Plant Biometrics and Biomass Productivity in the River Murray Dryland Corridor

A report for the
SA Centre for Natural Resource Management

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Executive Summary

Plant Biometrics and Allometric Relationships

Plant measurements and destructive samples from 54 individual plants, between 6.6 to 13.5 years old (average 10 years) and representing 18 plant populations, were analysed to 1/ determine their physical characteristics (e.g. moisture content and proportions of plant components) and 2/ identify relationships between simple plant measurements and above-ground biomass. Strong relationships exist between morphological observations and plant biomass and their fractions (stemwood, twig and leaf). A robust generalised model (r^2=0.84) of total green biomass (kg plant^{-1}) from stemwood volume (outer bark) calculations is represented by the formula:

$$\underset{[\text{kg plant}^{-1}]}{\textbf{Total Green Biomass}} = e^{\,0.9243 \times \ln((\text{Stemwood Volume} \times 1000\ [m^3]) + 1) + 0.9529} - 1$$

With the inclusion of species group and lifeform classifications model predictions of green biomass can be improved by a further 10%.

Plant Productivity

The total observed and annual rate of productivity of 30 plots were evaluated, 18 of those from destructive biomass sampling and 12 from models using simple morphological observations. The productivity of each species and site was standardised to 2 indices of productivity: 1/ 250mm rainfall equivalent; and 2/ regional soil-climate productivity model value of 1. Standardised productivity values allowed the evaluation of each plant species to determine the best performing species in terms of biomass productivity per year.

Regional Productivity and Carbon Sequestration

Using local averages of regional soil-climate productivity models for each River Murray Corridor zone, climatic models of plant suitability mapping and selected species productivity evaluations it was possible to estimate the likely biomass productivity of new plantations for each zone. In dryland sites in the Riverland region (Zones 1 & 2) this equates to approximately 7.7 green tonnes of biomass per hectare per year for the fastest growing mallee species (E*ucalyptus socialis*) planted at 1000 plants per hectare. In the Lower Murray region using the same species and planting density the biomass productivity is approximately 11.7 green tonnes of biomass per year. Using more productive species (e.g. *Eucalyptus cladocalyx*) and/or higher planting rates is likely to increase plantation total biomass production by 60% or more in the River Murray Corridor region. Short cycle (~10 year) dryland plantations of selected species can sequester over 2.4-2.5 tonnes of carbon per hectare per year in the Riverland region and 3.3-4.2 tonnes of carbon per hectare per year in the Lower Murray region.

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Acknowledgements

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1. Introduction

It is well recognised that many environmental and economic benefits can be achieved from increasing the use of perennial plant species in Australian landscapes (Australian Greenhouse Office & Murray Darling Basin Commission 2001). New plantations of woody perennial species can reduce groundwater recharge, dryland salinity, saline river discharges, wind erosion and drought risk, and increase landscape sustainability, biodiversity, livestock production, economic diversification and stability of financial returns. The losses from salinity affected agricultural land both in terms of productive capability and areal extent are increasing every year in Australia. The National Land and Water Audit (2000) found that 5.7 million hectares were at risk or affected by dryland salinity in Australia, and that in 50 years time this area could rise to 17 million hectares. Without substantial and immediate changes to agricultural systems to reduce groundwater recharge and impact of dryland salinity Australia's productive capability and wealth from farm exports will diminish (Stirzaker *et al.* 2000, 2002).

There is an increasing interest and awareness of the potential for renewable energy sources to be used to generate electricity, offset the use of fossil fuels, reduce greenhouse gas emissions and their influences on global climates (Stucley *et al.* 2004, Zorzetto & Chudleigh 1999, Hague *et al.* 2002). Electricity generation from biomass (bioenergy), especially when combined with co products of oil, charcoal, tannins or fodder, provides an environmental friendly opportunity in many regions of Australia (Zorzetto & Chudleigh 1999; Bennell, Hobbs & Ellis 2004; Bartle & Shea 2002; Olson *et al.* 2003, Enecon 2001). Stucley *et al.* (2004) have provided a recent review of 'Biomass energy production in Australia - Status, costs and opportunities for major technologies'. It provides an excellent review of the technologies available of transforming biomass into energy and a variety of fuel types. However, they declare "There is a general lack of information available on the growth of tree plantations in many parts of Australia".

The lack of productivity data has hindered early attempts to evaluate the potential of biomass industries in low rainfall regions. Studies of biomass productivity in the SA River Murray Corridor region (Figure 1) have been limited to work conducted by SA Wood and Forests (Kiddle *et al.* 1987, Boardman 1992) on revegetation sites at Monarto (near Murray Bridge), Fairlamb and Bulman (1994) on provenance trials at Murray Bridge as part of the Farm Tree Improvement Project, and more recent assessments by Bennell, Hobbs and Ellis (2004) as part on the FloraSearch project.

The Monarto assessments contain 9 species (7 Eucalypts) at 9-10 years of age, 3 mixed species plantings at 16-17 year of age, with both sets of observations dominated by WA species (see Appendix A). The Farm Tree Improvement (FTI) project trials at Murray Bridge were planted in 1990 and contain 4 species (with13 provenances) which are predominated by provenances of SA Bluegum (*Eucalyptus leucoxylon*) and WA Swamp Yate (*Eucalyptus occidentalis*). Other FTI trials were established between 1990-1993 at Peebinga, Paruna, Sherlock, Lameroo and Pinnaroo in the Murray Mallee region with a total of 15 native species planted across these sites with recent measurements from these FTI trials in 2003 yet to be fully analysed (Don McGuire, Forestry SA, pers. comm.; Rural Solutions SA 2003). FloraSearch has conducted limited

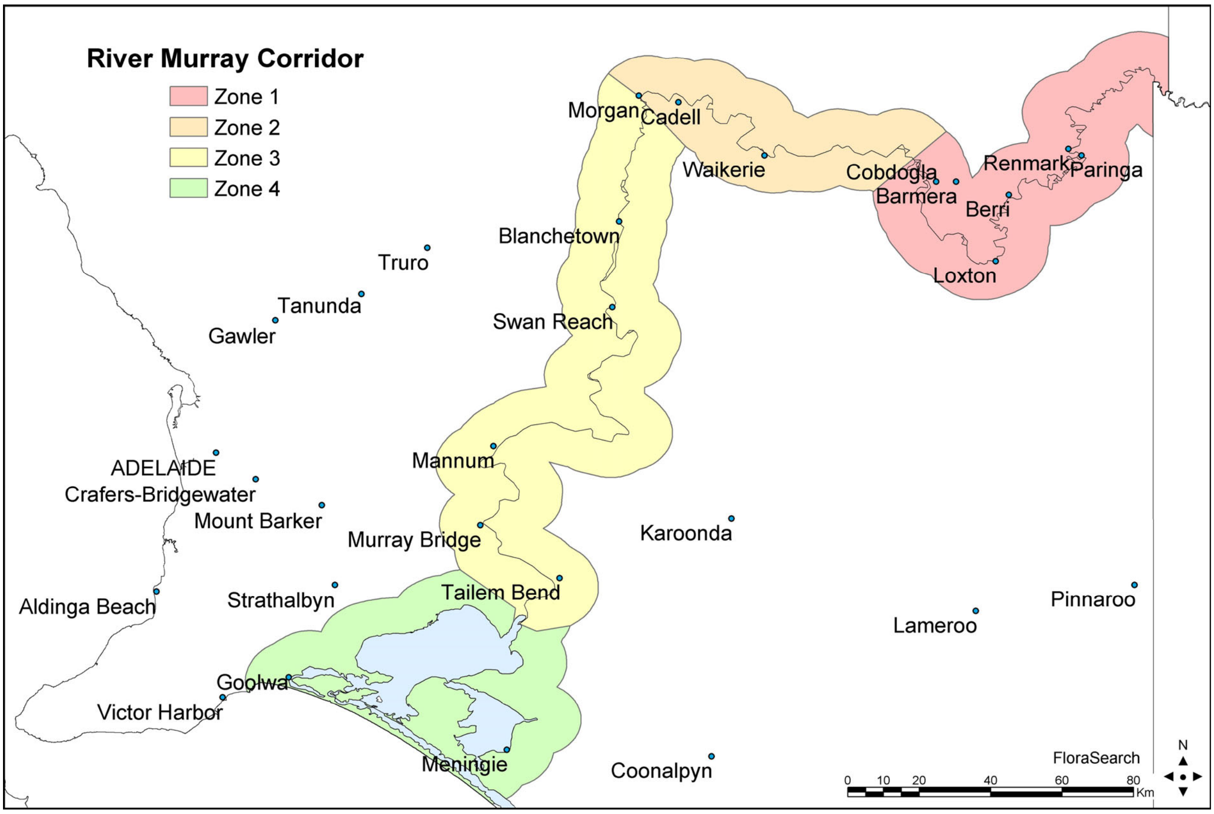

Figure 1 - The major zones of SA River Murray Corridor region (<10km from river).

assessments of 162 taxa of Eucalypts at Currency Creek (near Goolwa) and more detailed assessments of 30 populations in the River Murray Corridor region.

Poor plantation productivity data in the River Murray Corridor region has arisen from the lack of experimental trials that have been established in the region and the limited resources available to assess the productivity of the few existing plantations (or revegetation sites) on low rainfall sites. FloraSearch and the RIRDC funded 'Field Trials of Woody Germplasm' project have recently (2004) planted 43 species (56 provenances) trials at Murray Bridge (with more planned for 2005-2007) to help address the first issue. To increase the efficiency of productivity assessments of these new trials, and to more cost-effectively assess other existing plantation trials or revegetation plantings, requires reliable and rapid techniques of measurement and evaluation.

Allometrics is a commonly used technique to non-destructively assay plantation productivity from a limited number of measurements (biometrics). In classical forestry industries these allometric models are often based on measurements of tree diameter at breast height or basal area calculations (± tree height) to determine stemwood volumes or biomass, with models often being species specific (Snowdon *et al.* 2000, 2002, Grierson 2000, Kiddle *et al.* 1987). Allometric models based on higher rainfall forestry trees are unlikely to be reliable predictors of productivity for the mallee and shrub lifeforms more suited to lower rainfall regions. New allometric models must be developed to non-destructively and efficiently assess plantations of low rainfall agroforestry species.

New robust and reliable allometric models can then be applied to the results of rapid assessment biometric methodologies to determine the primary productivity of plantations of low rainfall agroforestry species. Reliable assessments of standing biomass of known age plantations are used to determine annual productivity rates, with the most productive species selected for use in new biomass industries or carbon sequestration plantings. Regional predictions of biomass production using geographic information system technologies, observed species productivity rates and regional productivity models (Raupach *et al.* 2001) can then be integrated with spatial data on industrial infrastructure, production systems and economic models to determine the commercial viability of proposed industries in the region (Bennell, Hobbs & Ellis 2004, Ward & Trengove 2004).

Preliminary evaluations of regional industry potential in the River Murray Corridor region conducted by FloraSearch have identified a range of biomass industries that may be commercially viable in all or part of the study region (Bennell, Hobbs & Ellis 2004). These current and potential widespread industries include fodder shrubs for livestock consumption, electricity generation from woody biomass and the "oil mallee" hybrid model of Eucalyptus oil and bioenergy production. Limited pulpwood production is also possible in higher rainfall areas within the region. Predicted annual farmer returns from these industries in the short term are often below those received from cereal cropping alone, but biomass industries can provide long term natural resource benefits, enterprise stability and climatic risk reduction. Fodder shrubs for livestock industries are already being used widely and profitably in the region with much potential for further expansion.

