6 Growth and yield models

P.W. West

6.1 Summary

Forests of the Murray-Darling Basin (MDB) have low productivity by Australian forest standards, principally because the annual rainfall of the Basin is relatively low. The forests have been exploited little commercially. Little growth and yield data have been collected from them and few efforts have been made to develop growth and yield models to predict their wood yields. Data on stand stem wood biomass and coarse woody debris biomass, collected from 79 stands of a wide range of non-mallee forest types across the MDB (see Section 5). The data were used to develop a stand-based, empirical growth and yield model to predict firewood harvest yields available from these forests, when live trees are removed from them as thinnings or when coarse woody debris is harvested from time to time during their lifetimes. The model predicts yields in relation to the productive capacity of the site on which a forest is growing; the measure of site productive capacity (maximum annual net primary production of plants growing on a site) had been determined in other work for sites across Australia (Appendix 5). It was found that if the model is used to predict the average stand stem wood biomass of stands of a particular site productive capacity across a wide area of the MDB, the 95% confidence limit about the predicted average would be ±17% of the predicted value. This level of precision was considered appropriate for broad-scale estimation of firewood yields available from the MDB. Using previously published data, a separate growth and yield model was developed to predict firewood yields obtained by clear-felling 20-100 year old mallee eucalypt forests in the MDB.

6.2 Introduction

The overall aim of the present project was to determine the sustainable production of firewood possible from the forests of the MDB, firewood obtained either by felling live trees or from the collection of the coarse woody debris present as standing dead trees or fallen from live trees. To do so, it is necessary to predict how much firewood will be available from time to time from the forest at any location in the MDB. In normal forest management practice, such predictions are made using a “forest growth and yield model”. For any particular forest type, such a model predicts how a stand in the forest grows with time and hence the amount of wood available for harvest from it at any stage of its lifetime. Such models take account also of the fact that the productivity of a forest, hence the amount of wood it can yield at any age, depends on the characteristics of the site on which it is growing, particularly the rainfall, temperature and soil fertility. The scope and nature of the growth and yield models developed in the more productive native forests in Australia are summarised by Rayner and Turner (1990a,b).

For the purposes of the present project, field work was undertaken to gather sufficient data on growth and yield of non-mallee forests of the MDB to allow development of a growth and yield model to predict firewood yields from them (see Section 5). This section describes the development of that model. Fortunately, sufficient information was available from the literature to allow growth and yield prediction for mallee forests, without the need to develop a new model system for that forest type; the model system for mallee forests is described also in this section.

6.3 Data

6.3.1 Stand measurements

Section 5 describes the methods used to find suitable stands to provide data on the wood biomasses[2] of both live trees and coarse woody debris in forests of the MDB. The sites selected for measurement included a wide range of forest types and ages which had a wide range of productive capacities. Since forests of the MDB include both even- and uneven-aged forest, it is important to recognise that stand "age" in the present context is defined as the time since a stand regenerated from bare ground following clearing, destructive wildfire or other natural calamity.

Data collected from all 79 stands were used to build the growth and yield model for non-mallee forests. A list of the properties, the stand number on each property, their locations and the species present in the measured stands are given in Appendix 8. From the information available about stand age, a specific age was assigned to each stand, usually determined as the mid-point of the period within which it was believed regeneration of the stand occurred from bare ground. The chosen ages are shown in Appendix 8.

6.3.2 Stand stem wood biomass

The data collected in the point samples (Section 5.7.1) were used to determine the stand stem wood biomass of live trees in each stand as follows.

Since only diameter at breast height over bark (D, cm) and tree total height (H, m) had been measured for most trees, it was necessary first to develop an individual tree stem volume function to allow stem wood volume (V, m^3) to be estimated for each tree from its height and diameter. The development of this function used the data from the trees of which the stem wood volume had been measured and is described in Appendix 9. The stem volume function developed was:

$$V = 0.246\text{x}10^{-4} D^{1.996} H^{0.947} \qquad (6.1)$$

This function was used, with the tree diameter and height data collected in the point samples, to determine stand stem wood volumes for the live trees of each of the 79 measured stands; West (2004) describes how individual tree volumes determined in a point sample are used to determine a corresponding stand stem wood volume.

These stand wood volume estimates were converted to stand wood biomass estimates, assuming that the basic density (oven-dry weight per unit green volume) of the wood of the trees was that of the most common species in the stand. The basic densities used were obtained from a recent collation of wood densities of Australian trees (Ilic et al.2000). The densities and the live tree stand stem wood biomasses determined for each measured stand are shown in Appendix 8.

6.3.3 Coarse woody debris stand biomass

Coarse woody debris stand biomass includes stem and branch wood of dead standing trees or pieces of fallen wood with length ≥0.5 m and mid-diameter ≥10 cm. Section 5.7.2. describes the methods for measuring and determining the stem volumes of sections of tree stems and branches. The stand stem wood biomasses thus determined are presented as part of the coarse woody debris for each stand in Appendix 8.

---

[2] Throughout this Section, use of the term 'biomass' refers to oven-dry biomass.

