acacia* (○), and *Casuarinaceae* (×). The universal relationship for tall shrubs include *Acacia* shrub

species.The universal relationship for small shrubs include: *Melaleuca* spp. shrubs (open triangles), and other shrubs (closed triangles). Parameters for these fitted equations are provided in Table 2.3. Dotted and dashed lines represent the 95% confidence interval of the regression, and the 95% prediction interval , respectively. Plot for trees in (a) includes only trees with stem diameters <40 cm (2% of the dataset were larger trees and not shown). Note, allometrics were fitted on transformed scale, but untransformed data are presented here. Source, Paul *et al*. (2013b).

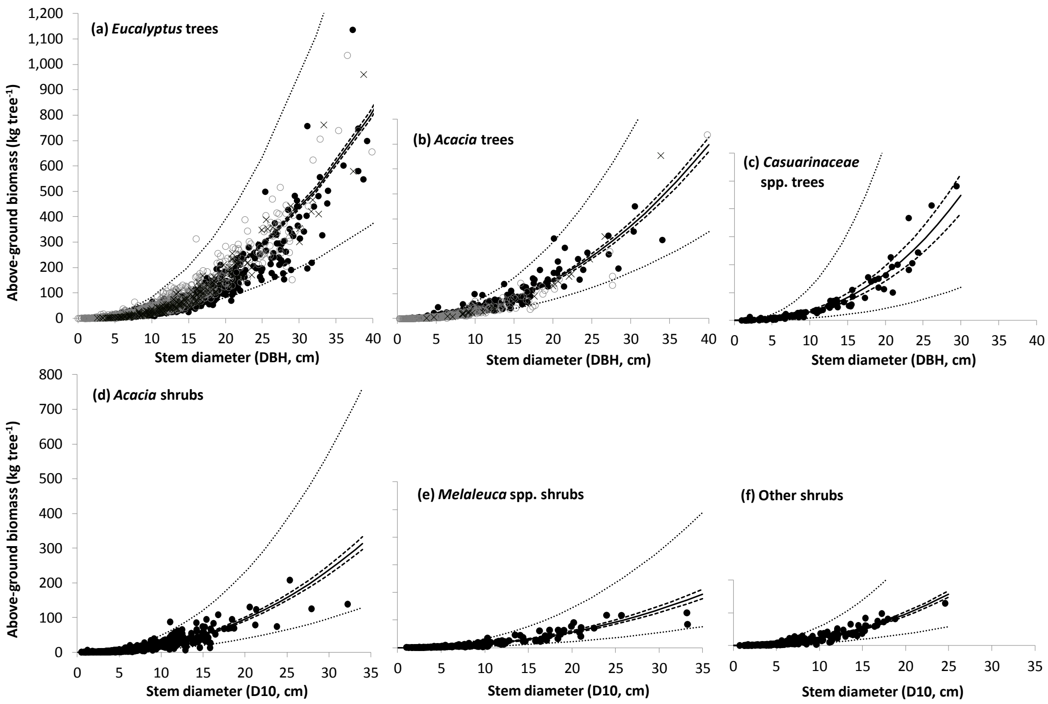

Figure 1.8 b. Allometric equations for above-ground biomass of the key genera/growth-habits found in environmental plantings, including: (a) *Eucalyptus* (namely) species trees, (b) *Acacia* trees, (c) *Casuarinaceae* tree species, (d) *Acacia* shrub species, (e) *Melaleuca* shrub species, and (f) other shrub. Plots (a) and (b) show data points from tropical regions (×), and temperate regions of low and high rainfall, defined as <500 (○) and >500 mm (●) MAR, respectively. Parameters for these fitted equations are provided in Table 2.3. Dotted and dashed lines represent the 95% confidence interval of the regression, and the 95% prediction interval , respectively. Plot for trees in (a) includes only trees with stem diameters <40 cm (2% of the dataset were larger trees and not shown). Note, allometrics were fitted on transformed scale, but untransformed data are presented here. Source, Paul *et al*. (2013b).

Parameters for these, and stem diameter ranges over which they are applicable, are listed in Table 1.9.

Table 1.9: Summary of values of the parameters *a* and *b* in generic allometric equations for above-ground biomass, where #Sites is the number of sites from which biomass data were derived, *N* is the number of sample number (i.e. number of individuals used to develop the allometric equation), CF is the Snowdon (1991) correction factor, EF is the model efficiency (Soares *et* al. 1995) and %CV is the percentage coefficient of variation.

Species	Explanatory variable	#Sites	*N*	*a*	*b*	CF	EF	%CV
Generic universal growth-habit allometric equations								
Tree (<100 cm)	DBH	148	3,352	-1.82	2.27	1.18	0.82	193
Tall shrub (<30 cm)	D10	39	611	-2.23	2.24	1.08	0.74	78.7

Small shrub (<35 cm)	D10	51	411	-2.45	2.08	1.09	0.80	60.2
Generic genus and growth-habit allometric equations								
Generic *Eucalyptus* tree	DBH	115	2,640	-1.71	2.21	1.29	0.80	204
Generic *Acacia* tree (<40 cm)	DBH	69	612	-1.59	2.19	1.05	0.89	937
Casuarinaceae sp. (<30 cm)	DBH	18	100	-2.33	2.44	1.01	0.93	44.0
Generic *Acacia* shrub (<30	D10	39	611	-2.23	2.24	1.08	0.74	78.7
Melaleuca sp. (<35 cm)	D10	29	172	-2.57	2.19	1.06	0.76	76.2
Shrub sp. (<25 cm)	D10	22	239	-2.68	2.16	1.09	0.89	42.1

For the species-specific equations the number of equations are too numerous, so just the Victorian-related species are detailed here, with equation parameters and stem diameter ranges over which they are applicable provided in Table 1.10.

Table 1.10. Summary of values of the parameters *a* and *b* in species-specific allometric equations for Victorian above-ground biomass; where the maximum stem diameter for which the equations apply are specified with the species description, #Sites is the number of sites from which biomass data were derived, *N* is the sample size, CF is the Snowdon (1991) correction factor, EF is the model efficiency (Soares *et al*. 1995), and precision expressed as a standard deviation *sd(e)*. Source, Paul *et al*. (2013b).

Species	**Sites**	***N***	***a***	***b***	**CF**	**EF**	***sd(e)***
Eucalyptus trees (using DBH as the explanatory variable)							
E. blakelyi (<20 cm)	8	47	-1.84	2.1	1.08	0.966	0.323
E. bridgesiana (<20 cm)	8	17	-1.35	1.9	1.06	0.953	0.335
E. camaldulensis (<70 cm)	8	89	-1.67	2.1	1.42	0.955	0.224
E. cinerea (<30 cm)	1	27	-1.21	1.8	1.15	0.868	0.513
E. cladocalyx (<55 cm)	4	37	-1.36	2.3	1.13	0.979	0.291
E. crenulata (<20 cm)	1	10	-1.97	2.3	1.08	0.952	0.274
E. globulus (<39 cm)	3	17	-1.66	2.1	1.01	0.963	0.285
E. kitsoniana (<31 cm)	2	34	-1.54	2.1	1.00	0.977	0.247
E. largiflorens (<20 cm)	2	57	-1.23	2.0	1.02	0.943	0.213
E. leucoxylon (<25 cm)	4	28	-1.37	2.0	1.04	0.979	0.140
E. melliodora (<39 cm)	7	169	-1.73	2.1	1.17	0.939	0.279
E. microcarpa (<110 cm)	5	30	-1.92	2.3	1.17	0.983	0.376
E. obliqua (<28 cm)	1	14	-2.16	2.2	1.00	0.954	0.259
E. occidentalis (<80 cm)	6	118	-2.12	2.4	1.18	0.979	0.198
E. ovata (for <30 cm)	2	24	-2.16	2.3	0.99	0.988	0.171
E. polyanthemos (<25 cm)	5	51	-1.46	2.0	1.07	0.961	0.264
E. tereticornis (<50 cm)	3	71	-2.15	2.3	0.97	0.959	0.347
E. tri-sideroxylon (<60 cm)	6	54	-2.39	2.4	1.10	0.954	0.125
E. viminalis (<30 cm)	4	365	-2.19	2.3	1.05	0.954	0.154
Acacia trees (using DBH as the explanatory variable)							
A. dealbata (<31 cm)	5	17	-1.21	2.1	1.06	0.968	0.361
A. implexa (<15 cm)	1	5	-1.53	2.1	1.03	0.990	0.182
A. mearnsii (<25 cm)	6	48	-2.02	2.4	0.95	0.967	0.157
A. melanoxylon (<25 cm)	4	51	-1.70	2.1	1.02	0.977	0.253
A. penninervis (<35 cm)	1	22	-1.00	2.0	0.95	0.952	0.295
A. pycnantha (<15 cm)	6	33	-1.90	2.3	0.99	0.974	0.204
A. salicina (<15 cm)	1	13	-1.78	2.1	1.01	0.959	0.208

A. stenophylla (<15 cm)	1	16	-2.22	2.4	0.99	0.936	0.240
Acacia shrubs (using D10 as the explanatory variable)							
A. calamifolia (<20 cm)	2	128	-2.23	2.4	1.02	0.939	0.347
A. hakeoides (<25 cm)	3	113	-2.10	2.1	1.10	0.946	0.343
A. pycnantha (<25 cm)	8	102	-2.37	2.3	1.05	0.927	0.262
A. rigens (<15 cm)	2	22	-2.68	2.4	1.02	0.973	0.174
A. rubida (<25 cm)	2	18	-2.01	1.9	1.11	0.812	0.492
A. trineura (<15 cm)	1	48	-1.74	1.8	1.15	0.699	0.790
A. verniciflua (<15 cm)	3	12	-2.66	2.4	1.07	0.941	0.435

A fourth type of allometric equation was also developed which was site-and-species specific. These were related to the eight direct measurement sites, three of which were in Victoria. Because these equations have less reliability outside the sites from which the data was obtained, the parameters are not listed here. They are graphically shown in Paul *et al* (2013b).