This study aims to provide reliable and robust methodologies to rapidly assess the primary productivity of low rainfall species using simple plant observations and allometric models, quantify production rates for a range of species grown on dryland sites in the River Murray Corridor, and evaluate to the capability of native species to provide plantation feedstock to biomass industries or sequester carbon in the region.

2. Methodology

2.1 Plant Biometrics and Allometric Relationships

Plants were sampled from dryland environments representing two broad geographic areas: 1/ Riverland Corridor (Zone 1 and 2 - Loxton to Waikerie); and 2/ Lower Murray Corridor (Zone 3 - Murray Bridge) at revegetation sites of known age (David Hein, pers. comm.; see Figure 2). The plant species were chosen to represent a range of lifeform types (shrubs, mallees, small trees) and those species naturally occurring within those locations. Three individuals of each species and location were chosen for detailed biometric measurements of plant morphology and biomass sampling.

Individual plant measurements included height, crown width, distance to neighbouring plants, stem count and circumference at two lower section heights (basal and intermediate: typically 0.5m and 1.3m for plants >2.5m high; 0.2 and 0.8m for plants 1.8-2.5m high; and 0.1 and 0.5 for plants <1.8m), and visual ranking of leaf density using reference photographs (8 classes). The stemwood volume (outer bark) of each plant was calculated from stem height and circumferences using standard forestry formulas for tree volumes of each stemwood section (1/ lower section – cylinder volume; 2/ mid section - Smalian's frustrum of a paraboloid volume, and 3/ upper section - paraboloid volume).

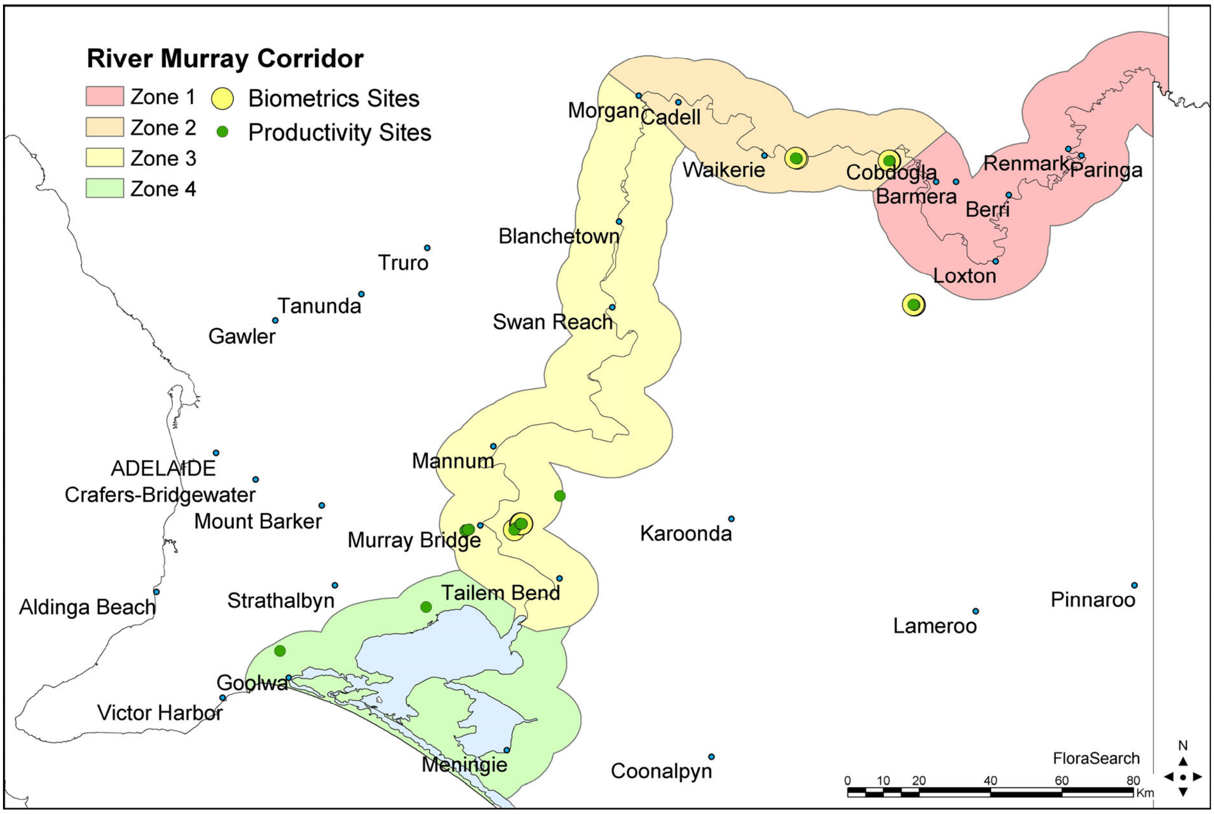

Figure 2 - The location of plant survey sites used for plant biometrics and productivity studies in the SA River Murray Corridor region.

Samples of wood and bark were taken from each basal and intermediate height for each plant with an additional sample taken half way between the intermediate height and the top of the plant. The diameter of the wood (minus bark) and bark thicknesses were measured across the north-south axis of the sample, and used to determine the bark proportion of the outer bark stemwood volume. The green weight of the wood only and bark only samples were measured immediately, the green volume of the wood only samples was determined by displacement in water, and the separate wood and bark samples were oven dried to a steady dry-weight to determine wood basic density and the moisture content of each sample component.

The whole of each plant was destructively sampled and sorted into three biomass fractions: 1/ stemwood and bark (>20mm diameter); 2/ twig and bark (2-20mm diameter); and 3/ leaf, fine twig and bark (<2mm diameter) and each fraction weighed immediately. Samples (>200g) from each green biomass fraction was weighed immediately, oven dried to a steady dry-weight and reweighed to determine their moisture content. The total dry biomass of each plant was calculated from the green weight of each biomass fraction and their observed moisture content. Whole plant carbon contents were calculated from the sum of dry biomass fractions and the commonly accepted generic conversion factor of 0.5 (Snowdon *et al.* 2002).

Allometric relationships between simple measurements of height, crown area, basal stem area, leaf density, stemwood volumes and observations of total green biomass (including stemwood and bark; twig and bark; and leaf, fine twig and bark) were plotted, explored visually and tested using linear regressions. Interactions between these simple measurements and lifeform or plant genera groupings were also evaluated.

2.2 Plant Productivity

Several species identified by the FloraSearch project as being worthy of testing for their agroforestry potential (Bennell, Hobbs & Ellis 2004) were selected for evaluations of their biomass productivity rates in low rainfall environments. Species and sites located within (or adjacent to) the River Murray Corridor zone were identified for rapid assessments of their productivity using a reduced set of measurements to those used for the biometrics study described above.

The height, crown width, stem count and circumferences at basal and intermediate heights, wood basic density and bark proportions at basal height, and leaf density were evaluated for 3 to 6 individuals of each species using the same methodology as the biometrics study. Relationships identified between rapid assessment parameters and plant biomass (total and fractions) from the biometric study were used to estimate biomass productivity for a wider range of species.

Observed and estimated plant biomass productivity values for each species and location from the biometrics and productivity studies were standardised to an annual biomass accumulation rate to account for the different ages of the plant studied. The average annual rainfall for each sampled locality was extracted from spatial coverages of annual rainfall (CSIRO Land & Water 2001) using ArcGIS (ESRI 2002). Observed and modelled annual biomass accumulation rates for each species and locality was then standardised to an annual rainfall of 250mm using a simple linear relationship to permit a simple comparison of each species' relative biomass productivity. To account for spatial variations in soil and climatic influences on local productivity within the River Murray Corridor data from regional indices of primary productivity (i.e. 'BiosEquil' soil-climate model, Raupach *et al.* 2001) were extracted from spatial datasets using ArcGIS. Annual biomass accumulation rates for each species and locality from the plant biometrics and productivity studies were then linearly standardised to a BiosEquil value of 1.

2.3 Regional Productivity and Carbon Sequestration

ArcGIS was then used to determine the average, minimum and maximum rainfall and BiosEquil values for each River Murray Corridor zone. Observed species productivity rates per BiosEquil value were applied for the average BiosEquil value in each River Murray Corridor zone. The climatic suitability of each species for each zone (and likely reliability of productivity predictions) was evaluated using individual species bioclimatic models developed by Hobbs and Bennell (2004). From these evaluations the most productive and reliable species could then be selected for each zone and plantation type.

Plantation productivity per hectare is dependent on individual species growth rates and appropriate planting densities that optimise the tradeoffs between the number of plants per hectare and plant competition effects. Observed planting densities (plants ha^{-1}) and calculations of possible planting densities (based on plant crown area) have been used to estimate a conservative planting rate for plantations in the region.

Species selected for their higher productivity rates, local suitability and likely planting rate were then used to predict likely rates of biomass accumulation per hectare per year for each River Murray Corridor zone. Moisture content observations from the biometric study, generic dry biomass to carbon content conversion factors (Snowdon *et al.* 2002) and plantation productivity data was combined to provide conservative estimates of carbon sequestration rates for new plantations in the region.

3. Results

3.1 Plant Biometrics and Allometric Relationships

Fifty-four individual plants were measured and destructively sampled for the biometrics study. These represent 18 plantations (16 species, see Table 1), and include 3 generic groupings (8 Eucalypts, 5 Acacias and 5 other species) and 3 lifeform types (8 shrubs, 7 mallees and 3 trees). Three species were sampled twice, with *Acacia oswaldii* and *Eucalyptus porosa* from different geographic regions, and *Atriplex nummularia* under two management regimes (1/ not grazed, 2/ slashed 18 months prior and grazed 2 months prior). The age of plantations sampled for this study ranged from 6.6 to 13.5 years (average 10 years). Table 1 and Table 2 provide summaries of a number of key plant characteristics for species and locations used in the biometrics study. Relationships between green biomass, dry biomass and carbon content are presented in Table 3. The average proportion of dry biomass to green biomass by weight (incorporating different moisture contents of each fraction) for all species ranges between 0.556 and 0.658 (mean=0.609). The carbon content expressed as a proportion of green biomass by weight ranges between 0.278 and 0.329 (mean=0.304).