6.4 Model for stand stem wood biomass growth

6.4.1 Approach

Forestry science has a long history of the development of growth models where observed data are available from a single measurement of each of a set of stands of different ages. An approach used commonly was suggested by Schumacher (1939), as discussed by Clutter *et al.*(1983, Chapter 4). In effect, Schumacher proposed that the production (in variables such as stand basal area, stand wood volume or stand wood biomass) by the live trees in a stand at any age can be represented using a model of the form:

$$\ln(B) = f(1/A,S,\rho) \quad (6.2)$$

where $\ln(\cdot)$ represents natural logarithms, B is the measure of production, which for the present work will be stand stem wood biomass, $f(\cdot)$ represents a function of the variables in parentheses, A is stand age, S is a measure of the productive capacity of the site on which the stand is growing (discussed below) and ρ is a measure of the density of the trees on the site (discussed below).

In this model, the logarithm of the production variable is generally used to ensure homoscedasticity of the data when it is fitted using least-squares regression. The reciprocal of stand age is used so that stand production will tend to an asymptotic value as age increases, a characteristic associated usually with aging in forests. The measure of site productive capacity is needed because stand production at any age will tend to be higher on sites with more fertile soils and a climate more amenable to tree growth. The measure of stand density allows that production will vary depending on the "degree of crowding" of trees on a site at any age; if the degree of crowding is insufficient that the resources of the site available for growth (light, water and nutrients) are not fully utilised by the stand, production on the site will be lower than if the resources were being fully utilised.

Sections 5.2.2 and 6.3.1 have described the way in which stand age has been defined and measured for the present work. In the next two Sections, the measures of site productive capacity and stand density used here are described.

6.4.2 Site productive capacity

Measures of site productive capacity attempt to describe the "quality" of a site for plant growth. Plant production is generally greater in wetter, warmer sites with the most fertile soils.

Recently, two attempts have been made to determine a measure of site productive capacity as it varies right across the Australian continent (Landsberg and Kesteven 2002, Barrett 2002). The measure is an estimate of the maximum annual net primary production (the net rate of production per unit area of biomass, both above- and below-ground) of plants growing on any site. In the present work, this measure of site productive capacity will be referred to as "net primary productivity index".

GIS surfaces are available with values of both Landsberg and Kesteven's and Barrett's indices (Section 4.2.2) for all of Australia, including the MDB. Further details of their derivation and a brief comparison of the two indices are given in Appendix 5. It was concluded that both indices are likely to be equally useful when applied in the MDB. In the present work, it was decided arbitrarily to use Barrett's index. The values of his NPP index for each of the stands measured in the present work are listed in Appendix 8.

6.4.3 Stand density

Stand density, or the "degree of crowding" of the trees in a stand, can be defined as the degree to which a stand approaches a condition of maximum density. It is assumed that a stand is at maximum density when it is suffering substantial and ongoing competition-induced mortality amongst the smaller, suppressed trees in a stand. Substantial work has shown that stands at maximum density conform to what is known as the "power rule of self-thinning". Under this rule, the relationship between stand biomass (W, g cm^{-2}) of the live plants in a stand (biomass can be expressed as total biomass above- and below-ground, above-ground biomass only or stem biomass only) and stand stocking density (N, stems m^{-2}) can be expressed by the relationship:

$$W = aN^b \tag{6.3}$$

where a and b are parameters and the value of b is close to -0.5.

This rule has been found to hold widely across the plant kingdom, not only for forests, and for both single- and mixed-species plant assemblages.

Weller (1987) has reviewed the validity of this rule. In effect, it sets an upper limit to the circumstances in which plant stands will be found in nature. No stand, of a particular stocking density, will be found with a biomass in excess of that predicted by equation (6.3); if it did have a biomass above that, it would suffer rapid mortality until its stocking density and biomass were reduced to a level such that it did conform to the rule.

This rule is used extensively in forestry science to provide a measure of stand density. If a stand has a biomass W_o (g cm^{-2}) and a stocking density N_o (stems m^{-2}), then its density (ρ, dimensionless) is defined as its actual stocking density divided by the stocking density it would have if it were at maximum density, that is if it were conforming to equation (6.3). That is, its density is determined as:

$$\rho = N_o/[(W_o/a)]^{(1/b)} \tag{6.4}$$

Works such as West (1983), Jack and Long (1996) and Avery and Burkhart (2002) may be consulted to learn how this, and other related stand density measures are derived and used in forestry. Stands with a density of 1 will be at maximum density. Stands with a density below 0.15-0.25 are unlikely to be using fully the resources for growth available at a site (light, water and nutrients) (Jack and Long 1996).

Unfortunately, work in Australia to quantify the power-rule of self-thinning for eucalypt forests generally is limited and none has been done for those of the MDB. Weller (1987) used some limited, published data from eucalypt forests which suggested their behaviour under the rule was somewhat deviant from other forests. However, West (1985) and Hamilton (1988) used more substantial and appropriate data sets from ash eucalypt forests of Victoria and Tasmania to suggest those forests conformed quite reasonably to the rule. West's results suggest that appropriate parameter values for equation (6.3) for those forests were $a=1.22\times10^4$ and $b=-0.5$ (where stand biomass was represented by stem wood biomass and it has been assumed here that basic stem wood density for those forests was 0.502 t m^{-3}).