For each of the four types of allometric equations developed, estimated biomass was compared with directly measured biomass at the site-level (Fig. 1.9). This shows that the two species-specific allometrics gave the best predictions, but that the generic universal and growth habit allometrics were very acceptable.

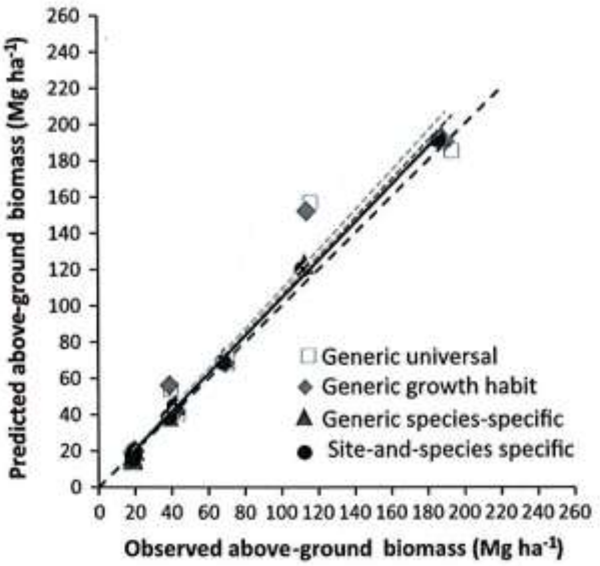

Figure 1.9: Relationship between predicted and observed above-ground biomass for each of the four classes of allometry, across the eight direct measurement sites. Dashed line indicates the 1:1 line. The best fits (when forced through the origin) for generic universal, generic growth habit, generic species-specific, and site-and-species specific relationships gave slopes (and R^2's) of 1.06 (0.94), 1.09 (0.96), 1.05 (1.00) and 1.04 (1.00), respectively. Source, Paul *et al*. (2013b).

In conclusion, although site-and-species-specific allometric equations are the most accurate for site-based predictions (assuming the sample number is >20 trees), the generic allometric equations developed here, particularly the species-specific allometric equations, can be confidently applied to provide regional estimates of above-ground biomass and carbon across a range of mixed-species environmental plantings currently growing throughout the low-medium rainfall regions of southern Australia.

Improved models for estimating carbon sequestration

Above-ground biomass data from 605 mixed-species environmental plantings was analysed to determine the effects of a range of planting characteristics on rates of growth. Within temperate regions, where plantings were more variable, the key factors influencing growth were planting width, stand density and species-mix (proportion of individuals that were eucalypt trees). For example, in these regions where plantings were tree-dominated, highly stocked, or planted in narrow linear configurations, on average there was 21%, 41% and 44% greater biomass accumulation after ten years compared with shrub-dominant, lower stocked, or block plantings, respectively.

These results are consistent with previous work and are discussed more fully in Paul *et al* (2013a). Eighteen categories (3 planting geometries x 3 stocking x 2 species-mix), provided the basis for improving the FullCAM calibration (estimation of appropriate modifiers), with the different rates of biomass accumulation (growth) requiring different tree yield curve calibrations in FullCAM, as detailed in Table 1.11.

Table 1.11. New default parameters (*G* and *y*) for various categories of plantings in temperate areas. *N* indicates the number of sites. The mean bias in AGB prediction (in t ha^{-1}) and model *EF* for each category of planting are provided. The maximum (Age Max) and 95th percentile of stand ages (years) is provided for each categories dataset. Source, Paul *et al.* (2013b).

Planting geometry#	Stand density (sph), (or trees ha^{-1})	Prop Tree	*G*	*y*	N	Bias	*EF*	Age Max	Age 95th Percent.
Narrow belt	< 1500	< 0.75	5.504	1.4	55	2.89	0.43	29	20
		≥ 0.75	3.627	1.5	27	2.05	0.11	30	24
	> 1500	< 0.75	3.380	1.4	53	0.20	0.59	18	17
		≥ 0.75	2.667	1.5	14	-0.26	-0.34*	24	24
Wide belt	< 1500	< 0.75	6.063	1.2	33	0.02	0.49	22	17
		≥ 0.75	3.893	1.3	33	-1.06	0.18	29	29
	> 1500	< 0.75	4.633	1.2	18	-2.15	-0.48*	17	16
		≥ 0.75	2.746	1.3	8	-1.18	-2.68*	19	19
Block	< 500	< 0.75	8.534	1.2	49	-2.04	0.16	33	28
		≥ 0.75	7.365	1.3	85	-1.20	0.56	37	33
	500-1500	< 0.75	5.460	1.2	77	-0.92	0.63	46	25
		≥ 0.75	4.828	1.3	49	-0.98	0.35	22	21
	> 1500	~	5.187	1.3	75	-0.73	0.51	33	20

Planting geometry was defined as narrow and wide linear plantings if the width of the planting was <20 m and 20-40 m, respectively. Block planting was where planting width was >40 m.

The ultimate objective of this project was to utilise the collated empirical observations and the analysis of key factors influencing growth to calibrate the yield curves for use in FullCAM. Specifically, this meant calibrating the Tree Yield Formula, which predicts growth increments and hence changes in above-ground biomass over time. In particular, two parameters of the Tree yield Formula were targeted; '*G*' and '*y*'. *G* is the tree age (years) of maximum growth rate (usually the age at which the crown canopy closes) and *y* is an adjustment of *M*, the prediction of maximum above-ground biomass accumulated. These parameters are often referred to as Type 1 (T1) and Type 2 (T2) modifiers of growth, respectively. The calibration is discussed in detail in Paul *et al* (2013a), where methodology for the iterative approach is outlined. This process determined that apart from the calibration of G and y for each planting type, no other additional T1 or T2 modifiers were required. For mixed-species environmental plantings in temperate areas, the new default parameters (*G* and *y*) for use in the different types of plantings (stand geometry, density, and proportion of trees) are provided in Table 1.11.

With these new modifiers of the Tree Yield Formula, the overall model efficiency was only 46% for mixed-species plantings. However, there was no apparent bias in model predictions and the model is satisfactory for most individual planting categories/types. Therefore, modelled estimates of biomass accumulation will be reliable on average. The calibrations for the 13 planting categories should provide greatly improved predictions of biomass accumulation when compared to the un-calibrated yield curves. Early growth that is likely to be more rapid, and total above-ground biomass may be higher for many plantings at maturity.

The implications for carbon accounting are significant, as on the basis of this research the methodology for quantifying carbon sequestration by permanent mixed-species native environmental plantings has recently been revised, and submitted as a methodology proposal to the Domestic Offsets Integrity Committee (DOIC) by the Department of Environment (DOE 2014). It is expected that in the near future this methodology will be endorsed by DOIC and become available for use in the CFI, or other similar carbon accounting schemes involving mixed-species environmental plantings in temperate regions.

Below-ground biomass (BGB) in open eucalypt forest

In researching the quantity of biomass stored below-ground in Open Eucalypt Forest, CCAP evaluated both native forest sites, and environmental plantings associated with this forest type. Primarily for budget reasons the research effort was focussed on environmental plantings, where below-ground biomass was more cost-effectively measured. The view was that the lessons from these sites could be used to develop methodology appropriate to the larger trees in native forests. Methods and results are detailed in Paul *et al*. (2014). Below-ground biomass, methods, results and uncertainty, can be summarised, as follows:

BGB - native forests and environmental plantings

Methods, results and uncertainty

The relative distribution of above-ground and below-ground biomass is important to the understanding of forest ecosystem carbon stocks. While distribution patterns are reasonably well understood for above-ground biomass, knowledge of below-ground biomass and its distribution is still quite limited (Snowdon *et al*. 2000). The mass of roots in forest tree species represents a significant proportion of total biomass in both native forests and reforestation plantings. While the allocation of above- and below-ground biomass is often in proportion (i.e. root : shoot ratios), it has been found that there is sufficient variation that spatial estimation should be based on allometric relationships and tree size distribution, not on root:shoot ratios (Snowdon *et al*. 2000). This variation is particularly important in regions of low-medium rainfall given that roots contribute an increasing proportion of total biomass with decreasing Mean Annual Rainfall (Mokany et al. 2006). Both Open Eucalypt Forest and mixed-species environmental plantings are found extensively in these regions. Consequently, the magnitude of sequestered carbon in root biomass may be of interest for carbon accounting purposes. However, there is relatively limited information on root biomass largely because of the methodological difficulties with measuring roots (e.g. Vogt et al. 1996). The most accurate method of measuring root biomass is through whole-plot excavation. However, this destructive measurement approach is typically a laborious and expensive process and is rarely, if ever, used. Whole-plot estimation of above-ground biomass is much more common, but has rarely been matched by a similar approach to measuring root biomass. Root biomass has more often been determined using limited excavation, use of soil cores, or small soil pits (Mokany et al. 2006).

In collaborative research, reported in Paul *et al*. (2014), CCAP explored root biomass estimation using direct measurement on 3 Victorian mixed-species environmental planting sites, and 3 other sites (Table 2.1). Sites targeted were young plantings in low-medium rainfall agricultural regions of southern Australia. Additional to this new data, existing root biomass data were collated from a number of different planting sites of varying ages.