Individual plant morphological measurements were converted into a range of biometric parameters commonly used to predict above ground plant biomass (see Table 4). These include plant height, basal stem area (outer bark), crown area (from crown widths), stemwood volume (outer bark; from plant height and 2 stemwood area observations), and foliage density. Foliage density classes were expressed as a percent of maximum density (i.e. very dense 100%, dense 86%, moderately dense 71%, moderate 57%, moderately sparse 43%, sparse 29%, very sparse 14%, no leaves 0%)

Allometric relationships between these morphological parameters and individual plant green biomass were explored. Separate analyses were conducted for total green biomass and green biomass fractions: 1/ wood (>20mm diameter) and bark; 2/ twig (2-20mm diameter) and bark; and 3/ leaf, fine twig (<2mm diameter) and bark. The biomass from fractions 1 and 2 were combined to create a fourth class (i.e. wood & bark + twig & bark) and tested against the morphological parameters. Preliminary plots and results illustrate a linear relationship between many parameters (and their interactions) and green biomass values. The small tree lifeform class was not modelled due to the limited number of observations (n=9). Due to non-normal distributions of data the biometric parameters and biomass values were transformed using natural logarithms prior to testing the strength of allometric relationships (see Figure 3 - Figure 10, Table 5). Green biomass and biomass fraction model equations take the form:

$$\boldsymbol{y} = \mathbf{e}^{\,\boldsymbol{a}.\ln(\boldsymbol{x} + 1) + \boldsymbol{c}} - 1$$

where $\boldsymbol{y}$ = green biomass [kg plant^{-1}], $\boldsymbol{x}$ = predictor morphological variables, $\boldsymbol{a}$ = predictor factor and $\boldsymbol{c}$ = intercept of the linear regression (see Table 5 for details).

The best generalised model (r^2=0.84) of total green biomass (kg plant^{-1}) from stemwood volume (outer bark) calculations (with no species group or lifeform interactions) is represented by the formula:

$$\textbf{Total Green Biomass [kg plant}^{-1}\textbf{]} = e^{0.9243 \times \ln((\text{Stemwood Volume} \times 1000\ [m^3]) + 1) + 0.9529} - 1$$

Basal area and height are poorer predictors of green plant biomass than more detailed measurements and calculations of stemwood volume, or measurements of height by crown area by foliage density (see Table 5). Stemwood volume measurements provide reasonable predictors of wood and bark or twig and bark fractions, however, the combined wood and bark plus twig and bark fraction is more strongly predicted from stemwood volume calculations. The leaf, fine twig and bark fraction is strongly predicted from height by crown area by foliage density observations and slightly less so from stemwood volume by foliage density data.

The interaction of species groups and lifeform classes on biomass predictions from morphological measurements are often significant (see Table 5, Figure 3 - Figure 10). They provide useful improvement to several models, especially: total green biomass from stemwood volume; wood and bark fractions from stemwood volume for Eucalypts/mallees; twig and bark fractions from stemwood volume for Acacias and shrubs; and leaf, fine twig and bark fractions from stemwood volume by foliage density for non Eucalypts.

Allometric models developed for the River Murray Corridor were compared against two other published allometric equations: 1/ green stem weight by Kiddle *et al.* (1987, pg 34), developed for low rainfall woodland species in South Australia; and 2/ dry biomass by Snowdon *et al.* (2000, pg 12), developed for separate woodland and shrubland species and used by the Australian Greenhouse Office for assessments of carbon sequestration (see Table 6). These models were applied to measurements from 54 plants observed in the River Murray Corridor region and the mean difference between modelled and observed biomass (expressed as a percent of the observed biomass) for each model was calculated. The trend of these differences indicates the degree to which models generally overestimate or underestimate plantation biomass productivity in the region.

Kiddle *et al.*'s allometric model is a poor predictor of green stemwood biomass in this region with a mean difference of 98% from the observed biomass and consistently overestimates by 44%. Snowdon *et al.*'s woodland (mallees and trees) model of dry biomass has a mean difference of 47% and overestimates by 36%. Their shrub model of dry biomass has a mean difference of 78% and underestimates by 71%. Allometric equations of Kiddle *et al.* and Snowdon *et al.* are especially poor predictors of shrub biomass. Generalised models developed in this study for River Murray Corridor plantations provide much more accurate predictions of biomass, with mean differences of 21-28% and they generally overestimate biomass by only 6%.

Table 1 - Plant species measured and destructively sampled for biometrics study, including some key plant characteristics (mean values, n=3).

Region / Species	Rainfall [mm]	Age [years]	Height [m]	Crown Width [m]	Lifeform [Tree/Mallee/Shrub]	Foliage Density [%]	Total Green Biomass [kg plant^{-1}]	Proportion Green Biomass by Weight		
								Wood & Bark	Twig & Bark	Leaf, Fine Twig & Bark
Riverland Corridor										
Acacia ligulata	247	8.5	1.80	2.97	S	81	26.30	0.09	0.60	0.31
Acacia oswaldii	253	8.5	1.35	1.72	S	57	7.55	0.10	0.57	0.32
Atriplex nummularia (ungrazed)	251	7.5	1.90	3.20	S	81	28.69	0.14	0.55	0.31
Atriplex nummularia (grazed)	251	7.5	1.17	1.60	S	34	5.29	0.11	0.76	0.13
Callitris gracilis	253	8.5	2.13	1.37	S	76	4.42	0.14	0.41	0.45
Eucalyptus calycogona	261	8.5	2.70	2.53	M	57	26.01	0.29	0.25	0.46
Eucalyptus cyanophylla	261	9.5	2.88	2.53	M	62	35.32	0.29	0.26	0.45
Eucalyptus gracilis	261	6.6	1.77	1.97	M	91	10.65	0.06	0.35	0.59
Eucalyptus largiflorens	261	10.5	3.77	2.57	T	52	32.57	0.54	0.22	0.24
Eucalyptus oleosa	261	10.4	2.93	3.53	M	76	40.35	0.32	0.28	0.40
Eucalyptus porosa	261	9.5	2.37	3.13	M	76	21.29	0.23	0.39	0.38
Eucalyptus socialis	261	10.5	3.30	4.50	M	71	80.40	0.33	0.30	0.37
Lower Murray Corridor										
Acacia oswaldii	340	12.5	2.03	2.90	S	95	44.54	0.19	0.41	0.40
Acacia pycnantha	340	13.5	4.10	3.80	T	43	50.73	0.55	0.28	0.17
Acacia rigens	340	12.5	2.60	2.13	S	100	42.07	0.27	0.35	0.38
Allocasuarina verticillata	340	12.5	5.67	3.27	T	43	80.32	0.64	0.19	0.17
Eucalyptus porosa	340	12.4	5.33	4.40	M	71	98.43	0.54	0.18	0.28
Melaleuca uncinata	340	12.4	1.83	1.70	S	100	17.63	0.12	0.44	0.44

Table 2 – Mean wood properties, bark proportions and moisture contents of biomass fractions for plant species sampled for biometrics study.

Region / Species	Basic Density [kg/m³]	Proportion Bark to Stemwood		Proportion Moisture by Weight			
		By Volume	By Weight	Wood & Bark	Wood Only	Twig & Bark	Leaf, Fine Twig & Bark
Riverland Corridor	(n=9)#	(n=9)	(n=9)	(n=3)	(n=9)	(n=3)	(n=3)
Acacia ligulata	840	0.33	0.32	0.36	0.35	0.32	0.55
Acacia oswaldii	869	0.26	0.23	0.35	0.31	0.36	0.46
Atriplex nummularia (ungrazed)	793	0.09	0.05	0.32	0.32	0.28	0.64
Atriplex nummularia (grazed)	762	0.12	0.08	0.33	0.32	0.30	0.69
Callitris gracilis	619	0.23	0.24	0.46	0.44	0.44	0.38
Eucalyptus calycogona	775	0.21	0.23	0.31	0.30	0.33	0.37
Eucalyptus cyanophylla	787	0.37	0.33	0.34	0.34	0.37	0.37
Eucalyptus gracilis	830	0.24	0.26	0.34	0.31	0.39	0.43
Eucalyptus largiflorens	687	0.30	0.28	0.37	0.36	0.40	0.46
Eucalyptus oleosa	793	0.28	0.27	0.35	0.33	0.40	0.38
Eucalyptus porosa	668	0.27	0.26	0.40	0.39	0.44	0.48
Eucalyptus socialis	757	0.27	0.26	0.33	0.32	0.37	0.37
Lower Murray Corridor							
Acacia oswaldii	859	0.17	0.19	0.33	0.32	0.32	0.55
Acacia pycnantha	785	0.20	0.21	0.30	0.27	0.39	0.41
Acacia rigens	776	0.21	0.23	0.37	0.37	0.37	0.49
Allocasuarina verticillata	723	0.24	0.25	0.36	0.36	0.43	0.51
Eucalyptus porosa	663	0.26	0.22	0.41	0.41	0.43	0.49
Melaleuca uncinata	711	0.19	0.21	0.37	0.38	0.36	0.42

(# number of samples per species and location)

Table 3 – Relationships between total green biomass, dry biomass and carbon content of plant species measured and destructively sampled for biometrics study (mean values, n=3).

Region / Species	Total Green Biomass [kg plant^{-1}]	Dry Biomass [kg plant^{-1}]				Proportion Dry Biomass to Green Biomass by Weight	Proportion Carbon to Green Biomass by Weight
		Wood & Bark	Twig & Bark	Leaf, Fine Twig & Bark	Total		
Riverland Corridor							
Acacia ligulata	26.30	1.47	10.67	3.74	15.89	0.604	0.302
Acacia oswaldii	7.55	0.50	2.79	1.33	4.62	0.612	0.306
Atriplex nummularia (ungrazed)	28.69	2.75	11.38	3.16	17.29	0.603	0.301
Atriplex nummularia (grazed)	5.29	0.39	2.79	0.21	3.40	0.642	0.321
Callitris gracilis	4.42	0.34	1.00	1.25	2.59	0.585	0.293
Eucalyptus calycogona	26.01	5.20	4.41	7.51	17.11	0.658	0.329
Eucalyptus cyanophylla	35.32	6.60	5.91	9.99	22.51	0.637	0.319
Eucalyptus gracilis	10.65	0.44	2.24	3.58	6.26	0.588	0.294
Eucalyptus largiflorens	32.57	11.03	4.31	4.32	19.66	0.603	0.302
Eucalyptus oleosa	40.35	8.41	6.83	9.91	25.15	0.623	0.312
Eucalyptus porosa	21.29	3.01	4.67	4.16	11.83	0.556	0.278
Eucalyptus socialis	80.40	17.77	15.15	18.61	51.53	0.641	0.320
Lower Murray Corridor							
Acacia oswaldii	44.54	5.78	12.35	7.90	26.02	0.584	0.292
Acacia pycnantha	50.73	19.69	8.54	5.14	33.38	0.658	0.329
Acacia rigens	42.07	7.17	9.19	8.20	24.56	0.584	0.292
Allocasuarina verticillata	80.32	32.98	8.66	6.63	48.27	0.601	0.300
Eucalyptus porosa	98.43	31.24	10.14	14.17	55.55	0.564	0.282
Melaleuca uncinata	17.63	1.38	4.97	4.47	10.81	0.613	0.307

Table 4 – Summary of key plant attributes tested for developing allometric models of total green biomass and biomass fractions (mean values, n=3).