Figure 6.1 shows a scatter plot of the stand stem wood biomasses against stand stocking densities (transformed as logarithms) for the data collected in the present work for the forests of the MDB (Appendix 8). Superimposed upon the diagram are the power-rule of self-thinning for ash eucalypts as determined by West (1985) and lines denoting various stand densities as stands approach the self-thinning line. The two stands which are closest to the self-thinning line were stands 6 and 7 from the property "Maragle", which is a New South Wales State Forest located in the more productive parts of the MDB on its south-eastern boundary. Those stands were 33 and 20 years old, respectively, and consisted principally of *Eucalyptus viminalis* and/or *Eucalyptus pauciflora*. This is a forest type which, whilst not as productive as the ash forests of southern Australia, could generally be expected to grow well and regenerate densely after felling. The fact that at least these stands fell at a position near the self-thinning line for ash eucalypts, in Figure 6.1, suggests that that line has at least some relevance to the forests of the MDB.

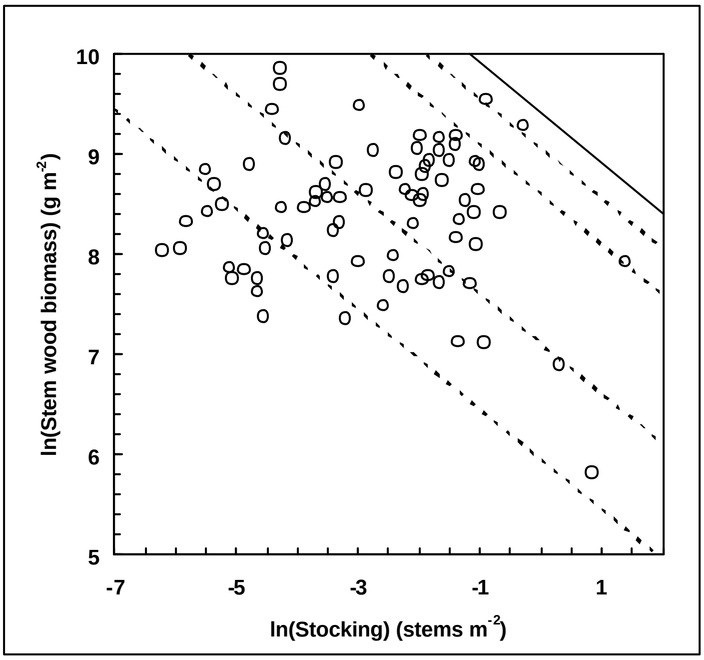

Figure 6.1. Logarithmically transformed scatter plot of stand stem wood biomasses against stand stocking densities for the data collected from non-mallee forests of the MDB. The power rule of self-thinning line, as determined by West (1985) for ash eucalypt forests in Tasmania, is shown as a solid line. The dashed lines indicate the positions in the space of the diagram which would be occupied by stands with densities (highest to lowest) of 0.5, 0.2, 0.01 and 0.001. Note that ln(·) represents natural logarithms.

However, it is apparent also that most of the stands measured here had relatively low densities. If stands need to be at a density of 0.15-0.25 to be fully utilising the available site resources, it is clear from Figure 6.1 that most of them were at densities well below this level. It must be borne in mind that work in forestry to develop this concept of full site utilisation has been with far more productive forests, including plantations, than those of the MDB.

Until much more detailed research work is done to study the ecophysiological behaviour of MDB forests, it is impossible to say how relevant the concept is. However, these concepts do allow that a measure of density can be determined for each of the stands measured here, a measure that may prove useful to predict their growth.

Further examination of these data suggested that there was a relationship between stand density, computed for each stand with model (6.4) and using West's parameter values for the model, and the productive capacity of the sites on which the stands were growing. A scatter-plot of the logarithm of density against the logarithm of NPP index is shown in Figure 6.2.

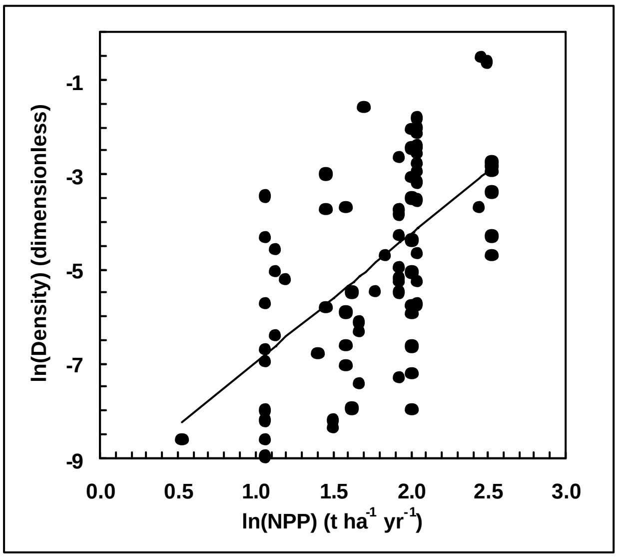

Figure 6.2 Scatter plot of logarithmic transformations of stand density against site productive capacity (NPP index) for the stands measured in the present work. The solid line shows the ordinary least-squares regression straight line fit to the data.

There appears to be a tendency for stand density to increase with increasing site productive capacity. The ordinary least-squares regression straight line fit to the data was highly significant ($p<0.01$ at least), but the relationship was only moderately strong ($r^2=0.34$). The fit to the data of the regression is shown on the figure. The model fitted was:

$$\rho = 0.000181S^{2.71} \tag{6.5}$$

where S is site productive capacity (NPP index, t ha^{-1} yr^{-1}). Note that the coefficient value 0.000181 in model (6.5) has been corrected to allow for the bias introduced in back-transforming predictions, from a regression fitted in logarithmic form, to their linear counterparts. In the present work, the bias correction value proposed by Snowdon (1991) was used. This is determined as the mean of the observed values of the dependent variable of the fitted regression divided by the mean of their predicted values from the logarithmic regression, after back-transformation from logarithms.