This root biomass study had three objectives: (i) investigate predictions of root biomass from equations derived from various studies with differing protocols for root excavation, (ii) investigate appropriate grouping of species when developing generic equations, and (iii) evaluate the accuracy of generic equations when tested against direct measurement of root biomass.

At each of the 6 direct measurement sites roots were excavated within three sub-plots (generally 10 m × 10 m) Paul *et al.* (2013a, b). There were between 96 and 371 trees or shrubs harvested per site (Table 2.2).

Table 2.1. Summary of 'direct measurement' site characteristics, for Victorian and 'Other' mixed-species environmental plantings studied. Including, location (latitude, longitude, in decimal degrees), mean annual rainfall (MAR), planting type (block or linear plantings), planting method, year of establishment, age of planting, and the main species which were present at measurement. Compiled from, Paul *et al.* (2014) and Paul *et al.* (2013b).

Site	Location	MAR (mm)	Plant. type	Plant. method	Year planted	Age (yrs)	Species present
				Victorian 'Direct measurement' plantings			
Jenharwill	-36.3958, 144.4304	406	Linear	Tubestock	1999	12	*A.calamifolia, A.hakeoides, A.pycnantha, E.leucoxylon*
Gumbinnen	-36.2447, 141.8148	347	Block	Tube & seeded	2001	10	*A.pycnantha, A.trineura, E.largiflorens, Melaleuca*
Leos	-37.8381, 147.7582	626	Linear	Tubestock	1996	16	*A.penninervis, C.cunninghamian, E.kitsoniana, E.melliodora, M.armillaris*
				Other 'Direct measurement' plantings			
Strathearn	-35.0485, 149.2325	637	Block	Direct seeded	1995	15	*E.viminalis, E.melliodora, E.blakelyi, E.polyanthemos, E.stellulata, A.baileyana*
Moir	-34.2809, 118.1820	439	Block	Direct seeded	1990	20	*A.acuminata, A.microbotrya, E.loxophleba, E.occidentalis, E.spathulata*
McFall	-33.7290, 117.3217	438	Linear	Seeded	1990	22	*A.acuminata, A.saligna, A.huegeliana, E.gardener, E.kochii, E.wandoo, M.unicinata*

The new and existing root biomass data from 464 individual trees or shrubs was collated to develop and test allometric equations for predicting root biomass based on stem diameter in these plantings. Paul *et al*. (2014) found that root biomass can be successfully predicted using allometric relationships from above-ground diameter (D10, or equivalent). Equations developed showed significant differences between groupings of species with differing growth habits or from different genera. Grouping species into categories of: (i) non-eucalypts, and (ii) eucalypt trees, provided equations with model efficiencies of 0.89-0.90, indicating a reasonable fit to the data. The developed equations were validated using data from the 6 environmental planting sites (Table 2.2), where direct measurement of root biomass was made through whole-plot excavation. Site-level predictions of root biomass from above-ground parameters were effective, with an efficiency of prediction of 0.98. These results indicate that the generic allometric equations developed (Table 2.3) can be confidently applied across a range of sites to obtain accurate regional estimates of root biomass in the currently relatively young environmental plantings in agricultural regions of Australia with low-medium rainfall.

Table 2.2. Summary of sites studied. Stand density (stems ha^{-1}), average stand basal area (BA, m2 ha^{-1}), and plot-average shoot biomass (t ha^{-1}) were calculated based on the plots measured at these sites by Paul et al. (2013c, d). The number of trees or shrubs excavated in the three strategically selected sub-plots (Trees/shrubs roots excavated), and the plot-average root biomass (t ha^{-1}) observed are provided. Compiled from Paul *et al.* (2014).

Site	Stand density (stems ha^{-1})	BA (m2 ha^{-1})	Shoot biomass (t ha^{-1})	Root biomass (t ha^{-1})	Trees/shrubs roots excavated
Jenharwill	6,456	16.92	69.1	21.34	163
Gumbinnen	2,282	4.38	19.1	4.48	305
Leos	845	26.61	113.6	44.94	96
Strathearn	2,827	11.37	38.9	25.30	371
Moir	2,708	4.72	42.4	17.07	346
McFall	2,440	30.50	189.6	76.00	313

Table 2.3. Root allometric equations; $Ln(y) = a' + b \times Ln(x)$, where *y* is the dependent variable (biomass, kg tree^{-1}), *x* is the independent variable (D10 stem diameter, cm); *CF, sd(e), EF* and *N* refer to the correction factor (Snowdon 1991), precision (expressed as a standard deviation of residuals), model efficiency (Soares et al. 1995) and sample number, respectively. Source, Paul *et al.* (2014)

Growth habit (D10 diam. range)	Explanatory variable	a	b	CF	sd(e)	EF	N
Non-eucalypts (<46 cm)	D10	-3.71	2.23	0.91	0.48	0.89	96
Non-eucalypts* (<40 cm)	DBH	-2.37	1.85	0.98	0.17	0.97	44
Eucalypts (<63 cm)	D10	-3.76	2.46	0.98	0.51	0.90	368
Eucalypts (<52 cm)	DBH	-1.26	1.74	1.24	0.58	0.87	368

This experience was used to review root biomass estimation in native forests and to develop an approach to estimation. It was determined that meaningful data could not be collected with the existing budget, and that additional funding was required. Root biomass estimation in native forests was deemed not to have sufficient priority to divert funds from other CCAP areas, hence it was not possible to extend the environmental planting's root biomass project into native forests. However, the fact remains that there is a significant lack of root biomass data on large trees, with the current study providing root biomass data to an above-ground diameter (D10) of 46 cm and 63 cm for non-eucalypts and eucalypts respectively.

On the CCAP native forest sites, these generic allometrics could be used for the estimation of root biomass where tree diameter (DBH, D130) did not exceed 52 cm in the case of eucalypts, and 40 cm for non-eucalypts. Hence, two of the Rushworth CCAP plots would be suitable for root biomass estimation; the remaining 21 CCAP plots would have trees that were outside of the DBH range for the allometric.

Soil carbon quantity and fractions (open eucalypt forest)

CCAP has been involved in researching the quantity of soil organic carbon and its various fractions in both native forest sites and environmental plantings associated with reforestation of this forest type. Methodology was initially developed at the environmental planting sites and then has been adjusted for use in native forests. The quantification of total soil carbon and its fractions, and the methods used can be summarised, as follows:

Methods and results

Soil carbon methods and results for the environmental plantings component are detailed in Madhavan *et al. (*In Prep.). Methods and results for the native forest component are detailed in Krishnaraj *et al*. (In Prep). A summary of these methods and results is reported under the headings of: (I) Native forests, and (2) Environmental plantings.

Native forests

In native forests, as part of the CWD and litter sampling (see 1.1.1.2), mineral soil to a depth of 10 cm was collected using a soil bulk density corer. All litter and soil samples were oven dried at 40ºC, sub-sampled, sieved, ground to a fine powder (<0.1 mm) in a vibration mixer mill (Retsch MM301; Daigger, Vernon Hills, USA) before further analysis. Total organic carbon (TOC) and total nitrogen (TN) concentrations were determined by dry combustion elemental analyser (LECO CNS-2000). The CCAP soils were also supplemented with soils collected from a range of native forest sites, with varying soil texture, parent mineralogy, and dominant eucalypt species (see Table 3.1). A sample set of 102 soil samples with TOC ranging from 27 to 240 g $kg^{-1}$and a mean of 85 g kg^{-1} was used to develop a mid-infrared (MIR) - partial least squares regression (PLSR) calibration model.

Table 3.1. Description of soil samples used to develop a MIR-PLSR calibration model for CCAP. Source, Krishnaraj *et al.* (In Prep).

Primary Species	Coordinates.		No. sites	No. Reps	Soil texture	Parent material	Soil order	pH	C stock (Mg/ha)
	Long	Lat							
Alpine ash	147.32	-36.88	3	4	Clay Loam	Rhyolite /Ignimbrite /Gneiss/Schist	Dermosol	4.9	102.2
Mountain ash	145.81	-37.65	3	4	Clay Loam	Rhyolite /Ignimbrite /Dacite	Dermosol	4.4	79.0
Blue Gum/ Nar-	146.18	-36.79	2	4	Sandy	Sand/Clay/Gravel	Dermosol	5.6	59.1

row-leaved Peppermint					loam				
Long-leaved Box/Red Stringybark	146.16	-36.74	1	4	Sandy clay loam	Sand/Clay/Gravel	Dermosol	5.9	38.4
Red Ironbark	143.18	-37.00	1	4	Sandy clay loam	Shale/Sandstone	Chromo-sol	5.0	45.9
Red Box/Red Stringybark	143.19	-37.01	2	4	Sandy clay loam	Shale/Sandstone	Chromo-sol	5.4	39.4
Yellow Stringybark /Red Ironbark	146.76	-37.85	4	4	Sandy loam	Siltstone/ Clay-stone	Chromo-sol/Sodosol	5.1	59.4
Yellow Gum /Grey Box	145.02	-36.76	2	4	Sandy clay loam	Siltstone/ Sand-stone/Claystone	Sodosol	5.1	35.4
Brown Stringybark	146.43	-38.13	2	3	Sandy	Siltstone/ Sand-stone/Claystone	Sodosol	4.4	61.8
Messmate Stringybark/Narrow-leaved Peppermint	144.01	-38.39	3	3	Sandy	Arkose/ Mud-stone/Sandstone	Kurosol	4.7	36.8
Silver top ash	146.00	-38.05	2	3	Sandy	Siltstone/ Sand-stone/Claystone	Ferrosol	4.3	60.7
Silver top ash /Broad-leaved Peppermint	145.95	-38.06	3	3	Sandy	Siltstone/ Sand-stone/Claystone	Ferrosol	4.1	58.5

The frequency of TOC concentrations in the 102 soil samples is shown in Fig. 3.1. A reasonable correlation between measured and predicted TOC concentration values were obtained, with r^2 = 0.92 and RPD=3.4 (Fig. 3.2). Source, Krishnaraj *et al.* (In Prep).