Region / Species	Height [m]	Basal Area [cm²]#	Crown Area [m²]	Foliage Density [%]	Stemwood Volume x 1000 [m³]	Green Biomass [kg plant^{-1}]				
						Total	Wood & Bark	Twig & Bark	*Wood & Bark + Twig & Bark*	Leaf, Fine Twig & Bark
Riverland Corridor										
Acacia ligulata	1.80	62.6[2]	6.92	81	14.09	26.30	2.31	15.73	18.04	8.26
Acacia oswaldii	1.35	22.3[1]	2.58	57	2.11	7.55	0.78	4.34	5.11	2.44
Atriplex nummularia (ungrazed)	1.90	133.3[1]	8.17	81	12.74	28.69	4.06	15.84	19.90	8.79
Atriplex nummularia (grazed)	1.17	37.5[1]	2.06	34	3.28	5.29	0.58	4.02	4.60	0.69
Callitris gracilis	2.13	17.0[2]	1.49	76	3.13	4.42	0.62	1.80	2.42	2.00
Eucalyptus calycogona	2.70	76.0[2]	5.09	57	8.88	26.01	7.58	6.55	14.13	11.88
Eucalyptus cyanophylla	2.88	62.2[5]	5.24	62	9.80	35.32	10.07	9.33	19.41	15.92
Eucalyptus gracilis	1.77	31.4[1]	3.04	91	2.48	10.65	0.66	3.70	4.35	6.30
Eucalyptus largiflorens	3.77	95.4[5]	5.41	52	19.78	32.57	17.45	7.19	24.64	7.94
Eucalyptus oleosa	2.93	85.8[5]	9.91	76	14.13	40.35	12.91	11.34	24.25	16.10
Eucalyptus porosa	2.37	67.5[5]	7.83	76	7.42	21.29	4.98	8.31	13.29	8.00
Eucalyptus socialis	3.30	136.7[5]	16.04	71	25.77	80.40	26.63	24.06	50.69	29.71
Lower Murray Corridor										
Acacia oswaldii	2.03	132.5[2]	6.62	95	23.38	44.54	8.64	18.27	26.91	17.62
Acacia pycnantha	4.10	68.4[5]	11.53	43	16.18	50.73	28.03	14.02	42.04	8.68
Acacia rigens	2.60	92.3[5]	3.68	100	17.25	42.07	11.31	14.61	25.92	16.15
Allocasuarina verticillata	5.67	183.8[5]	8.39	43	54.77	80.32	51.47	15.18	66.65	13.67
Eucalyptus porosa	5.33	218.1[5]	17.87	71	57.57	98.43	52.74	17.80	70.54	27.88
Melaleuca uncinata	1.83	73.4[1]	2.32	100	10.90	17.63	2.19	7.72	9.91	7.72

(# [1] basal area at 0.1m height, [2] 0.2m, [5] 0.5m)

Table 5 – Correlations between plant morphological measures and above ground green biomass (kg plant^{-1}), including allometric model parameter values.

Variable (y)	Predictor (x)	n	$r^{2\#}$	Allometric Model Parameters: Factor (a)	Allometric Model Parameters: Intercept (c)
Total Green Biomass	Basal Area [cm²]	54	0.57^{***}	0.8405	-1.3258
	Basal Area [cm²] x Height [m]	54	0.62^{***}	0.5909	-0.7962
	Height [m] x Crown Area [m²]	54	0.78^{***}	0.7975	1.1352
	Height [m] x Crown Area [m²] x Foliage Density [%]	54	0.81^{***}	0.7309	-1.6831
	Stemwood Volume x 1000 [m³]	54	0.84^{***}	0.9243	0.9529
	Stemwood Volume x 1000 [m³] x Foliage Density [%]	54	0.79^{***}	0.7607	-1.7423
Wood & Bark	Stemwood Volume x 1000 [m³]	54	0.77^{***}	1.1978	-0.9743
Twig & Bark	Stemwood Volume x 1000 [m³]	54	0.68^{***}	0.6126	0.7501
Wood & Bark + Twig & Bark	Stemwood Volume x 1000 [m³]	54	0.89^{***}	0.9838	0.3929
Leaf, Fine Twig & Bark	Foliage Density [%]	54	0.13^{**}	0.5440	0 ns
	Height [m] x Crown Area [m²]	54	0.58^{***}	0.6120	0.6216
	Height [m] x Crown Area [m²] x Foliage Density [%]	54	0.76^{***}	0.6309	-2.0190
	Stemwood Volume x 1000 [m³]	54	0.59^{***}	0.6955	0.5168
	Stemwood Volume x 1000 [m³] x Foliage Density [%]	54	0.72^{***}	0.6461	-2.0003
Total Green Biomass	Height [m] x Crown Area [m²] x Foliage Density [%]				
Acacias		15	0.81^{***}	0.8645	-2.5101
Eucalypts		24	0.82^{***}	0.7377	-1.8059
Non Eucalypts		30	0.80^{***}	0.7694	-1.8711
Non Eucalypts/Acacias		15	0.76^{***}	0.7355	-1.6801
Mallee		21	0.84^{***}	0.7659	-2.0462
Shrub		24	0.74^{***}	0.7151	-1.5668
Total Green Biomass	Stemwood Volume x 1000 [m³]				
Acacias		15	0.84^{***}	0.9519	0.9099
Eucalypts		24	0.87^{***}	0.7687	1.5469
Non Eucalypts		30	0.90^{***}	1.0344	0.5191
Non Eucalypts/Acacias		15	0.95^{***}	1.0136	0.4092
Mallee		21	0.91^{***}	0.8009	1.5142
Shrub		24	0.91^{***}	1.2410	0 ns

Table 5 (continued)

Variable (y)	Predictor (x)	n	$r^{2\#}$	Allometric Model Parameters: Factor (a)	Allometric Model Parameters: Intercept (c)
Wood & Bark	Stemwood Volume x 1000 [m³]				
Acacias		15	0.44^{*}	0.7757	0 ns
Eucalypts		24	0.95^{***}	1.1526	-0.5497
Non Eucalypts		30	0.74^{***}	1.2042	-1.2444
Non Eucalypts/Acacias		15	0.89^{***}	1.2358	-1.3769
Mallee		21	0.95^{***}	1.1603	-0.5709
Shrub		24	0.69^{***}	0.8960	-0.7246
Twig & Bark	Stemwood Volume x 1000 [m³]				
Acacias		15	0.89^{***}	0.6850	0.7943
Eucalypts		24	0.66^{***}	0.5373	0.9186
Non Eucalypts		30	0.71^{***}	0.6781	0.6083
Non Eucalypts/Acacias		15	0.70^{***}	0.8192	0 ns
Mallee		21	0.75^{***}	0.5785	0.8774
Shrub		24	0.84^{***}	0.9640	0 ns
Wood & Bark + Twig & Bark	Stemwood Volume x 1000 [m³]				
Acacias		15	0.75^{***}	1.1413	0 ns
Eucalypts		24	0.93^{***}	0.9100	0.6943
Non Eucalypts		30	0.88^{***}	1.0971	0 ns
Non Eucalypts/Acacias		15	0.94^{***}	1.0502	0 ns
Mallee		21	0.94^{***}	0.9305	0.6681
Shrub		24	0.88^{***}	1.0794	0 ns
Leaf, Fine Twig & Bark	Height [m] x Crown Area [m²] x Foliage Density [%]				
Acacias		15	0.43^{*}	0.3434	0 ns
Eucalypts		24	0.73^{***}	0.5561	-1.4073
Non Eucalypts		30	0.72^{***}	0.6313	-2.0790
Non Eucalypts/Acacias		15	0.78^{***}	0.6051	-1.9938
Mallee		21	0.73^{***}	0.5444	-1.2862
Shrub		24	0.77^{***}	0.7369	-2.6587
Leaf, Fine Twig & Bark	Stemwood Volume x 1000 [m³] x Foliage Density [%]				
Acacias		15	0.89^{***}	0.6259	-1.9430
Eucalypts		24	0.63^{***}	0.3931	0 ns
Non Eucalypts		30	0.91^{***}	0.7102	-2.6643
Non Eucalypts/Acacias		15	0.96^{***}	0.7010	-2.7389
Mallee		21	0.74^{***}	0.4048	0 ns
Shrub		24	0.93^{***}	0.7371	-2.8484

(n=number of observations. # correlation coefficients & significance levels: * p<0.05; ** p<0.01; *** p<0.001. ns=not significant)

Figure 3 – Relationships between total green biomass and plant height by crown area by foliage density for species groups and lifeforms.

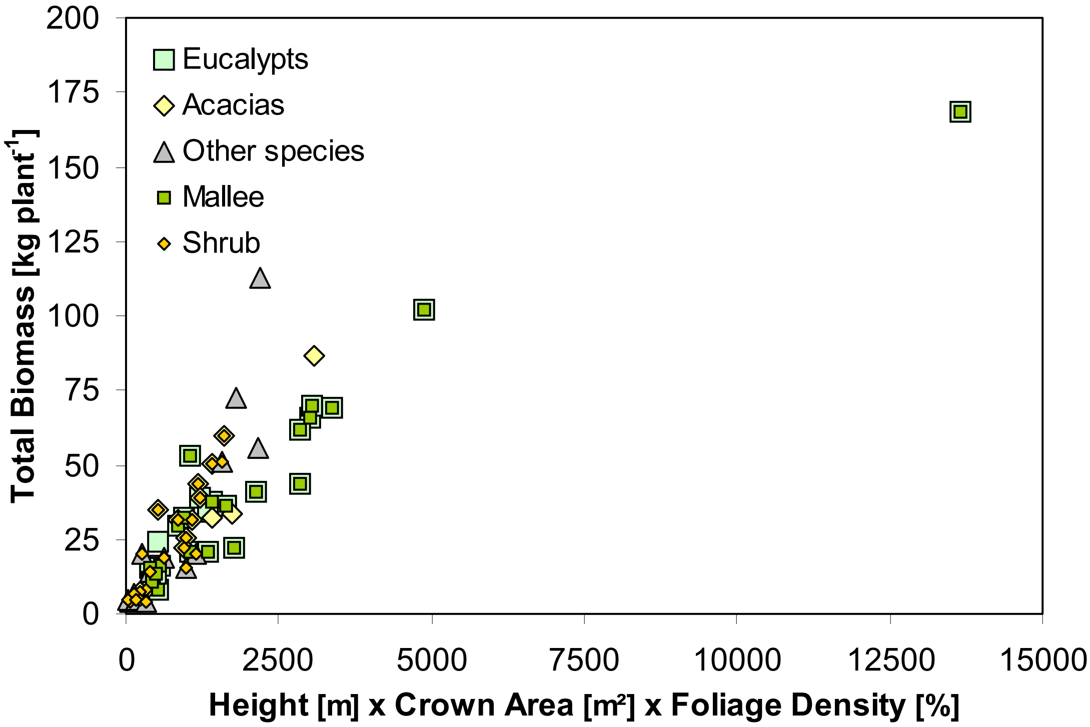

Figure 4 – Relationships between total green biomass and stemwood volume for species groups and lifeforms.