For the present work, model (6.5) will be used to estimate the average density of forests in the MDB found on sites of a particular productive capacity. For any one stand, it is likely that its density will change with age, but there was no evidence in the data available here that any such trend could be identified. Furthermore, other work has suggested that the intercept of the self-thinning line may change with site productive capacity (e.g. Zeide 1985, Jack and Long 1966), whereas a single value of the intercept has been assumed appropriate for the present work. Considerable research would be necessary to establish in detail a full description of the growth dynamics of the various forest types of the MDB. However, it was felt that for the purposes of the present work, model (6.5) provides at least some opportunity to take account of the very wide range of stand densities that obviously occur in the forests of the MDB and the consequences that may have for their productivity.

6.4.4 Fitted model

Given these various considerations, a model was developed to predict stand stem wood biomass at age A (years), $B_S(A)$ (t ha^{-1}), in relation to age, site productive capacity (NPP index, S, t ha^{-1} yr^{-1}) and stand density (ρ, dimensionless as determined using equation 6.4) for the stands measured here. As is evident in Appendix 8, a very wide range of forest types are represented in the data set, none with more than a few observations. This meant that it was impossible to develop separate growth models for different forest types, but only to develop a single growth model which would represent the average behaviour across all non-mallee forest types of the MDB.

The model developed was based on the functional form shown in equation (6.2). The independent variables considered in fitting the model were 1/A, S, ln(ρ), their squares, their first-order interactions and the squares of those interactions. The model was then fitted, using ordinary least-squares regression, with a forward selection procedure (Draper and Smith 1981) to determine which combination of the independent variables minimised the residual variance of the fitted regression.

The model determined by this procedure (after back-transformation of the dependent variable from logarithms) was

$$B_S(A) = 0.852\exp[5.0483-0.1837S+0.0149S^2-0.1791\rho'-0.0318(\rho')^2 \\ +0.8195(S/A)^2+10.4604(\rho'/A)+13.7934(\rho'/A)^2] \qquad (6.6)$$

where ρ' is the natural logarithm of ρ and the model has been back-transformed from logarithms. Note that the coefficient 0.852 is a bias correction factor, to allow for the back-transformation from logarithms, calculated using the method of Snowdon (1991). The fitted model was statistically significant ($p<0.001$) with $r^2=0.79$. Scatter plots of the residuals from the regression against the fitted values and the independent variables showed no evidence of any lack of fit to the data.

6.4.5 Predicting growth at young ages

The data set used to build model (6.6) contained no data from stands less than 10 years of age and only six observations from stands less than 20 years of age (Appendix 8). Examination of the fit to the data, suggested that predictions of stem wood biomass made with model (6.6) should be considered reliable only for stands 20 years or older.

An approximate model was constructed to allow predictions of stem wood biomass to made between 1 and 19 years of age. It was assumed that the form of the growth curve over that time period in any stand was:

$$B_S(A) = \exp(c+d/A) \qquad (2 \le A \le 19) \qquad (6.7)$$

where c and d are parameters.

It was assumed that the stem wood biomass at one year of age of any stand, $B_S(1)$ (t ha^{-1}), was 0.01 t ha^{-1}; alteration of this value affects the shape of the growth curve ultimately derived and this value appeared to give a shape consistent with the shape of the curve after 20 years of age described for any stand with model (6.6). Values for the parameters c and d were then determined for any stand as:

$$d = 0.95 \ln[B_S(1)/B_S(20)] \qquad (6.8)$$

where $B_S(20)$ (t ha^{-1}) was the stem wood biomass for the stand concerned predicted from model (6.6), and:

$$c = \ln[B_S(1)] - d \qquad (6.9)$$

Determining the values for the parameters of the model in this way ensures that the stem wood biomass which would be predicted with it at 20 years of age is exactly the same as that predicted using model (6.6).

6.5 Model to predict coarse woody debris biomass

The total stand biomass of coarse woody debris present, in each of the stands in which debris was measured, was determined by summing the amounts present as dead standing trees and in each of three classes of woody debris measured on the ground (Appendix 8).

Unfortunately, it is likely that there had been removal of coarse woody debris at one time or other from many of the measured stands. The owner may have removed it as firewood or for other purposes, or fire passing through the stand may have burnt the debris present. Of the total 79 stands in Appendix 8, coarse woody debris on the ground was measured in only 45 of them. In four of those, no debris was found on the ground. Sufficient was known of the history of the 45 stands that it was felt reasonably certain that there had been no removal of coarse woody debris from 11 of them during their lifetime. Those 11 stands are indicated in Appendix 8.

Figure 6.3 shows a scatter plot of the measured amount of coarse woody debris measured in these stands against the corresponding stem wood biomass of the live trees in the stand.