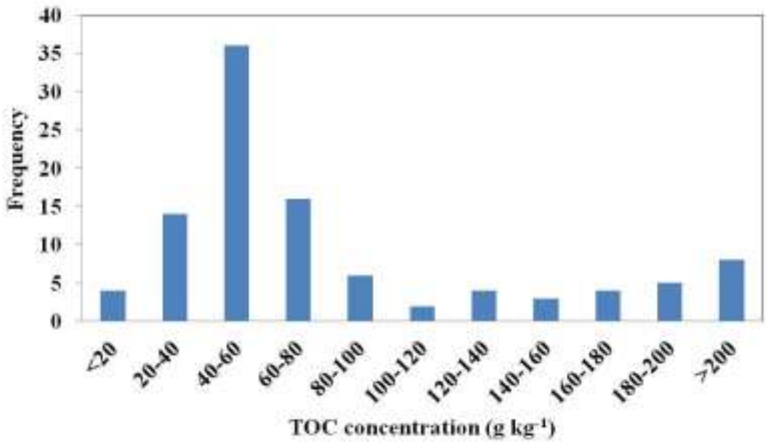

Figure3.1. Frequency distribution of total organic carbon (TOC) concentrations in the 102 soil samples used for MIR-PLSR calibration.

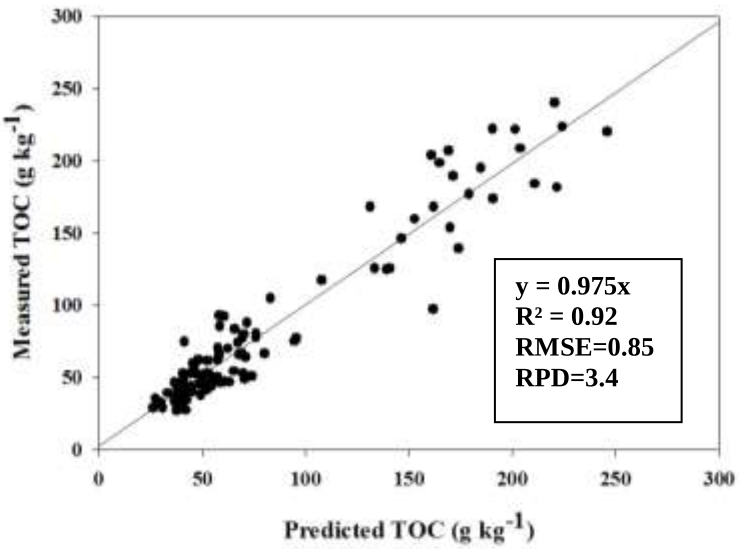

Figure 3.2. PLSR cross validation plot for measured Vs predicted total soil organic carbon (TOC) concentration, n=102. Source, Krishnaraj *et al.* (In Prep).

There was an uncertainty concerning the degree to which a single calibration could fit a wide range of soil carbon values. Results demonstrated that MIR spectroscopy combined with PLSR multivariate analysis proved to be a promising tool to calibrate organic carbon content of soils of distinct mineralogy and texture. On completion of nutrient and particle size analysis, additional calibrations using sub sample sets based on soil texture classes and mineralogy will be attempted to improve the robustness of MIR-PLSR calibration model.

Environmental plantings

In a collaborative national project, as part of Filling the Research Gap Program, new and existing data on soil and litter carbon under environmental plantings were collated. These plantings were established on ex-agricultural lands from ca. 120 sites (England *et al.* 2014). Soil organic carbon (SOC) analysis has been extended to include particulate (POC), humic (HOC) and resistant (ROC) organic carbon fractions, with estimation and characterisation using MIR spectroscopy and ^{13}C nuclear magnetic resonance spectroscopy (NMR) (see, Madhavan *et al.* 2014, and Madhavan, Read and Baker 2014). MIR spectra (7800-450 cm^{-1}) were collected from finely ground soil samples. Preliminary MIR spectroscopy and PLSR analysis for TOC and SOC fractions were carried out using standard soils (n = 287) from the national Soil Carbon Research Programme (SCaRP, Sanderman *et al*, 2011), which were randomly split into calibration (70%) and validation samples (30%). While calibration and leave-one-out cross validation results were robust for TOC and SOC fractions, validation results indicated potential for improving POC and ROC prediction. Various improvements were made to achieve better prediction and minimise errors, viz., increasing soil fine grinding duration in ring mill from one minute to two minutes or more based on soil texture; using different standard spectral pre-processing and data transformation techniques and spectra range (e.g., 6000 to 450 cm^{-1}); and using principal component analysis to identify and manage outlier samples.

Madhavan *et al.* (In Prep) reports that a sub-set of < 2 mm soils from environmental plantings (n = 12, 0-10 cm) were fractionated by wet-sieving into 2000-50 µm and $\leq$ 50 µm fractions. TOC contents were analysed in < 2 mm soils and fractionated samples by dry combustion (Dumas method). These samples were analysed in NMR to estimate ROC fraction in each, and POC and HOC were calculated by subtracting ROC from total C present in 2000-50 µm and ≤ 50 µm size fractions respectively. These SOC fractions were supplemented with SCaRP results to develop MIRS-PLSR calibrations. Figure 3.3 shows scatter plots of measured vs. predicted (a) TOC, (b) POC, (c) HOC and (d) ROC values from the calibrations and leave-one-out cross validations. Statistics of calibration and leave-one-out cross validation (Table 3.2) indicate robust and accurate predictions for TOC and C fractions (POC, HOC, ROC). Another sub-set of physical fractionated soils (n = 26), representing soils from Victoria, Western Australia and South Australia, are currently being used to improve POC and ROC predictions

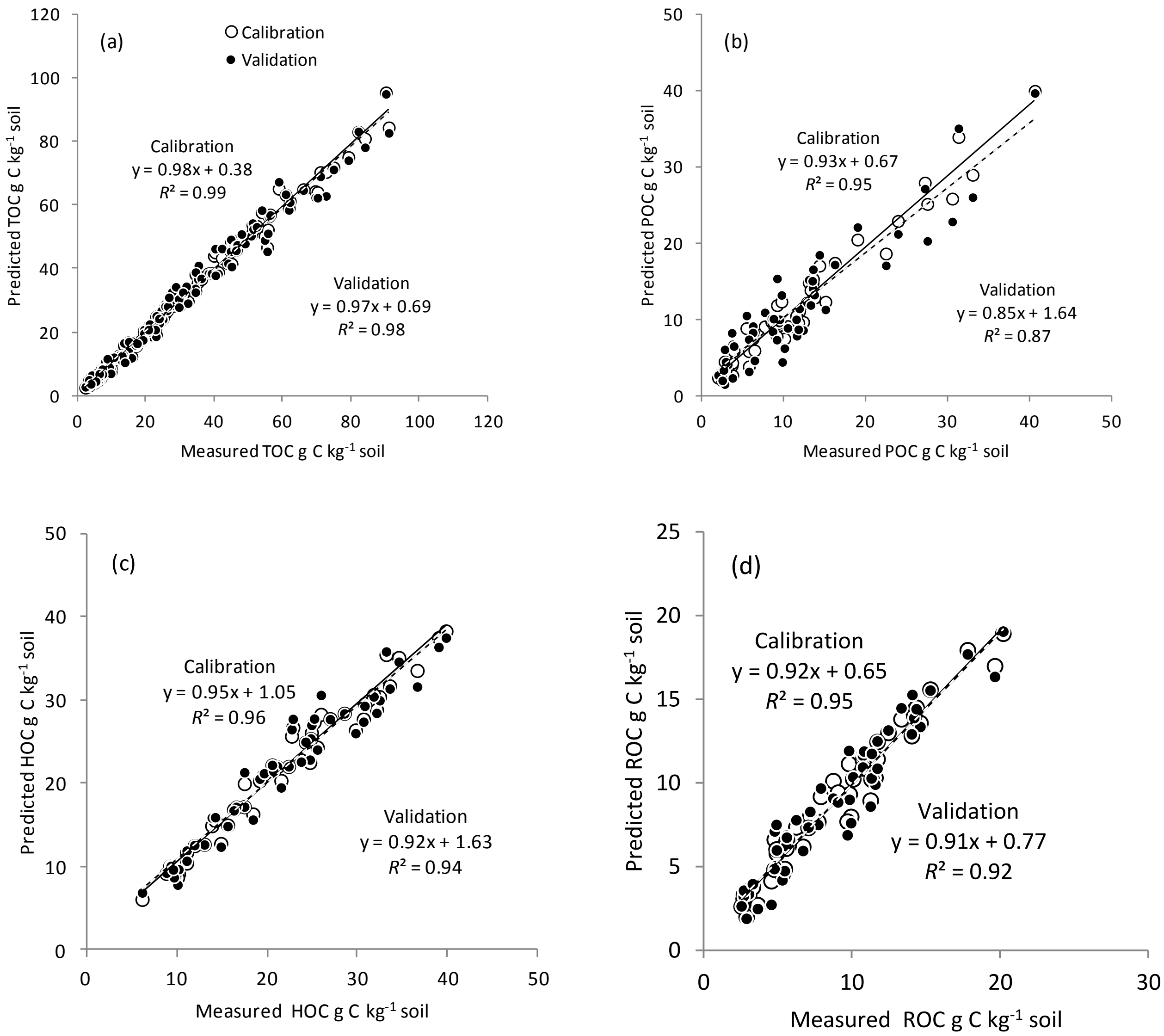

Figure 3.3. Scatter plots of measured vs. predicted (a) TOC, (b) POC, (c) HOC and (d) ROC values from the calibrations and leave-one-out cross validations. Soils (0-10 cm) from environmental plantings. Source Madhavan *et al* (In Prep).