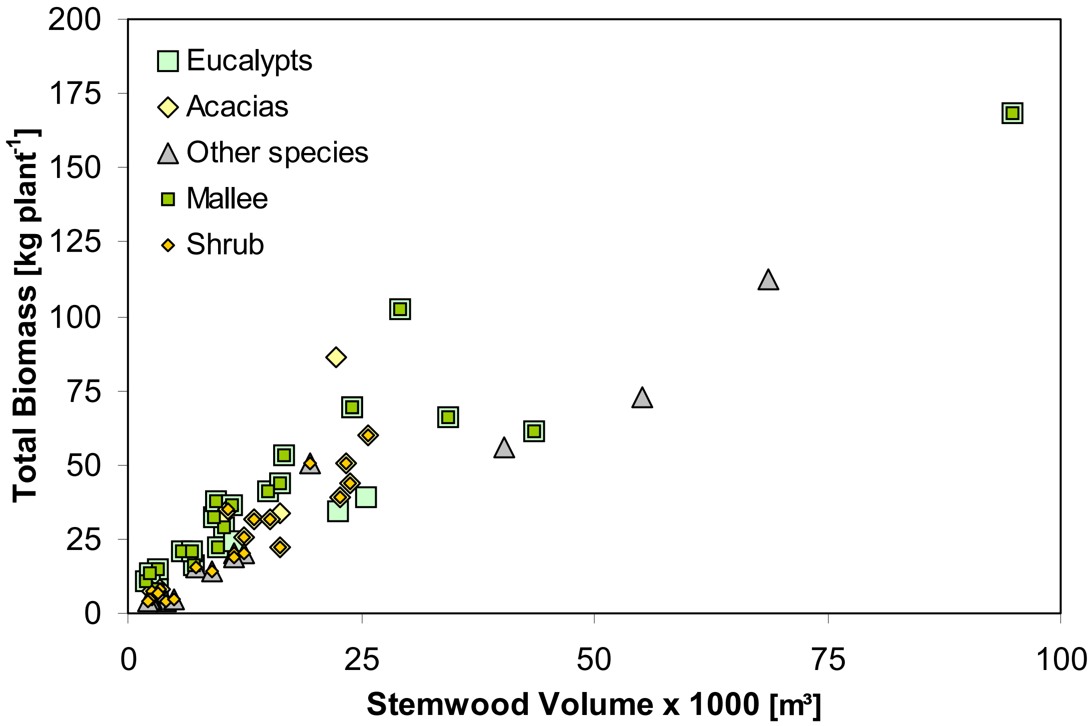

Figure 5 – Relationships between wood and bark green biomass fraction, and stemwood volume for species groups and lifeforms.

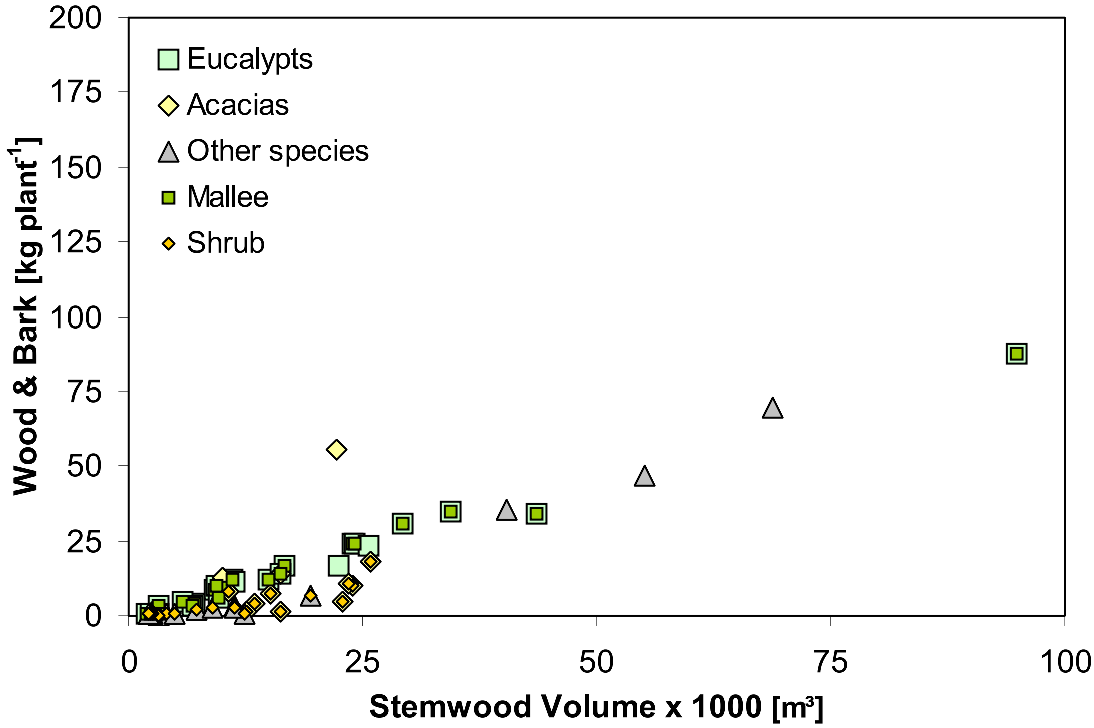

Figure 6 – Relationships between twig and bark green biomass fraction, and stemwood volume for species groups and lifeforms.

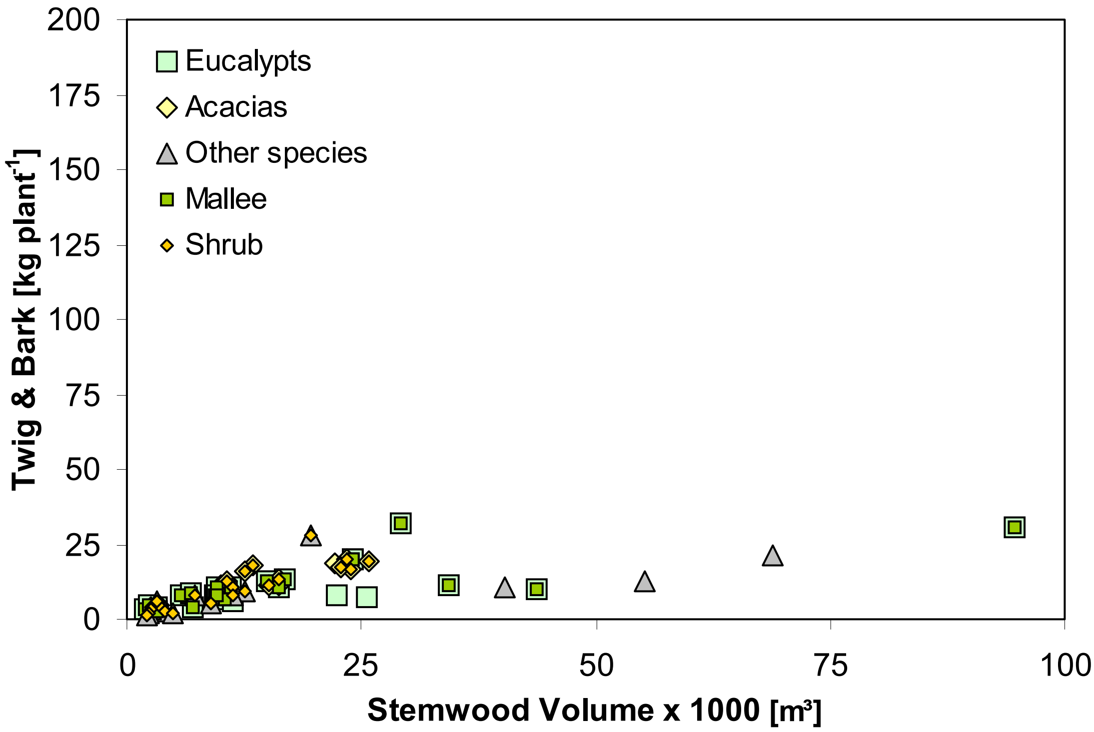

Figure 7 – Relationships between wood and bark plus twig and bark green biomass fraction, and stemwood volume for species groups and lifeforms.

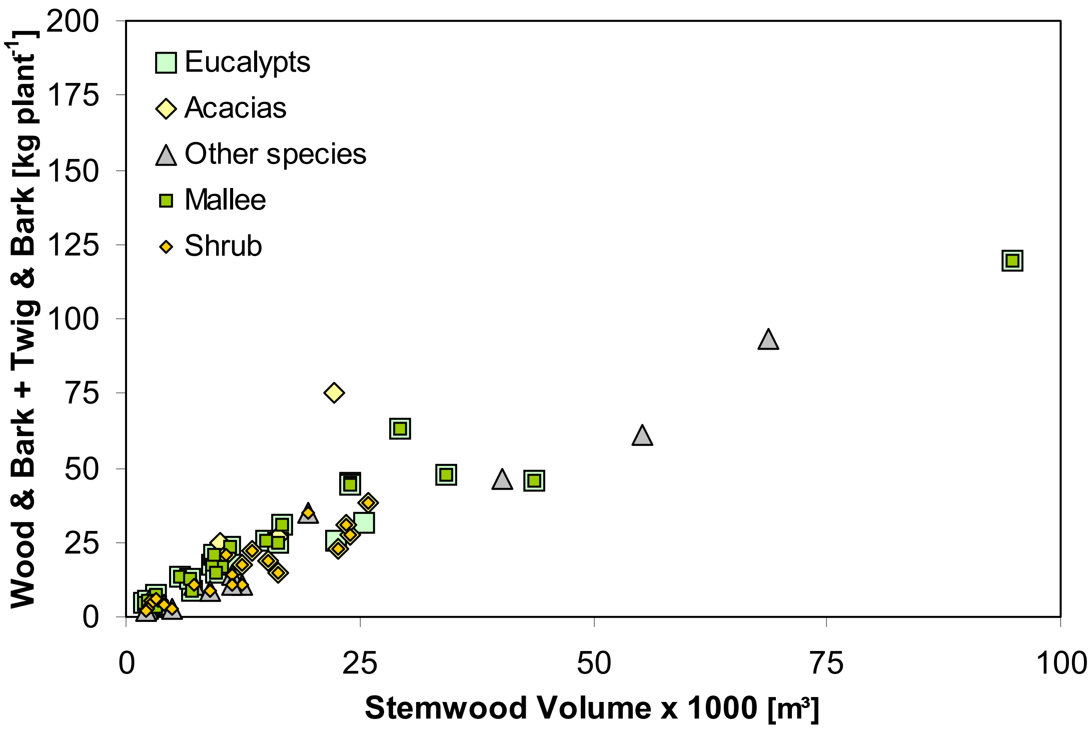

Figure 8 – Relationships between leaf, fine twig and bark green biomass fraction, and stemwood volume for species groups and lifeforms.

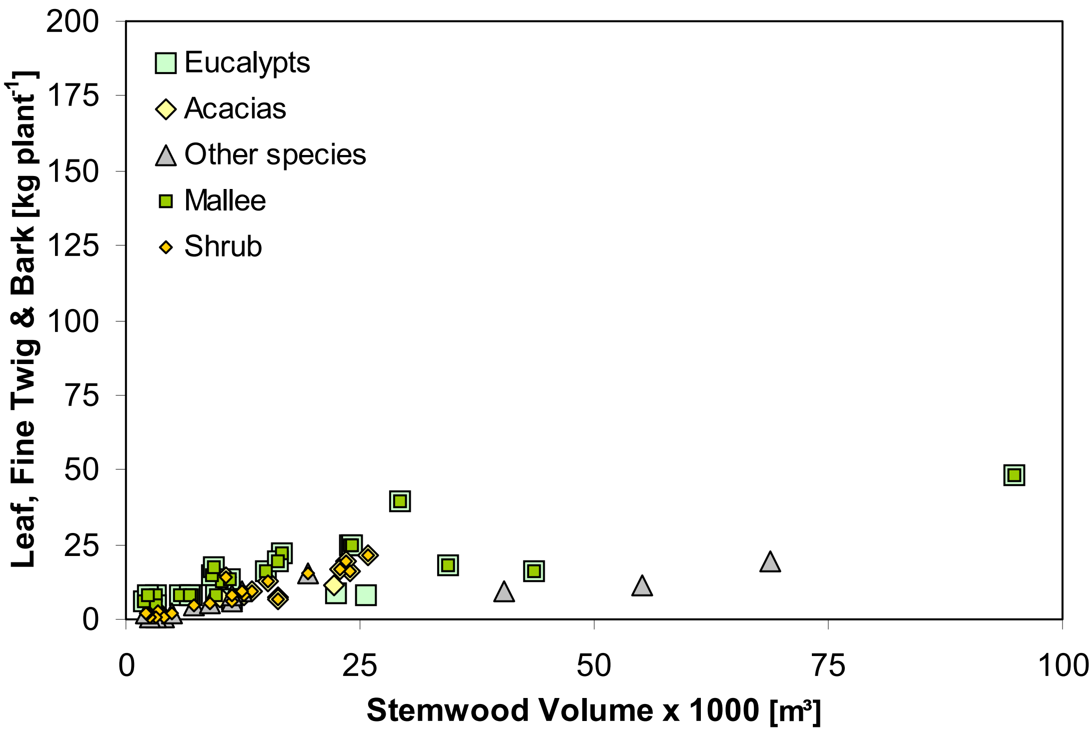

Figure 9 – Relationships between leaf, fine twig and bark green biomass fraction, and stemwood volume by foliage density for species groups and lifeforms.