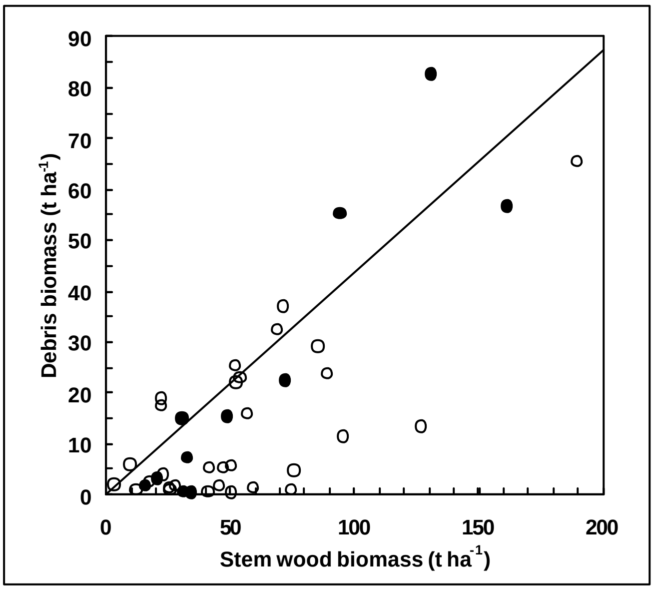

Figure 6.3 Scatter plot of the amount of coarse woody debris biomass measured in non-mallee forest stands in the MDB against the corresponding stem wood biomass of the live trees in the stand. Results are shown for stands from which it was believed coarse woody had not been removed during the lifetime of the stand (●) and for those for which it was uncertain whether or not coarse woody had been removed (○). The solid line shows the fit to the data from the 11 sites thought to have experienced no removal of coarse woody debris.

For the 11 stands in which it was believed that the coarse woody debris was undisturbed, there appears to be a close correlation between the coarse woody debris biomass and the live tree stem wood biomass. This is not surprising; where the live trees in the stand are larger, whether because the forest is older, denser or growing on land of higher site productive capacity, it might reasonably be expected that more coarse woody debris would be present. However, assuming such a straightforward correlation exists, it appears from Figure 6.3 that some of the stands, for which it was uncertain whether or not their coarse woody debris had been disturbed, may in fact have been undisturbed. Also, it appears that some of the stands believed to have been undisturbed may, in fact, have been so.

However, the trends in the data of Figure 6.3 appeared to make it reasonable to assume that, for undisturbed stands, there is a simple correlation between stand coarse woody debris biomass and stand stem wood biomass. This relationship was quantified by fitting a straight-line, least-squares regression relationship passing through the origin, using the data only from the 11 stands it was believed were undisturbed. The fitted relationship was:

$$B_C(A) = 0.437 B_S(A) \qquad (6.10)$$

where $B_C(A)$ (t ha^{-1}) was the stand biomass of coarse woody debris at an age A (years). The fit to the data of this relationship is shown on Figure 6.3.

6.6 Growth and yield model

The results of the last two sections have established models (6.5-6.10) which are capable of predicting the change with age in the biomass of stem wood and coarse woody debris in non-mallee forest stands of the MDB, growing on a site of a particular productive capacity and which are undisturbed by wood harvesting throughout their lifetime. In this section, these models are incorporated into a complete model system capable of predicting yields obtained when firewood is harvested from time to time from such stands.

This complete model system was built and is used in two parts. The first part predicts stand growth assuming the stand is undisturbed throughout its lifetime. The results from this part of the system, together with certain other assumptions about growth behaviour of thinned stands, are then used in the second part of the system to predict firewood yields obtained by removal of live trees and/or of coarse woody debris from time to time during the lifetime of the stand.

6.6.1 Undisturbed stands

Consider first a stand which is undisturbed throughout its lifetime, so that no live trees are ever harvested from it by thinning and no firewood is ever harvested from woody debris. Suppose the stand is growing on a site of known site productive capacity (NPP index), S (t ha^{-1} yr^{-1}). Suppose that at some age A (years), the stand stem wood biomass of the live trees in the stand is $B_S(A)$ (t ha^{-1}). model (6.5) may be used to predict the stand density, ρ (dimensionless) and then model (6.6) with (6.7 - 6.9) may be applied to predict the values of $B_S(A)$ in the stand for all ages from 1 to, at most, 200 yr, the oldest age for which data were available in the present work.

Given those estimates of $B_S(A)$, model (6.10) may then be applied to predict the stand biomass of coarse woody debris, $B_C(A)$ (t ha^{-1}), at any age A in an undisturbed stand.

In live trees, firewood may be obtained from branch wood as well as stem wood, so it was necessary to predict their branch wood biomass as well as their stem wood biomass. This was done using the generalized model for Australian native forests of Snowdon et al.(2000), which predicts the total above-ground stand biomass, $B_T(A)$ (t ha^{-1}), of the stand at any age A (see their Figure 2.3b, with rearrangement of the function they quoted there) as:

$$B_T(A) = 1.720B_S(A)^{0.962} \tag{6.11}$$

Using data from *Eucalyptus grandis* plantations provided by J. Knott (pers. comm.), it was found that stand branch biomass including bark, $B_K(A)$ (t ha^{-1}), at any age A was directly proportional to the difference between total above-ground and stem wood biomasses and could be predicted as:

$$B_K(A) = 0.324[B_T(A)-B_S(A)] \tag{6.12}$$

Wall (1997) studied the firewood industry on the northern tablelands of New South Wales. He measured the wood and bark biomasses of branches of trees of three eucalypt species, *Eucalyptus caliginosa*, *Eucalyptus laevopinea* and *Eucalyptus melliodora*, which are used for firewood in the region. He found (p 68 et seq.) that the proportions of bark biomass in branches varied little with tree diameter (at least in the range of tree diameters at breast height over-bark 20-90 cm), but that the proportion of bark in *Eucalyptus melliodora* was somewhat higher than in the other two species. Averaging Wall's results for those species, it was assumed here that branch wood stand biomass, $B_B(A)$ (t ha^{-1}), at any age A could be estimated from total branch stand biomass as:

$$B_B(A) = 0.88B_K(A) \tag{6.13}$$

To develop the second part of the model to predict firewood harvest yields, it was necessary to predict the amount of coarse woody debris in an undisturbed stand at any age, as well as to predict how the change in the amount of coarse woody debris between any two ages occurred. Between ages A and A+1, the change, $\Delta B_C(A)$ (t ha^{-1} yr^{-1}) can be determined simply as:

$$\Delta B_C(A) = B_C(A+1) - B_C(A) \tag{6.14}$$

However, this change can be described in more detail by using the model for woody debris change described in equation A1.5 of Barrett (2002), an equation which was part of the overall model system used by Barrett in developing his NPP index for Australia. Barrett's equation was a differential equation, which predicts the rate of production of woody debris in a stand as:

$$dq_C/dA = q_W/\tau_W - q_C/\tau_C \tag{6.15}$$

where A is age (years), q_C is the biomass of woody debris (t ha^{-1}), q_W is the biomass of wood in the stem and branches of the live trees in the stand (t ha^{-1}), τ_W is the turn-over time (years) of the wood of the live trees and τ_C is the time (years) which woody debris takes to decay completely in the stand. Another way of viewing τ_W is to recognise that its reciprocal represents the proportion per year of the wood of live trees which is lost from the stand as woody debris. Similarly, the reciprocal of τ_C is the proportion per year of woody debris which is lost from the stand by decay. In Barrett's model system, woody debris included wood in twigs or whole branches which have fallen from live trees as well as the total amount of stem and branch wood in whole trees which have died and fallen to the ground or have remained standing. It was assumed that model (6.15) applies just as well to the coarse woody debris measured in the present work (stem wood of dead standing trees and fallen wood with length ≥0.5 m and mid-diameter ≥10 cm) as to the entire amount of woody debris which Barrett considered.

In the present work, it was assumed, unlike Barrett, that τ_W might change with stand age, so that at any age A, the proportion per year of the wood of live trees which is converted to coarse woody debris is $[1/\tau_W(A)]$. Then, using the same terminology as earlier and rewriting equation (6.15) as a difference, rather than a differential equation, a second expression for the change in the amount of coarse woody debris between age A and A+1 is:

$$\Delta B_C(A) = [B_S(A) + B_B(A)]/\tau_W(A) - B_C(A)/\tau_C \tag{6.16}$$

Equating the right hand sides of equations (6.14) and (6.16) and rearranging the results gives:

$$\tau_W(A) = \{B_S(A) + B_B(A)\}/\{B_C(A+1) - B_C(A)[1-1/\tau_C]\} \tag{6.17}$$

Furthermore, the amount of new coarse woody debris added to that already in the stand, between ages A and A+1, $\Delta B_{CN}(A)$ (t ha^{-1} yr^{-1}), is given by the left hand term in the right hand side of (6.16) as:

$$\Delta B_{CN}(A) = [B_S(A) + B_B(A)]/\tau_W(A) \tag{6.18}$$

Suppose also that the total amount of new coarse woody debris that has been produced by a stand up to any age A is denoted as $B_{CT}(A)$ (t ha^{-1}); the value of this can be determined as:

$$B_{CT}(A) = \Delta B_{CN}(1) + \Delta B_{CN}(2) + \ldots + \Delta B_{CN}(A) \tag{6.19}$$

Results (6.17 - 6.19) will be used in the second part of the model system.

Barrett (2002) reported in his Table 3 an estimate of the value of τ_C (it is actually termed τ^*_C in his table) for tall forests in Australia of 23 years and for open woodlands of 3 years. However, Mackensen and Bauhus (1999) have reviewed the Australian and world literature on the decay rates in forests of coarse woody debris (defined by them generally as woody material with a diameter of 2.5-10 cm or greater). The values of $t_{0.95}$ they showed in their Appendix 1, values determined from a wide range of experiments throughout the world where decay rates of woody debris have been studied, can be considered as values of τ_C appropriate to different forest circumstances.

Mackensen and Bauhus (1999) were unable to draw any conclusions as to what value would be most appropriate generally for τ_C for Australian forests, or indeed for forests generally around the world. The time taken for woody debris to decay completely in forests has been found to vary enormously, from perhaps slightly less than one year to several hundred years. The rate of decay varies with the size of the material (small twigs decay much faster than the large stem of a standing dead tree), with the quality of the wood and its natural resistance to decay and with the environmental characteristics of the site, particularly the moisture and temperature regimes which affect the activity of decay micro-organisms.

The results in Mackensen and Bauhus (1999) Appendix 1 for decay rates of large logs and standing trees, material of a size from which firewood might be cut, vary from 20 to >100 years. This suggests that the value of τ_C=23 years determined by Barrett (2002) for tall forests in Australia generally might be appropriate for use in the present model system. Until experimental data on coarse woody debris rates are collected specifically from the forests of the MDB, it is impossible to determine exactly what value of τ_C is most appropriate to use in model (6.17).