Table 3.2. Statistics for MIRS-PLSR calibration and leave-one-out cross validation (spectra range 6000 to 450 cm^{-1}) from SCaRP and environmental planting soils. Source Madhavan *et al* (In Prep).

	TOC	POC	HOC	ROC
Spectra pre-processing	MSC (mean) 1st derivative Mean center	MSC (mean) 1st derivative Mean center	1st derivative Mean center	SNV 1st derivative
Data transformation	Cube root	Cube root	Cube root	Cube root
		-- Calibration --		
Latent Variables	5	6	6	6
R^2_{cal}	0.98	0.95	0.96	0.94
$\mathbf{Bias_{cal}}$	-0.05	-0.09	-0.06	-0.05
$\mathbf{SE_C}$	2.40	1.34	1.49	0.86
$\mathbf{RPD_{cal}}$	7.11	4.29	5.22	4.25
		-- Cross validation --		
R^2_{cv}	0.97	0.92	0.95	0.92
$\mathbf{Bias_{cv}}$	-0.05	-0.12	-0.06	-0.04
$\mathbf{SE_{CV}}$	2.79	1.63	1.64	1.02
$\mathbf{RPD_{cv}}$	6.12	3.53	4.76	3.57

MSC (mean) = Multiplicative scatter correction, 1st derivative = Polynomial order: 2, window: 15 pt
SNV = Standard Normal Variate scaling, SE = Standard error, RPD = Ratio of Performance to Deviation

Above-ground biomass in tall open forest (Mountain Ash)

CCAP is collaborating with NSW DPI (Fabiano Ximenes, Project Manager) and VicForests (Project Partner) in a Forest & Wood Products Australia (FWPA) funded project, titled “Carbon stocks and flows in native forests and harvested wood products in SE Australia”. This project is not due for completion until December 2014 when a final report will be prepared for FWPA and a copy to DEPI, as a Project Partner. The major focus for CCAP has been with the Mountain Ash biomass component, in Victoria’s Central Highlands. CCAP has been involved in site selection, inventory, weighing, recording and analysis. This overview report is an interim report pending completion of reporting in December. It provides a brief summary of the project to-date, with particular reference to the estimation of Mountain Ash biomass. In part it is based on information from a presentation by Fabiano Ximenes in February 2014 to project participants, from the December 2013 Milestone report and shared data between CCAP and NSW DPI.

AGB – tall open forests

The aim of this project is to "provide a whole of life assessment of the implications of native forest management for carbon stocks and fluxes for three representative commercial native forestry areas in NSW and VIC, based on information contained in State agencies databases and new data collected through field work, and which will be incorporated into existing forest management scenarios, together with an assessment of the associated economic costs and revenues." More specifically this can be expressed as:

1. To refine the estimates of above-ground biomass for a range of key native forest types in NSW and VIC.
2. To apply a whole-of-life approach in the assessment of the greenhouse implications of production and conservation forests.

CCAP has been actively involved in estimating the above-ground biomass for stands of Mountain Ash. The key component of this is to determine above-ground biomass using direct measurement (destructive sampling) techniques and to use this data to develop allometric equations suitable for off-site above-ground biomass estimation across a broad range of diameters (DBH).

Methods and results

The project has three study areas:

1. Eden, South Coast NSW (Silver Top Ash (*Eucalyptus sieberi)* dominated)
2. Wauchope, North Coast NSW (Blackbutt (*Eucalyptus pilularis*) dominated)
3. Toolangi, Central Highlands Victoria (Mountain Ash (*Eucalyptus regnans)* dominated)

Paired production and conservation sites were selected to represent "conservation" and "production" scenarios at each of the study areas. The paired NSW North Coast biomass sites were located near Wauchope and dominated by Blackbutt. The paired NSW South Coast biomass sites were located near Eden and dominated by Silver Top Ash. The Victorian Mountain Ash "production site" was located in Toolangi SF, approximately 30 km north of Healesville in 74 year old regrowth. The "Conservation site" was located in the same forest a few kilometres away in what is thought to be about 109 year old Mountain Ash (1905 regrowth). At each of these representative sites a plot approximately 0.5 ha in area was established and all trees >10 cm diameter at breast height over bark (DBH) were numbered, identified, and measured for DBH and tree height. At all sites, with the exception of the Toolangi "conservation" site, all numbered trees on each of the plots were felled, cut into extraction lengths (including the upper stem and crown/canopy) and extracted to a central landing for conversion to log product and weighing. A tandem weigh-trailer suitable for weighing large logs (to 5 tonnes) was loaded by a crab-grab excavator and the weight of the freshly felled and cross-cut tree section was recorded by merchantable component.

In Victoria, the Toolangi Mountain ash "production" site (55 E 445400; N 6544700) was located on an east facing slope, in a harvest area along Hardy Creek Rd, with all trees being regrowth from the 1939 wildfire. The dominant species is Mountain Ash (*Eucalyptus regnans*) with a sub canopy of Silver wattle (*Acacia delbata*), Hickory Wattle (*Acacia obliquinervia*) and Mountain Pepper (*Tasmania lanceolata*). Shrub cover is mostly made up of Correa spp and tree ferns. Groundcover is light with a heavy mulch layer around live trees. There is no evidence of any fires since 1939, and only a few stumps from a light thinning of the stand in the 1960's. The 0.5 ha plot was part of a larger scheduled VicForests harvest coupe. On the plot, a total of 98 Mountain Ash were measured, with 20% of these having DBH <50cm (Fig. 4.1)

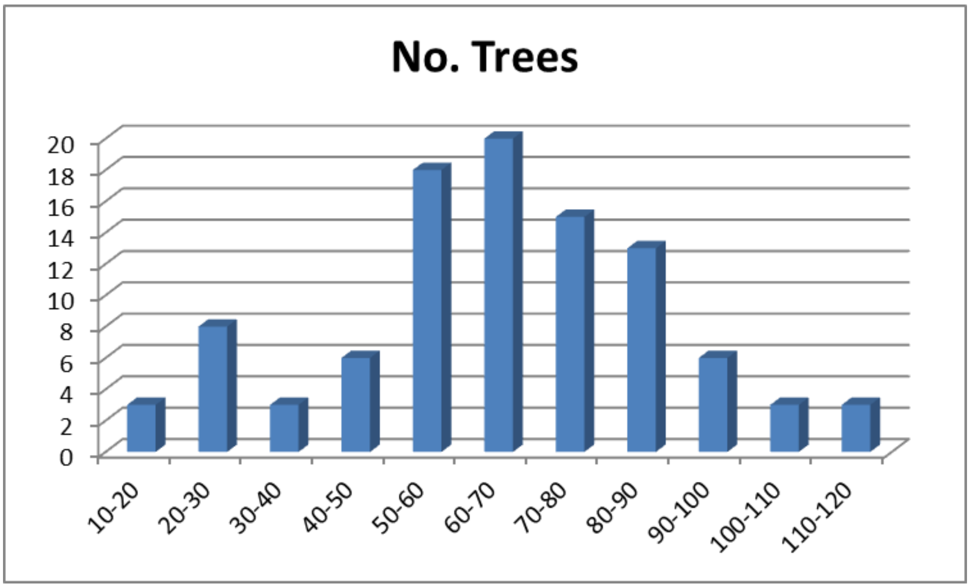

Figure 4.1: Mountain ash “production” site - frequency of trees on a 0.5 ha plot by diameter (DBH) class (cm). Source, December 2014 FWPA Milestone report.

The Mountain ash “conservation” site was located a few kilometres away from the production coupe, on a gentle slope in an area off Sylvia Creek Rd, with the majority of trees Mountain Ash originating from a wildfire disturbance around 1905. The dominant species is Mountain Ash (*E. regnans)* with a sub canopy of Blackwood (*A. melanoxylon),* Austral Mulberry *(Hedycarya angustifolia)* and Mountain Pepper. Shrub cover is mostly made up of tree ferns. Groundcover is light with a heavy mulch layer around live trees. There is no evidence of any fires since 1905 and only slight evidence of limited thinning nearby. The site is currently not part of a scheduled VicForests harvest coupe. Consequently, biomass assessment must be done by ‘indirect measurement,’ using an allometric equation developed from the production plot and extended with selectively sampled trees from another VicForest coupe. The trees that are to be selectively sampled to ‘extend’ the allometric derived from the production plot have diameters in the range of 100-160 cm (DBH) and are likely to be of 1926 origin. Felling and measurement of these trees is scheduled for July 2014, from a coupe located a few kilometres away. Currently, the conservation plot has been marked and measured, with a total of 40 *E. regnans* trees measured, all DBH >50cm (Fig. 4.2).