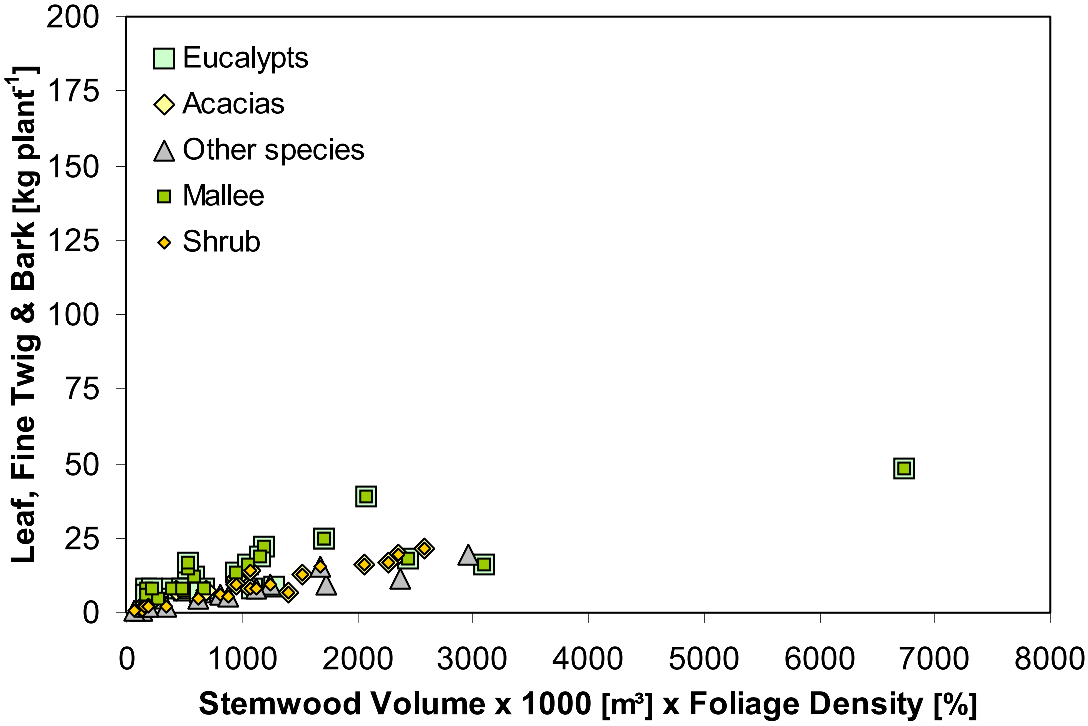

Figure 10 – Relationships between leaf, fine twig and bark green biomass fraction, and plant height by crown area by foliage density for species groups and lifeforms.

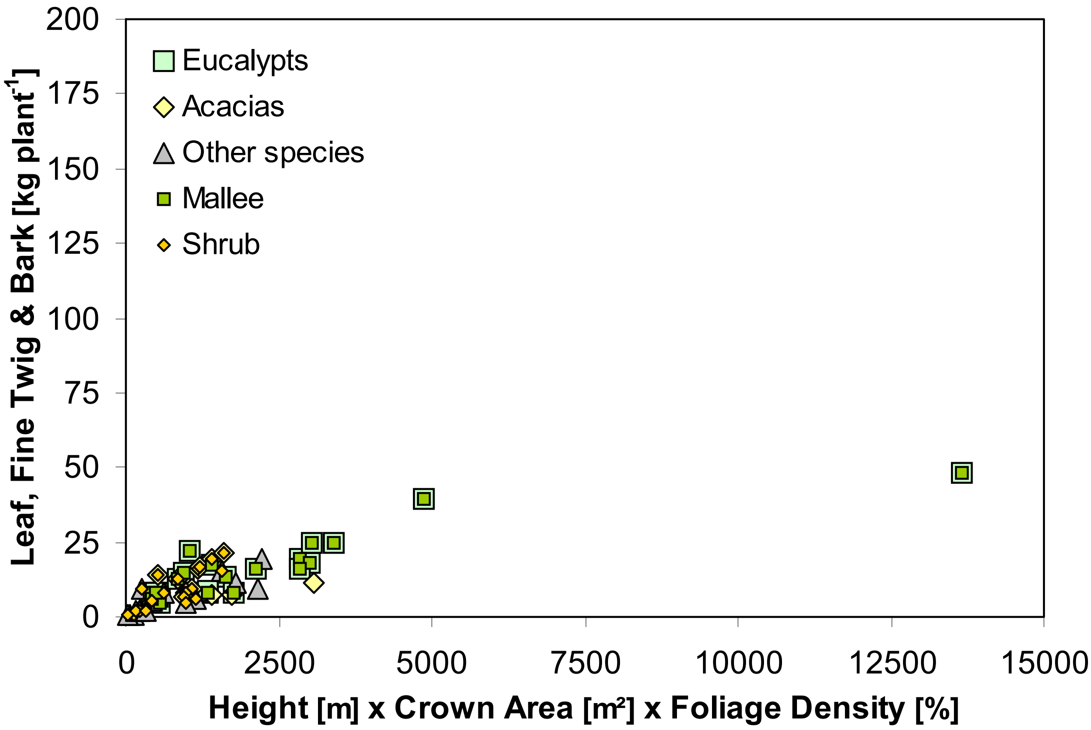

Table 6 – Mean percent difference and mean trend (+ overestimate, - underestimate) of predicted plant biomass from allometric models and observed plant biomass.

	Green Wood & Bark + Twig & Bark Biomass [kg plant^{-1}]				Total Dry Biomass [kg plant^{-1}]			
	Kiddle *et al.* 1987		Hobbs & Bennell 2005		Snowdon *et al.* 2000		Hobbs & Bennell 2005	
Lifeforms	Diff. [%]	Trend [%]	Diff. [%]	Trend [%]	Diff. [%]	Trend [%]	Diff. [%]	Trend [%]
All (n=54)	98	+44	28	+6	61	-10	21	+6
Mallees & Trees (n=30)	68	+39	23	-9	47	+36	22	+6
Shrubs (n=24)	138	+52	34	+26	78	-71	18	+6

3.2 Plant Productivity

Morphological measurements and leaf density observations were made from 3 to 6 plants of 12 additional plant populations (see Figure 2). Allometric models of total green biomass from stemwood volume by species group or lifeform class (see Table 5) were used to predict the total green biomass of each plant for these additional species and locations. Summaries of these observations and modelled results have been combined with biometrics study results and are presented in Table 7.

ArcGIS was used to determine the average annual rainfall and BiosEquil values for each species and location (see Table 8). Data from field surveys of species biomass productivity (green kg plant^{-1} year^{-1}) were linearly regressed with the rainfall and BiosEquil values at each sample site and then standardised to an equivalent rainfall of 250mm and a BiosEquil value of 1. The relative productivity of each species could then be compared to select species with the highest productivity rates.

Table 8 also contains information on the observed planting density of plants sampled in the biometrics study. The observed green biomass production per hectare may be calculated by multiplying the observed planting density with the observed green biomass production per plant. An indicative planting rate per hectare for each species may be deduced from dividing the hectare area (i.e. 10,000m²) by the crown area of the species. This 'crown' density of plants per hectare may be appropriate for short-cycle plantings but the optimum density to maximise biomass productivity per hectare will depend on the degree of plant competition for light, water and other nutrients.

Two species *Acacia pycnantha*, *Acacia oswaldii* [Riverland] were sampled from direct seeding plantings where their crowns overlap and their observed plant density is higher than the 'crown' density. Planting at rates higher than the 'crown' density rate may potentially increase productivity per hectare, however, this can only be accurately determined from more detailed trials and research. Where the observed planting density is lower than the calculated 'crown' density for a plantation it is likely that the productivity per hectare can be increased by planting at a higher rate than the observed rate. The 'crown' density data suggests that the minimum planting density for the short cycle biomass crops in the region is 1000-1500 plants per hectare for trees and mallees and 2000-3000 plants per hectare for shrub species. A range of factors, including species selection, rainfall, soil types and crop duration, will influence the optimal planting rate.

Table 7 – Growth observations, stemwood volumes and biomass productivity of plant species in the River Murray Corridor region.

Species	Observations	Age [years]	Height [m]	Basal Area [cm²]	Crown Area [m²]	Foliage Density [%]	Stemwood Volume x 1000 [m³ plant⁻¹]	Total Green Biomass [kg plant⁻¹]
Acacia ligulata	3	8.5	1.80	63	6.92	81	14.09	26.30
Acacia oswaldii [Riverland]	3	8.5	1.35	22	2.58	57	2.11	7.55
Acacia oswaldii [Murray Bridge]	3	12.5	2.03	132	6.62	95	23.38	44.54
Acacia pycnantha	3	13.5	4.10	68	11.53	43	16.18	50.73
Acacia rigens	3	12.5	2.60	92	3.68	100	17.25	42.07
Allocasuarina verticillata [MB - State Flora]	6	19.0	5.54	253	12.47	50	75.44	121.13^{m}
Allocasuarina verticillata [MB - Army Range]	3	12.5	5.67	184	8.39	43	54.77	80.32
Atriplex nummularia (grazed)	3	7.5	1.17	37	2.06	34	3.28	5.29
Atriplex nummularia (ungrazed)	3	7.5	1.90	133	8.17	81	12.74	28.69
Callitris gracilis [Murray Bridge]	6	11.0	6.79	183	3.64	66	56.52	90.61^{m}
Callitris gracilis [Riverland]	3	8.5	2.13	17	1.49	76	3.13	4.42
Eucalyptus brachycalyx	3	10.0	3.67	132	5.63	71	29.13	66.29^{m}
Eucalyptus calycogona	3	8.5	2.70	76	5.09	57	8.88	26.01
Eucalyptus cneorifolia	6	17.5	5.21	574	13.19	71	158.73	263.07^{m}
Eucalyptus cyanophylla	3	9.5	2.88	62	5.24	62	9.80	35.32
Eucalyptus gracilis	3	6.6	1.77	31	3.04	91	2.48	10.65
Eucalyptus incrassata	6	15.0	4.40	105	5.87	59	24.21	57.31^{m}
Eucalyptus largiflorens	3	10.5	3.77	95	5.41	52	19.78	32.57
Eucalyptus leucoxylon	6	12.5	5.00	358	6.90	71	89.80	144.92^{m}
Eucalyptus nortonii	3	7.0	6.33	292	10.60	57	81.81	137.11^{m}
Eucalyptus oleosa	3	10.4	2.93	85	9.91	76	14.13	40.35
Eucalyptus porosa [Murray Bridge]	3	12.4	5.33	218	17.87	71	57.57	98.43
Eucalyptus porosa [Riverland]	3	9.5	2.37	68	7.83	76	7.42	21.29
Eucalyptus socialis	3	10.5	3.30	137	16.04	71	25.77	80.40
Eucalyptus viminalis ssp. cygnetensis	5	7.0	6.05	290	12.37	52	72.18	125.43^{m}
Melaleuca armillaris ssp. armillaris	6	11.0	2.68	379	8.05	93	65.50	105.23^{m}
Melaleuca lanceolata	6	10.0	2.79	197	8.52	93	16.47	26.36^{m}
Melaleuca uncinata [MB - Army Range]	3	12.4	1.83	73	2.32	100	10.90	17.63
Melaleuca uncinata [MB - State Flora]	6	19.0	3.25	378	11.89	93	37.55	60.05^{m}
Myoporum platycarpum	6	10.3	4.17	102	6.72	59	22.88	36.60^{m}