The second part of the complete model system required consideration of growth behaviour of stands after some trees are removed by thinning, how the amounts of coarse woody debris that remains in stands is affected by removal from time to time of some of it for firewood and what proportion of the wood biomass of live trees or coarse woody debris will actually constitute firewood. These issues are addressed in Sections 6.6.2 and 6.2.3.

6.6.2 Thinned stands

To predict the growth behaviour and wood yields from thinned stands, it was assumed that total above-ground biomass production to any age of a thinned stand (that is the above-ground biomass of the live trees in the stand at that age plus the total amount of coarse woody debris that had been produced up to that age plus the total amount of live tree biomass which had been removed from the stand by thinning up to that age) was the same as the total above-ground biomass production of the corresponding unthinned stand to the same age. This assumes that total production by a stand, whether thinned or unthinned, is determined by the resources at the site available for growth (light water and nutrients) and that thinning does not reduce the capability of the stand to use those available resources. West and Osler (1995) have described the biological mechanisms on which this assumption is based. This concept has been developed from research undertaken in plantation and high yield native forests, but remains untested for the rather slower growing forests of the MDB. However, in the absence of any other information for those forests, it seemed a reasonable assumption to make here.

To apply this assumption and develop the second part of the model system, similar terminology will be used to that already established for the first part. However, where a stand is to be thinned during its lifetime, the same symbols will be used as those used for the corresponding unthinned stand, but with the addition of a prime symbol (’) to denote variables which refer to the thinned stand. Thus, the symbol $B'_S(A)$ will refer to the stand biomass of the stem wood of the live trees which remain in a thinned stand at age A, whilst if the stand had not been thinned, the corresponding stand biomass would be denoted as $B_S(A)$. Suppose also that the total above-ground biomass of all trees which have been removed in all thinnings which have been done in a stand up to age A is denoted as $B'_{Tt}(A)$ (t ha^{-1}).

Using this terminology, the time course of development of a stand which is to be thinned once or several times during its lifetime could be determined as follows. Following the assumption that total production to any age, A (years), by a thinned stand would equal that of the same stand if unthinned to that age, it follows that

$$B'_T(A) + B'_{Tt}(A) + B'_{CN}(A) = B_T(A) + B_{CN}(A) \qquad (6.20)$$

and, hence, by rearrangement of (6.20):

$$B'_T(A) = B_T(A) + B_{CT}(A) - B'_{Tt}(A) - B'_{CT}(A) \qquad (6.21)$$

If it is assumed that the stand is unthinned at one year of age, that is $B_{CT}(1)=B'_{CT}(1)$ and $B'_{Tt}(1)=0$, equation (6.21) provides the basis by which growth of a thinned stand may be determined year by year from one year of age, provided growth of the corresponding unthinned stand has been determined already, using the first part of the model system.

When a thinning occurs at any age, some proportion of the total biomass of the live trees in the stand would be removed from that stand at the thinning. The proportion to be removed would be chosen by the model user. Model (6.11) can then be rearranged and used to predict the stem wood biomasses, from the total above-ground biomasses, of both the trees removed at thinning and the trees remaining. Models (6.12) and (6.13) would then be used to determine branch wood biomasses of both the thinned and remaining trees. The above-ground biomasses removed at thinnings would be accumulated to provide values of $B'_{Tt}(A)$ for use in equation (6.21).

The value of $B'_{CT}(A)$ in (6.21) may be determined using model (6.18) and equation (6.19), but with the corresponding variables for the thinned stand replacing those for the unthinned stand. However, it would be assumed that the rate of production of new coarse woody debris by the remaining trees in the thinned stand is equivalent to that of the live trees in the corresponding unthinned stand so that the value of $\tau_W(A)$ in equation (6.18) for the thinned stand has the same value as that determined for the corresponding unthinned stand.

6.6.3 Firewood harvests

To complete the second part of the model system, it remains only to predict the biomass of firewood that could be harvested at any age A, from either the live trees removed at a thinning or from the coarse woody debris that is in the stand at that age.

The stand wood biomass in stems and branches removed from a stand in thinned trees is available simply from the user's choice of what proportion of the above-ground biomass of the live trees in the stand is removed at any thinning.

For harvests from coarse woody debris, the user needs to make a choice as to what proportion of the biomass of the coarse woody debris in the stand at any particular age is to be removed at the harvest. The amount removed is then subtracted from the total that was in the stand at the time of harvest. If the amount then remaining in the stand at age A is $B'_C(A)$, the amount remaining at age A+1 is then determined, using model (6.16), as:

$$B'_C(A+1) = [B'_S(A) + B'_B(A)]/\tau_W(A) - B'_C(A)/\tau_C \qquad (6.22)$$

where the primed terms represent biomass amounts in the stand from which coarse woody debris has been harvested and which may or may not have been thinned; if it had been unthinned then the terms $B'_S(A)$ and $B'_B(A)$ would have exactly the same values as $B_S(A)$ and $B_B(A)$ for the unthinned stand.

Not all the biomass of the wood removed from the stand either at thinning or as coarse woody debris will be of a size large enough to be used for firewood. In his study of the firewood industry on the northern tablelands of New South Wales, Wall (1997) found that 82% of the stem and branch wood of trees harvested for firewood was large enough to be sold as firewood. Given this, it was assumed in the present model system that 82% of the biomass of the stem and branch wood of trees removed at thinning or of coarse woody debris which was harvested would actually constitute firewood.