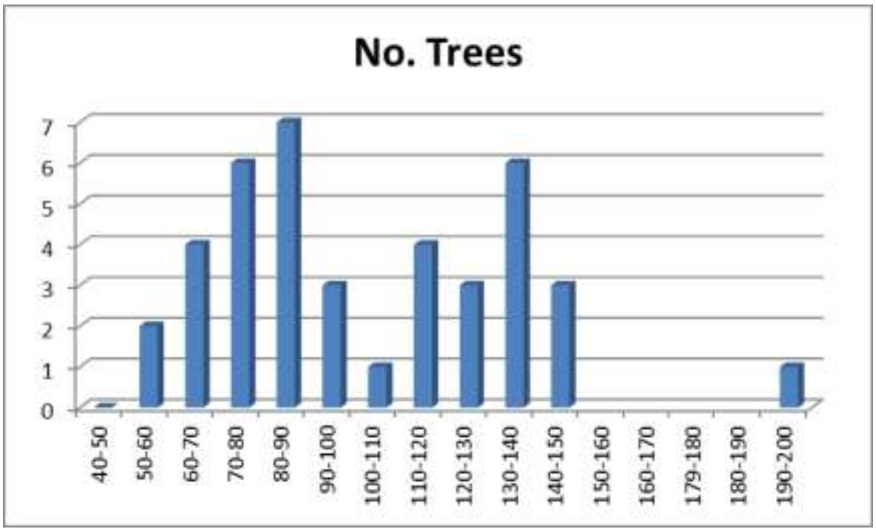

Figure 4.2: Mountain ash "conservation" site - frequency of trees on a 0.5 ha plot by diameter (DBH) class (cm). Source, CCAP shared data.

The Mountain Ash "production" site had at least double the fresh weight (FW) biomass of all the other sites (Table 4.1), reflecting the high productivity of Mountain Ash forests.

Table 4.1. Fresh Weight (FW) of live and dead standing eucalypts (>10 cm DBH), NSW North Coast, NSW South Coast and Victorian sites, on a plot and /ha^{-1} basis. Source, December 2014 FWPA Milestone report and CCAP shared data.

Site	Live trees (FW t, '0.5 ha' plot)	Live trees (FW t/ha)	Dead trees (FW t/ha)
NSW South Coast - Eden Production	156.7	342.6	24.7
NSW South Coast - Eden Conservation	334.3	714	6.9
NSW North Coast – Wauchope Production	189.4	389.8	19.5
NSW North Coast – Wauchope Conservation	334.5	697	5.1
Victoria – Toolangi Production	745.3	1490.6	22.3
Victoria – Toolangi Conservation*	777.1	1432.5	14.7

*Indicative at best - estimation of FW using allometric derived from "production" plot. Some large trees were well outside the limits of this allometric.

The relationship between DBH and fresh weight of live *E. regnans* at the Toolangi production site is shown in Figure 4.3.

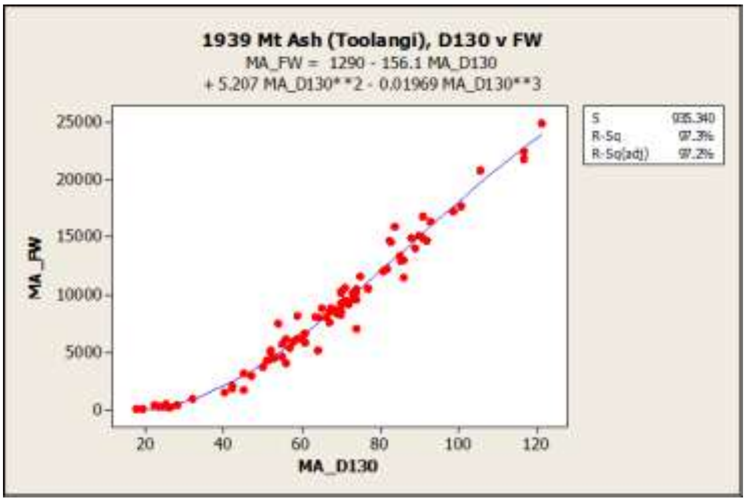

Figure 4.3: Relationship between DBH (cm, D130) and fresh weight (FW, kg) of live *E. regnans* at the Toolangi "production" site. Source, CCAP shared data.

Harvested trees were sampled for moisture content (MC) and basic density following weighing on the landing, to derive dry weight (DW, 0% MC) DW:FW ratios for converting fresh weight to a dry weight equivalent (Table 4.2). The relationship between DBH and the dry weight equivalents for live Mountain Ash biomass at the Toolangi production site is shown in Figure 4.4.

Table 4.2. *E. regnans* basic density and moisture content averages from the "production" site at Toolangi, by tree component. Source, December 2014 FWPA Milestone report.

Tree component	Basic Density		Moisture Content	
	Mean	Stdev.	Mean	Stdev.
Base Logs	474	42.7	56.6	3.3
Middle Logs	533	41.6	48.9	3.5
Crown Logs	566	54.9	45.1	3.1
Branches	606	34.7	44.3	2.8
Overall	524		47.1	

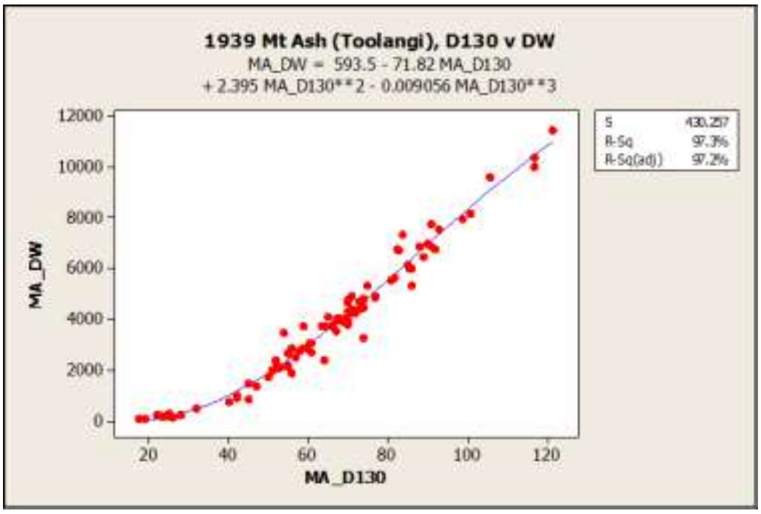

Figure 4.4: Relationship between DBH (cm, D130) and dry weight equivalent (DW, kg) of live *E. regnans* at the Toolangi "production" site. Source, CCAP shared data.

Conclusions

The research undertaken through CCAP has provided a much improved capacity to estimate carbon in biodiverse ecosystems, which will also have flow-on benefits to a range of ecosystem services. This has been achieved by developing two methodologies, destructive and non-destructive sampling, that allow more accurate determination of AGB across a range of native forests. To date the primary focus has been on the native and reforested open eucalypt forests across a range of productivities, with extension to the wetter more productive tall open mountain ash forests.

Destructive sampling at 8 native open forest plots (0.5 ha each) has resulted in the harvest of 337 trees across 13 eucalypt species and a diameter (DBH) range of 10 - 143 cm. Both site and species specific allometrics have been developed and used to derive AGB per hectare for the 23 CCAP plots. Averaged for each of the three sites, these were: Rushworth, 163 t ha^{-1}; Pyrenees, 234 t ha^{-1}; and Toombullups, 328 t ha^{-1} on a dry weight basis. Live AGB was compared to FullCAM predictions, with the current version (3.55) performing well for dryer and less productive (Rushworth) sites (Δ4%) and significantly under predicting as sites became wetter and more productive (Pyrenees, Δ60%; Toombullups, Δ85%). In the more productive Mountain Ash open forests, the destructive measurement of 98 trees, with a diameter range of 17-121 cm (DBH), has enabled development of allometric equations describing the relationship between live tree diameter (DBH) and tree fresh- and dry-weight. AGB of the mountain ash in these tall open forests were typically around 370 t ha^{-1} (on a dry weight basis), with additional AGB from understorey elements.

Non-destructive sampling at two native open forest plots (0.5 ha each) using terrestrial laser scanning (TLS) has given very promising results. When compared to the destructively-derived data the TLS approach showed an overestimation of 9.68% in AGB compared to an underestimation of 36.57% to 29.85% using existing allometric equations.

On areas reforested with environmental plantings, destructive sampling (or 'direct measurement') was used as part of a larger data set to successfully develop a range of allometric equations for providing regional estimates of above-ground biomass/carbon for a range of open eucalypt forest species. Recalibration of the FullCAM's yield curves (Tree Yield Formula) on the basis of planting geometry, spacing, and proportion of trees provided greatly improved predictions of biomass accumulation when compared to un-calibrated yield curves. This provided greater certainty in carbon estimation.

The ability to estimate the quantity of BGB/carbon has been significantly improved, for native forests and more particularly for reforested environmental plantings. This has been achieved by developing a destructive sampling methodology (whole plot excavation) for environmental plantings, which has allowed more accurate determination of BGB. Root allometric equations for eucalypts (<52 cm DBH) and non-eucalypts (<40 cm DBH) have been developed. Environmental planting data shows that root-to-shoot ratios can be high in water- and nutrient-limited environments. Ratios ranged between 0.28 and 0.81, and were higher in tree-dominated sites, where the ratio tended to decline as productivity increased.

Significant progress in using the MIR-PLSR calibration approach has greatly improved the ability to estimate TOC more cost-effectively. This has been demonstrated across a range of native forest sites, with varying soil texture, parent mineralogy, and dominant eucalypt species. It has also been demonstrated across a broad range of ex-agricultural soils in which environmental plantings have been established. Additionally, for these soils the MIR spectroscopy methodology has also been able to predict the proportion of soil organic matter with different classes of decomposability (ie. POC, HOC and ROC), providing a relatively cost-effective means for more completely describing the carbon sequestration ability of reforestation soils. While this methodology has been demonstrated for the reforested environmental planting soils it is still being developed for native forest soils.

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Appendix A

CCAP – genesis and evolution

In 2010, the Victorian State Government's Department of Sustainability and Environment received $2.5M initiative funding from the Budget and Economic Review Committee to deliver two Carbon projects:

1. *Comprehensive Carbon Assessment Program (CCAP)* – intensive physical sampling of specific native forest sites, consistent with Commonwealth technical protocols; and
2. *Forest Remote Sensing Program* - rollout and testing of remote sensing technology, to improve existing carbon measurements (in addition to other attributes) in State Forest.