(# observed from biometrics study or ^{m} modelled from morphological measurements)

Table 8 – Green biomass productivity, plant density and standardised total green biomass accumulation rates of plant species in the River Murray Corridor region.

Species	Age [years]	Total Green Biomass # [kg plant^{-1}]	Observed Plant Density [plants ha^{-1}]	Plant Density [plants ha^{-1}] @ Maximum Crown Density	Rainfall [mm]	BiosEquil Value	Annual Biomass [g kg plant^{-1} yr^{-1}] @ 250mm rainfall	Annual Biomass [g kg plant^{-1} yr^{-1}] @ BiosEquil Value of 1
Acacia ligulata	8.5	26.30	1062	1455	247	0.985	3.124	3.134
Acacia oswaldii [Riverland]	8.5	7.55	9250	7120	253	1.011	0.876	0.877
Acacia oswaldii [Murray Bridge]	12.5	44.54	390	1524	340	1.935	2.624	1.844
Acacia pycnantha	13.5	50.73	2038	923	340	1.935	2.771	1.948
Acacia rigens	12.5	42.07	581	3059	340	1.935	2.476	1.741
Allocasuarina verticillata [MB - State Flora]	19.0	121.13^{m}		927	357	1.857	4.465	3.433
Allocasuarina verticillata [MB - Army Range]	12.5	80.32	702	1198	340	1.935	4.728	3.323
Atriplex nummularia (grazed)	7.5	5.29	1819	5345	251	1.123	0.701	0.626
Atriplex nummularia (ungrazed)	7.5	28.69	1183	1307	251	1.123	3.800	3.397
Callitris gracilis [Murray Bridge]	11.0	90.61^{m}		3325	357	1.857	5.768	4.436
Callitris gracilis [Riverland]	8.5	4.42	868	7117	253	1.011	0.513	0.514
Eucalyptus brachycalyx	10.0	66.29^{m}		1830	357	1.857	4.642	3.570
Eucalyptus calycogona	8.5	26.01	263	2046	261	1.053	2.920	2.895
Eucalyptus cneorifolia	17.5	263.07^{m}		781	357	1.857	10.527	8.095
Eucalyptus cyanophylla	9.5	35.32	644	2212	261	1.053	3.569	3.539
Eucalyptus gracilis	6.6	10.65	621	3298	261	1.053	1.552	1.539
Eucalyptus incrassata	15.0	57.31^{m}		1794	357	1.857	2.676	2.057
Eucalyptus largiflorens	10.5	32.57	910	2286	261	1.053	2.977	2.952
Eucalyptus leucoxylon	12.5	144.92^{m}		1688	357	1.857	8.119	6.243
Eucalyptus nortonii	7.0	137.11^{m}		958	507	2.406	9.658	8.141
Eucalyptus oleosa	10.4	40.35	762	1053	261	1.053	3.723	3.691
Eucalyptus porosa [Murray Bridge]	12.4	98.43	590	973	340	1.935	5.818	4.089
Eucalyptus porosa [Riverland]	9.5	21.29	546	1364	261	1.053	2.144	2.126
Eucalyptus socialis	10.5	80.40	309	645	261	1.053	7.348	7.285
Eucalyptus viminalis ssp. cygnetensis	7.0	125.43^{m}		943	507	2.406	8.836	7.448
Melaleuca armillaris ssp. armillaris	11.0	105.23^{m}		1493	362	1.997	6.607	4.791
Melaleuca lanceolata	10.0	26.36^{m}		1481	357	1.857	1.846	1.419
Melaleuca uncinata [MB - Army Range]	12.4	17.63	507	4695	340	1.935	1.042	0.732
Melaleuca uncinata [MB - State Flora]	19.0	60.05^{m}		867	357	1.857	2.213	1.702
Myoporum platycarpum	10.3	36.60^{m}		1668	329	1.515	2.598	2.256

(# observed from biometrics study or ^{m} modelled from morphological measurements)

3.3 Regional Productivity

ArcGIS was used to determine the average annual rainfall and BiosEquil values (Raupach *et al.* 2001) for each of the 4 Murray River Corridor zones (see Table 9). Standardised biomass accumulation rates from BiosEquil productivity models were then applied to the average BiosEquil values of each River Murray Corridor zone (see Table 10) to estimate the likely total plant biomass productivity for each zone. BiosEquil models were chosen for this step because they incorporate climatic and soil interactions on primary production and provide more spatially reliable predictors of primary production than rainfall alone. Climatic suitability models developed by Hobbs and Bennell (2004) provide an indication of which species are suited to each zone and the reliability of biomass productivity models for each species and zone.

Mallee species *Eucalyptus socialis*, *Eucalyptus oleosa* and *Eucalyptus cyanophylla* are the most reliable and productive species for the Riverland region of River Murray Corridor (Zones 1 & 2, see Table 10). On average they will produce between 3.7 and 7.9 green kilograms of biomass per plant per year (g kg plant^{-1} yr^{-1}) in the first 10 years of growth. Mallee species in the Lower Murray Corridor region (Zones 3 & 4) can provide, on average, between 5.0 and 14.6 g kg plant^{-1} yr^{-1} (but note the oldest mallee, *Eucalyptus cneorifolia*, was sampled at 17.5 years of age). Tree form Eucalypts (*Eucalyptus nortonii*, *Eucalyptus viminalis* ssp. *cygnetensis* & *Eucalyptus leucoxylon*) can provide between 8.7 and 14.7 g kg plant^{-1} yr^{-1} but are less climatically suited to lower rainfall regions. Shrubs (*Atriplex nummularia* & *Acacia ligulata*) are reliably productive in both the Riverland (3.2 – 3.7 g kg plant^{-1} yr^{-1}) and Lower Murray (4.4 – 6.1 g kg plant^{-1} yr^{-1}) regions. Additionally, shrubs may be planted at higher densities per hectare than mallees or trees. At these higher planting rates shrubs may produce an equivalent (or greater) total biomass per hectare than mallee species.

The annual green biomass accumulation rate per hectare (g t ha^{-1} yr^{-1}) for productive species suited to dryland sites in River Murray Corridor is simply calculated from the individual plant productivity rate multiplied by a suitable planting density. Using appropriate species selection, and a minimum planting rate of 1000 plants per hectare for mallees and trees and 2000 plants per hectare for shrubs, the likely conservative biomass accumulation rate ranges between 3.8 and 14.7 g t ha^{-1} yr^{-1} for mallees and trees, and 6.8 to 12.3 g t ha^{-1} yr^{-1} for shrub species. Less conservative planting densities are likely to be appropriate for most species and locations, and should result in higher biomass accumulation rates per hectare than those reported here. Plant productivity research conducted by the FloraSearch project (Bennell, Hobbs & Ellis 2004) suggest alternate dryland species, such as *Eucalyptus cladocalyx*, can be 60%+ more productive than the best performing species observed in this study.

Estimates of above ground carbon sequestration rates (tonnes carbon ha^{-1} yr^{-1}) for plantations of short-cycle woody crops (~10 year cycle) in dryland regions of the River Murray Corridor are presented in Table 11. Only data from productive and climatically suited species are presented. The mallee *Eucalyptus socialis* can readily sequester between 2.5-4.2 t carbon ha^{-1} yr^{-1} across the region. Results suggest that carbon sequestration rates in such plantations may be more than 100% greater than those predicted by well recognised national models of net carbon accumulation (Raupach *et al.* 2001)

Table 9 – Annual rainfall and BiosEquil productivity values for the River Murray Corridor zones.

Region	Rainfall [mm]					BiosEquil Value				
	Avg	Min	Max	SD	Count	Avg	Min	Max	SD	Count
Zone1	250	236	271	7.53	111	1.083	0.851	1.332	0.139	129
Zone 2	258	242	294	11.10	74	1.035	0.494	1.473	0.203	88
Zone 3	303	256	389	35.59	201	1.401	0.568	2.764	0.363	204
Zone 4	417	358	727	58.21	103	1.808	0.847	3.033	0.335	113

Table 10 – Modelled average biomass accumulation rates (green kg plant^{-1} year^{-1}) from BiosEquil models of regional productivity for different species and River Murray Corridor zones.

Shading and italics represents zones where climatic conditions may not be suitable for each species and their modelled productivity values may be unreliable.

Species	Biomass accumulation rates [green kg plant^{-1} year^{-1}]			
	Zone 1	Zone 2	Zone 3	Zone 4
Eucalyptus nortonii	8.817	8.426	11.406	14.719
Eucalyptus cneorifolia	8.767	8.378	11.341	14.636
Eucalyptus viminalis ssp. cygnetensis	8.066	7.709	10.435	13.466
Eucalyptus socialis	7.890	7.540	10.207	13.172
Eucalyptus leucoxylon	6.761	6.462	8.746	11.287
Melaleuca armillaris ssp. armillaris	5.189	4.959	6.712	8.662
Eucalyptus oleosa	3.998	3.821	5.172	6.674
Eucalyptus brachycalyx	3.866	3.695	5.002	6.455
Eucalyptus cyanophylla	3.832	3.663	4.958	6.398
Atriplex nummularia	3.679	3.516	4.759	6.142
Allocasuarina verticillata	3.658	3.496	4.733	6.108
Acacia ligulata	3.394	3.243	4.390	5.666
Eucalyptus porosa	3.365	3.216	4.354	5.618
Eucalyptus largiflorens	3.197	3.055	4.135	5.337
Eucalyptus calycogona	3.136	2.997	4.056	5.235
Callitris gracilis	2.680	2.561	3.467	4.474
Myoporum platycarpum	2.443	2.335	3.161	4.079
Eucalyptus incrassata	2.228	2.129	2.882	3.719
Acacia pycnantha	2.109	2.016	2.729	3.521
Acacia rigens	1.885	1.801	2.439	3.147
Eucalyptus gracilis	1.667	1.593	2.156	2.783
Melaleuca lanceolata	1.537	1.469	1.988	2.566
Acacia oswaldii	1.473	1.408	1.906	2.460
Melaleuca uncinata	1.318	1.260	1.705	2.201

Table 11 – Predicted above-ground carbon sequestration rates for selected species in short rotation crops (~10 year cycle) on dryland sites in the River Murray Corridor region. Shading represents zones where climatic conditions may not be suitable for selected species.