Both projects aimed to improve understanding of carbon in Victorian native systems and to better position Victoria to manage any expansion of land sector carbon accounting and /or trading in the future. At the time, DSE's EPCC Division was responsible for delivery of CCAP, while Forests & Parks Division was responsible for the Forest Remote Sensing Program. Funding was provided over four years, from 2010/11 to 2013/14. Funding was shared equally between both projects (i.e. $1.25M for each project over the four years).

Part way through the four year period, in June 2012, the Victorian Centre Climate Change Adaptation Research Centre (VCCCAR) Funding Agreement between the State of Victoria (through DSE) and the University of Melbourne (dated 14 July 2009) was varied to include a new clause (4.4.4), as follows:

"The University agrees that it will allocate and use the Funds provided for the Comprehensive Carbon Assessment Program in the manner set out in the table titled "Comprehensive Carbon Assessment Program Milestones" in Schedule 3 Milestones".

The funding contributed by the State to these Milestones was $700,000. The 11 Milestones from Schedule 3 have been grouped into 4 broad research areas for the purpose of clarity and utilty, and are detailed in Table A.1.

Table A.1. Comprehensive Carbon Assessment Program Milestones, as outlined in Schedule 3 and grouped into 4 broad research areas.

Deliverable or Milestone #	Deliverable
1. Open Eucalypt Forest, below-ground biomass - *Quantity of biomass, how to improve its estimation, and the relationship between below- and above-ground biomass.*	
4	Summary report on the Initial below-ground biomass assessment and associated standard operating procedures that will be used to complete the analysis across additional sites completed to the State's reasonable satisfaction
8	Final report on the quantity of biomass stored below-ground in open forest across Victoria and the relationships between below and aboveground biomass completed

	to the State's reasonable satisfaction

2. Open Eucalypt Forest, above-ground biomass - *Quantity of biomass, how to improve its estimation using an 'improved' FullCAM, and what would be the implications for carbon accounting.*

1	Summary report on the assessment of above-ground biomass In the Rushworth State Forest and implications for the broader program of analysis completed to the State's reasonable satisfaction
6	Final report on all sites above-ground biomass assessment and Implications for carbon accounting completed to the State's reasonable satisfaction
7	Technical Report on the standard operating procedures developed from the pilot above-ground biomass assessment completed to the State's reasonable satisfaction
9	Final report: Comprehensive Carbon Assessment Program CCAP that outlines the Improvement generated within the FullCAM model for Victoria's forests completed to the State's reasonable satisfaction

3. Open Eucalypt Forest - *soil carbon quantity and fractionations.*

5	Scientific paper on Soil carbon analysis protocols to assess forest soil carbon fractions completed to the State's reasonable satisfaction
10	Final report on Soil sampling analysis report, outlining the quantity and fractionation of carbon in CCAP sites completed to the State's satisfaction
3	Report on Soil carbon sampling and protocols and their ability to inform carbon accounting completed to the State's reasonable satisfaction

4. Tall Open (Mountain Ash) Forest, above-ground biomass - *Quantity of biomass and FullCAM carbon and the implications for carbon accounting.*

2	Technical Progress report on Forest Wood Products Australia (FWPA) Research project: Outlining the design and how the project will Improve the accuracy of biomass and FullCAM carbon estimation of native forests In South-Eastern Australia and the role of harvested wood products site selection and sampling design completed to the State's reasonable satisfaction
11	Final report on the FWPA Research project: Detailing the assessment of biomass and FullCAM carbon estimation of native forests In South-Eastern Australia and the role of harvested wood products site selection and sampling design completed to the State's satisfaction

Appendix B

CCAP - rationale

As the international negotiations around mitigation and adaptation to climate change progress, there has increasingly been an emphasis on the role that terrestrial stocks of carbon can play in mitigating atmospheric carbon dioxide. This is particularly relevant to Australia, given the fact that the Federal Government has signed on to the second round of the Kyoto Protocol, with provisions being made for Article 3.4, which covers carbon emissions from forest management. In addition to this, there are the potential opportunities in carbon sequestration afforded by reforestation of previously cleared or disturbed areas of forest, exemplified by the Australian Government's Carbon Farming Initiative (CFI), which seeks to financially reward landholders for "re-carbonising" their landscapes.

This context has resulted in a great deal of interest in the carbon sequestration potential of native forests of Australia from a variety of stakeholders, from government to the private sector, in addition to academics, the timber industry and conservation groups.

This research project, to validate above-ground carbon estimates of Open Eucalypt Forest in Victoria, was initiated to give greater certainty to carbon estimation, by reducing the uncertainty in estimating biomass for this forest type. While the primary focus was on native Open Eucalypt Forest on public land in Victoria, there was also a focus on private land, particularly where there was reforestation using Open Eucalypt Forest native species.

This project came about as a consequence of DSE's LandCarbon project and the frustration experienced with existing carbon modelling tools. The LandCarbon project estimated the amount of carbon stored in Victoria's public forests, parks and reserves using the national carbon accounting system (NCAS) (Norris, 2010). During this project there was an awareness of significant uncertainty for some generated carbon estimates, and a recognition that this needed to be addressed.

DSE's LandCarbon Project was initiated in late-2008 to generate a spatially explicit estimate of the terrestrial carbon stocks on Victorian public land. This represents approximately 7.2 million hectares of land, representing ecosystems as diverse as desert, grassland, mallee, lowland forests, montane forests, and alpine areas. This was the first attempt since Grierson *et al*. (1991) to produce an estimate of carbon stocks for Victorian public forest. While this previous estimate used regressions derived from inventory data the LandCarbon project used a purpose built carbon accounting system (NCAS). Initially, the project used a comparatively simple database, averaging the effect of timber harvesting and wildfire on carbon stocks on a decadal time scale. The rationale of this was to simplify the inputs of spatial data to FullCAM and speed up analysis of carbon stocks and fluxes, as reported in Norris (2010).

Further iteration of the LandCarbon project sought to provide a vastly more complex spatial database and included annual carbon stock estimates, differentiation between Single Tree, Clearfell and Thinning timber harvesting events, the inclusion of wildfire severity (where available), the differentiation of wildfire and prescribed burning, and a consideration of the regeneration mechanism of the major forest overstorey species (i.e. respouters versus obligate-seeders). The results of this project have been reviewed by Polglase (2011), and presented by Fairman and Law (2011). Figure B.1 illustrates the results of this further iteration. The project also identified that at the interface of public land and private land there were extensive opportunities for reforestation, particularly in the low-moderate rainfall zone associated with Open Eucalypt Forest, and that these areas could be reforested under the CFI (DOIC, 2011).

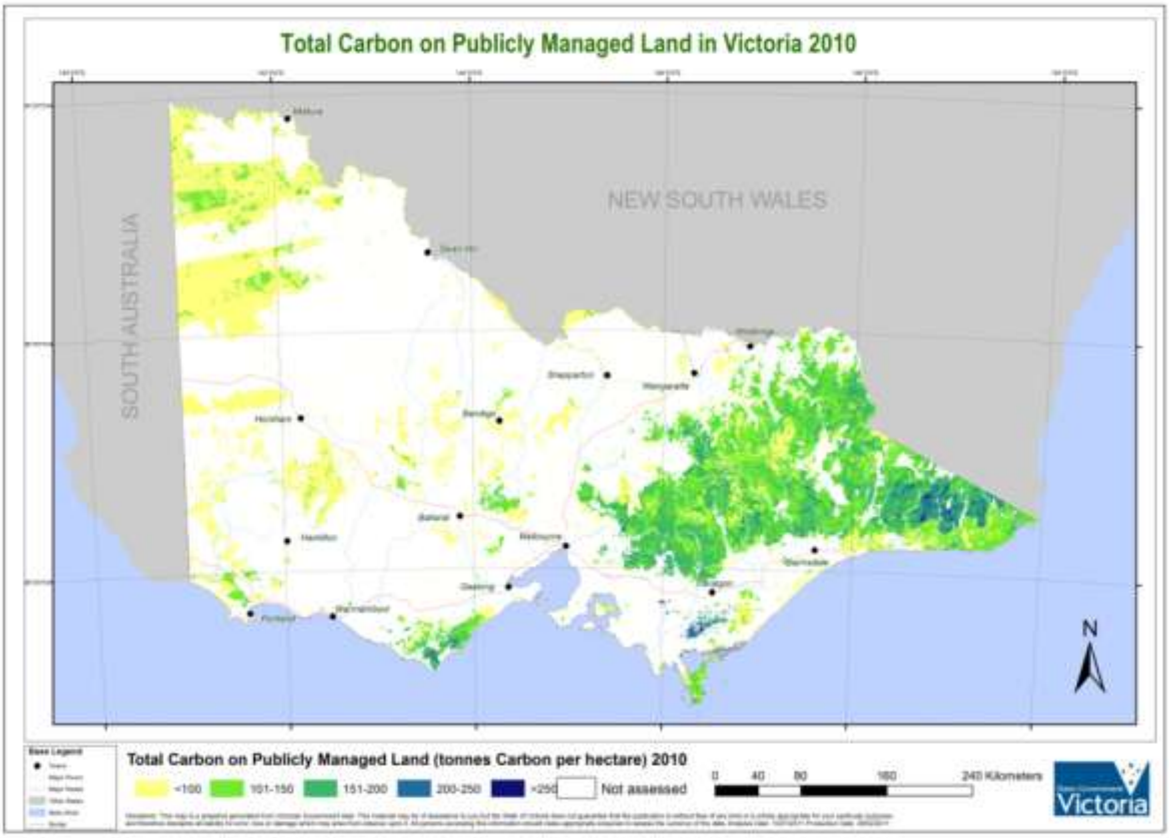

Figure B.1: Above-ground carbon estimate for publically managed land in Victoria 2010. Source, Fairman and Law (2011).