Plantation Type / Species	Annual Carbon Sequestration Rates [tonnes carbon ha^{-1} $year^{-1}$]			
	Zone 1	Zone 2	Zone 3	Zone 4
Mallees at 1000 plants ha^{-1}				
Eucalyptus socialis	2.528	2.416	3.271	4.221
Eucalyptus oleosa	1.246	1.191	1.612	2.080
Eucalyptus cyanophylla	1.221	1.167	1.579	?2.038
Eucalyptus porosa	0.942	0.901	1.219	1.573
Shrubs at 2000 plants ha^{-1}				
Atriplex nummularia	2.218	2.119	2.869	3.702
Acacia ligulata	2.050	1.959	2.652	3.422
Trees at 1000 plants ha^{-1}				
Eucalyptus leucoxylon			2.713	3.501
Eucalyptus nortonii				4.105
Eucalyptus viminalis ssp. cygnetensis				3.317

4. Discussion

The biometrics study provides very strong allometric relationships between simple measures of plant morphology and above ground biomass. Analyses also show that simple classifications of species groups and lifeforms can improve the predictive capability of these models by a further 10%. Only a limited number of tree species were sampled during this study due to the prioritisation of mallee and shrub forms, which are better suited to the predominantly low rainfall (<400mm) regions of the study areas. From limited tree samples the allometric relationships are still useful but will require further validation, especially in higher rainfall regions (400-650mm). Plant basal area measurements are commonly used in classical forestry assessments and allometric calculations of tree biomass (Snowdon *et al.* 2000, 2002). Results from the biometrics study show that allometric models of biomass from basal area measurements (± height) are significantly (>22%) less powerful than models based on stemwood volumes. Allometric biomass equations developed Kiddle *et al.* (1987) for low rainfall areas of South Australia, and Snowdon *et al.*'s (2000) generalised models for woodland and shrub species, can seriously miscalculate standing biomass by between 47-138% in the River Murray Corridor. This strongly demonstrates the need for more robust allometric models of plant biomass in the region.

The data gathered on biomass fractions, stemwood volumes, basic densities, moisture contents and other plant characteristics are critical for the initial evaluation of species suitability for industry development due to their influences of these properties on woody crop harvest yields, plant processing and cost of transportation. This information has also been used to determine the carbon content of each plant sampled.

Any biomass industry development is highly dependent on the primary productivity of the species selected for biomass crops. The work presented in the productivity study provides a solid evaluation of the biomass productivity of a wide range of species grown in River Murray Corridor region. Standardisations of observed productivity data at different sites to reference values of rainfall and regional soil-climate productivity models allow more consistent comparisons of the performance of each species. These plant productivity results provide direction to the selection of priority species useful for further research and development.

Other productivity studies by FloraSearch (Bennell, Hobbs & Ellis 2004, Kiddle *et al.* 1987, Boardman 1992, Fairlamb and Bulman 1994) detail a number of other tree species which are often more productive than *Eucalyptus leucoxylon* within low rainfall environments (350-400mm). These highly productivity species, which are climatically suited to the Lower Murray Corridor region, include *Eucalyptus cladocalyx*, *Eucalyptus occidentalis*, *Eucalyptus spathulata* and *Eucalyptus gardneri.*

Using regional averages of BiosEquil productivity models (Raupach *et al.* 2001) for each River Murray Corridor zone, climatic models of plant suitability mapping and selected species productivity evaluations it was possible to estimate the likely biomass productivity of new plantations for each zone. In dryland sites in the Riverland region (Zones 1 & 2) this equates to approximately 7.7 green tonnes of biomass per hectare per year for the fastest growing mallee species (E*ucalyptus socialis*) planted at 1000 plants per hectare. In the Lower Murray region using the same species and planting density the biomass productivity is approximately 11.7 green tonnes of biomass per year.

The specific green biomass productivity rates and above ground carbon accumulation rates reported in this study should be considered conservative estimates only, as optimum planting rates for each species and site has not been determined. Using more productive species (e.g. *Eucalyptus cladocalyx*) and/or higher planting rates is likely to increase plantation total biomass production by 60% or more in the River Murray Corridor region. Short cycle (~10 year) dryland plantations of selected species can sequester over 2.4-2.5 tonnes of carbon per hectare per year in the Riverland region and 3.3-4.2 tonnes of carbon per hectare per year in the Lower Murray region. Total carbon sequestration estimates will need to include quantification of root biomass components (Gifford 2000).

The standardised biomass accumulation rates reported here can be readily applied, using geographic information systems and BiosEquil modelling, to estimate productivity and potential carbon sequestration over the entire River Murray Corridor and surrounding regions. These regional models of plant productivity can then be incorporated into regional industry potential analyses, like those conducted by FloraSearch (Bennell, Hobbs & Ellis 2004), to provide more accurate economic evaluations of the potential woody biomass industries in the region. Results from the productivity study have identified three low rainfall mallee species (*Eucalyptus socialis, Eucalyptus oleosa* & *Eucalyptus cyanophylla*) as being far more productive (up to 230% more green biomass per hectare) than the species (*Eucalyptus porosa*) used in the initial oil mallee industry evaluations conducted by the FloraSearch project.

Dryland plantations of native species can provide many environmental services and economic opportunities in River Murray Corridor and surrounding region. The value of perennial plant systems to reduce salinity and carbon sequestration is well recognised, with correctly managed and designed planting providing an additional positive contribution to biodiversity. Existing commercial livestock industries are already utilising fodder shrubs in the region with potential for further development and expansion. Potential biomass industries creating bioenergy, activated carbon and Eucalyptus oil products are developing in Australia, with opportunities for expansion into low rainfall regions of the Murray Basin.

The results of this study into plant biometrics and biomass productivity in the River Murray Dryland Corridor provides a robust methodology for assessing above ground biomass of low rainfall species in the region. It also evaluates the productive capability of a range of dryland species growing within the region, and provides conservative estimates of regional biomass production and carbon sequestration rates for new plantations of woody perennial crops. Such information can provide strong guidance to those seeking to evaluate the potential development of new plantations and biomass industries in the River Murray Corridor region.

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Appendix A – Monarto Productivity Data

Table 12 – Observed productivity of woodland plantations at Monarto, estimated total green biomass production from allometric relationships, and annual green biomass accumulation rates standardised to 250 mm rainfall and a regional soil-climate productivity model value of 1 (BiosEquil, Raupach *et al.* 2001).

	Observed Productivity After Boardman (1992) - 379mm rainfall site							Estimated Green Biomass		
Species	**Plot No.**	**Age [years]**	**Observed Plant Density [plants ha^{-1}]**	**Basal Area @ 30cm [m² ha^{-1}]**	**Height [m]**	**Green Stemwood [t ha^{-1}]**	**Volume (outer bark) [m³ ha^{-1}]**	**Total Green Biomass [kg plant^{-1}]**	**Annual Biomass [g kg plant^{-1} yr^{-1}] @ 250mm rainfall**	**Annual Biomass [g kg plant^{-1} yr^{-1}] @ BiosEquil Value of 1**
Allocasuarina verticillata	166	9.0	252	4.03	7.00	20.80	14.71	112.00	8.20	5.69
Allocasuarina verticillata	167	9.0	331	0.86	4.30	0.20	1.98	14.61	1.07	0.74
Casuarina cristata	164	9.0	246	4.25	5.60	22.50	12.54	98.91	7.24	5.02
Casuarina cristata	165	9.0	295	1.37	6.40	3.30	4.59	33.71	2.47	1.71
Eucalyptus astringens	136	10.0	242	4.63	6.70	25.30	21.94	150.41	9.91	6.88
Eucalyptus astringens	150	9.0	292	5.07	5.90	26.90	23.33	136.54	10.00	6.94
Eucalyptus astringens	151	9.0	287	2.11	6.70	7.70	6.68	53.52	3.92	2.72
Eucalyptus brockwayi	142	10.0	244	4.70	7.50	25.70	21.35	146.38	9.65	6.69
Eucalyptus brockwayi	141	10.0	204	4.47	7.30	25.40	21.10	166.37	10.96	7.61
Eucalyptus brockwayi	140	10.0	202	3.09	7.80	15.70	13.04	116.01	7.64	5.30
Eucalyptus brockwayi	155	9.0	252	7.47	11.70	45.80	38.04	222.30	16.27	11.29
Eucalyptus brockwayi	156	9.0	113	1.24	6.30	5.60	4.65	82.33	6.03	4.18
Eucalyptus dundasii	147	9.0	306	10.67	7.80	68.10	56.56	259.67	19.01	13.19
Eucalyptus dundasii	148	9.0	277	5.04	6.10	27.10	22.51	138.33	10.13	7.03
Eucalyptus gardneri	159	9.0	260	10.55	7.40	69.60	57.81	299.24	21.91	15.20
Eucalyptus gardneri	158	9.0	237	6.73	6.50	40.80	33.89	213.26	15.61	10.83
Eucalyptus gardneri	160	9.0	613	6.52	6.10	28.90	24.00	79.27	5.80	4.03
Eucalyptus leucoxylon	144	10.0	239	10.44	6.10	70.00	58.14	320.63	21.13	14.66
Eucalyptus leucoxylon	143	10.0	240	6.02	6.20	35.50	29.49	189.85	12.51	8.68
Eucalyptus leucoxylon	168	9.0	190	5.32	8.30	32.20	26.74	210.67	15.42	10.70
Eucalyptus leucoxylon	169	9.0	184	3.12	6.10	16.40	13.62	128.80	9.43	6.54
Eucalyptus leucoxylon	170	9.0	260	0.95	6.40	1.50	1.25	17.16	1.26	0.87
Eucalyptus occidentalis	146	9.0	288	12.76	9.80	85.90	74.50	336.12	24.61	17.07
Eucalyptus spathulata	139	10.0	204	7.41	6.00	47.70	39.62	269.73	17.77	12.33
Eucalyptus spathulata	138	10.0	227	7.33	6.30	45.90	38.12	241.24	15.90	11.03
Eucalyptus spathulata	137	10.0	255	5.83	5.70	33.50	27.82	173.31	11.42	7.92
Eucalyptus spathulata	152	9.0	231	10.52	9.20	71.30	59.22	333.81	24.44	16.96
Eucalyptus spathulata	153	9.0	322	7.48	6.30	43.10	35.80	175.84	12.87	8.93
Eucalyptus spathulata	154	9.0	721	4.69	7.70	15.80	13.12	44.52	3.26	2.26
E. spathulata, torquata, eremophila, brockwayi (mixture)	216	17.5	260	7.34	7.21	38.64	32.20	191.00	7.21	5.00
E. spathulata, woodwardii, porosa, torquata (mixture)	215	16.5	303	10.28	8.13	60.13	50.11	238.43	9.55	6.63