The LandCarbon project was ambitious at the time because of its spatial consideration of various forest disturbances when estimating the carbon stocks and fluxes over an 80 year period (1930 – 2010). During modelling there was a recognition that this disturbance data had some uncertainty associated with it, but there was also a greater concern that the NCAS modelling used for this project, which accounted for the greenhouse gas emissions and removals from land-based activities, was also significantly in error. In particular, the ecosystem biomass modelling tool, the Full Carbon Accounting Model (FullCAM) was generating questionable estimates, usually under-estimating the above-ground biomass. This high-degree of uncertainty around the accuracy of FullCAM derived carbon estimates has also been observed by others (Montagu *et al*. 2003; Wood *et al*. 2008; Lowson 2008; Paul *et al*. 2010; Keith *et al*. 2010; Fensham *et al*. 2012; Preece *et al*. 2012). FullCAM tracks greenhouse gas emissions and carbon stock changes associated with land use and management, to estimate and predict biomass, litter and soil carbon in both forest and agricultural systems.

A review of the performance of FullCAM triggered by the LandCarbon project found that site-based estimates of above-ground biomass were systematically under-predicted where vegetation carbon is greater than 100t/ha, as illustrated in Figure B.2. Additional review found that there was a very strong correlation between increasing basal area and increasing underestimation of the FullCAM model, along with a very strong correlation between decreasing basal area and increasing overestimation of the FullCAM model (Hammersla, 2010). In Victoria, there are many forest types which would be significantly under-estimated or over-estimated as a consequence, a discrepancy which could result in significant carbon accounting errors at the broader landscape level.

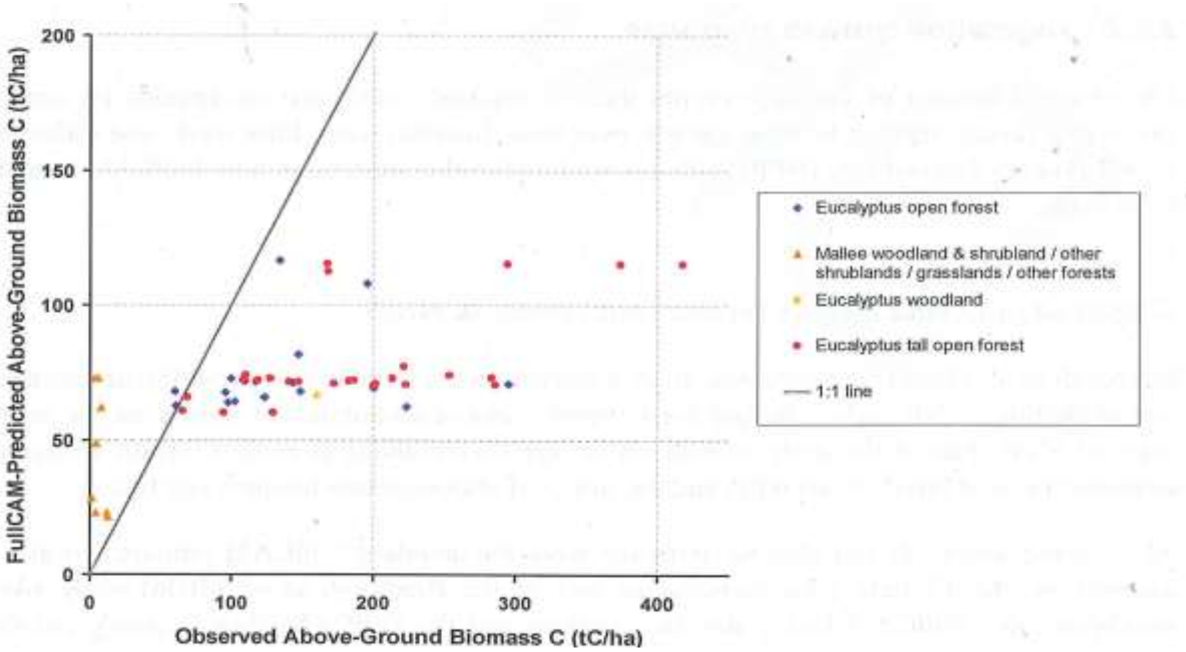

Figure B.2: Observed vs FullCAM prediction of above-ground biomass carbon (Victoria). Source, Roxburgh *et al*. (2010)

While FullCAM is capable of simulating carbon dynamics for a wide range of vegetation types, extensive application and testing of the model in Victorian native ecosystems had not been undertaken, apart from limited review. Further verification of predictions was required across a wider-range of native ecosystems of various ages if the uncertainty associated with FullCAM was to be reduced (e.g. Polglase *et al*, 2013). In particular, FullCAM's aboveground biomass multiplier (an input affecting carbon yields in tree biomass) was identified as a high priority for further review. Figure B.3 illustrates how FullCAM is capable of generating better estimates in native forest stocks; it is purely the data required to parameterise the models that is lacking. CCAP will endeavour to address this issue to some extent.

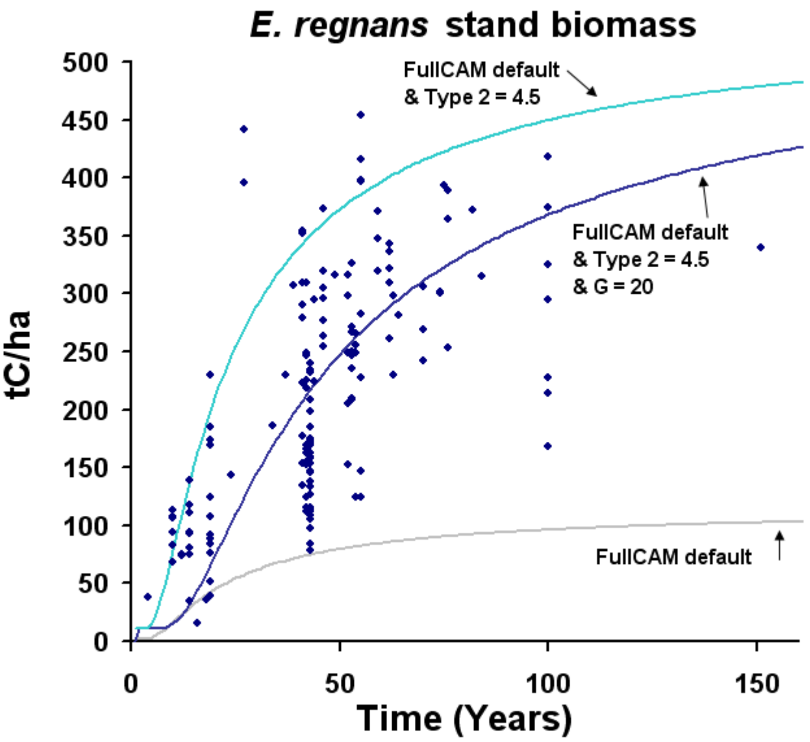

Figure B.3: Illustration of modifications to default FullCAM parameters to increase the predicted above-ground biomass stock using a multiplier (the Type 2 modifier) and also the shape of the growth curve (through changing the Tree age at maximum growth parameter (G)). Source, Roxburgh *et al*. (2010)

Roxburgh *et al.* (2010) examined the current capabilities and limitations of the FullCAM model for simulating carbon stocks and fluxes in Australian native ecosystems. The report established clear benefits that could be achieved for major forest types by collecting additional data using destructive sampling techniques. It advised that such techniques could substantially enhance the estimation of stand level carbon mass and reduce uncertainties associated with FullCAM modeling of carbon stocks. In particular, the report recommended that new data include roots, which are rarely sampled, understory components and collation of data on litterfall and tree mortality.

In the context of voluntary carbon offset markets and investment planning for the introduction of larger-scale carbon reduction schemes, there has been increasing interest in the potential of mixed-species environmental plantings to sequester carbon in low-medium rainfall regions. Indeed, most new plantings established for carbon sequestration in Australia are in the 300-600 mm rainfall zone, where relatively low land values make such revegetation more viable (Polglase *et al.* 2011; Paul *et al.* 2013a). These plantings also have a role in providing other environmental benefits and public good outcomes over and above carbon mitigation. They can be integrated into existing agricultural landscapes such that they have no negative, and possibly a beneficial, impact on agricultural production (e.g. GHD Hassall 2010; Paul *et al.* 2013a). However, there are few measurements of carbon storage in such plantings, and limited verification of models for predictive purposes (Roxburgh *et al*, 2010). The FullCAM model forms the basis of the Reforestation Modelling Tool (RMT), an approved methodology for estimating project-level carbon sequestered by such plantings under the CFI (DOIC, 2011). Although reliable growth modifiers of FullCAM's yield curves have already been developed for many traditional plantation species (Waterworth *et al*. 2007), this is not so for mixed-species environmental plantings. Prior to the undertaking of the recent collaborative research on environmental plantings, the FullCAM tree growth curve was not calibrated specifically for environmental plantings and generally under-estimated their biomass (Paul *et al*. 2013b).

A business case analysis, undertaken for DSE to evaluate options for improving the uncertainty associated with the use of FullCAM, concluded that so long as the carbon storage estimate could be improved by at least 2.5-5 per cent, and there was at least 5,000-10,000 hectares of forest available to participate in carbon forestry, then there was sufficient justification to undertake a program of carbon research that would improve the parameterisation of FullCAM, given the expectation of a reasonable carbon prices (DSE, 2011).