6.7 Testing and applying the model

The complete model system has been devised in a way such that it predicts amounts of stand stem wood biomass and coarse woody debris in undisturbed stands consistent with models (6.6) and (6.10), the models derived from the measured data.

To test the first part of the model system, it was applied to predict live tree stand stem wood and coarse woody debris biomasses in each of the observed stands (Appendix 8) at the ages at which they were measured and assuming they had been undisturbed by thinning or removal of coarse woody debris up to that age. Figure 6.4 shows a scatter plot of the observed stand stem wood biomasses against those predicted by the model.

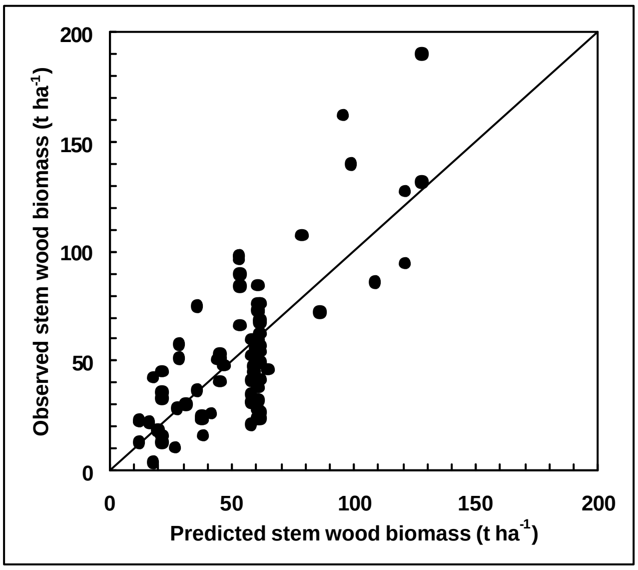

Figure 6.4 Scatter plot of the observed stand stem wood biomasses in the measured stands against their values predicted from the first part of the model. The solid line shows where the points would lie if there was exact agreement between the observed and predicted values.

There is little indication in the results of Figure 6.4 of any substantial bias in stand stem wood biomass estimation with the model. They do suggest there might be a tendency to underestimate biomasses at high levels of biomass, but there were insufficient data available to judge if this was actually so.

Using methods of Reynolds (1984), the information in Figure 6.4 can be used to show that the 95% confidence limit about predictions made with the model of stand stem wood biomass of a **single** stand in the MDB is ±153% of the predicted value. This is a very low precision of estimate, probably too low to be useful practically. However, if the model is used to predict the **average** stand stem wood biomass of stands of a particular site productive capacity across a wide area of the MDB, the 95% confidence limit about the predicted average would be ±17% of the predicted value, a far more acceptable precision of estimate. The model was only used to make estimates of average biomass across large areas (Sections 7 and 8).

Figure 6.5 shows a scatter plot of observed against predicted biomasses of coarse woody debris for those stands where coarse woody debris amounts were measured. As discussed earlier, when developing the coarse woody debris model (6.10), it was uncertain for many of the measured stands whether or not there had been disturbance of the coarse woody debris up to their age of measurement. The model assumes no disturbance has occurred. However, comparison of the results of Figure 6.5 with those of Figure 6.3 suggests that the model does make reasonable estimates of coarse woody debris biomasses in undisturbed stands, albeit with possibly a slight tendency to underestimate coarse woody debris amounts in stands with higher amounts of debris. The limitations of these data make it impossible to assess reasonably the precision of those coarse woody debris estimates.

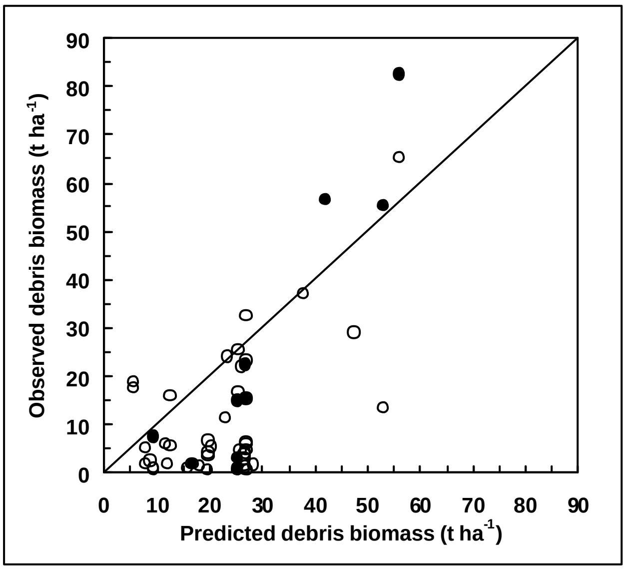

Figure 6.5 Scatter plot of the observed coarse woody debris biomasses in the measured stands against their values predicted from the model. Results are shown for stands from which it was believed coarse woody had not been removed during the lifetime of the stand (●) and for those for which it was uncertain whether or not coarse woody had been removed (O). The solid line shows where the points would lie if there was exact agreement between the observed and predicted values.

Figure 6.6 shows examples of the results obtained when the complete model system is applied in practice. It illustrates how the model predicts the time course development of firewood biomass in both live tree stems and coarse woody debris in three undisturbed stands of site productive capacities of 2, 9 and 12 t ha^{-1} yr^{-1}.

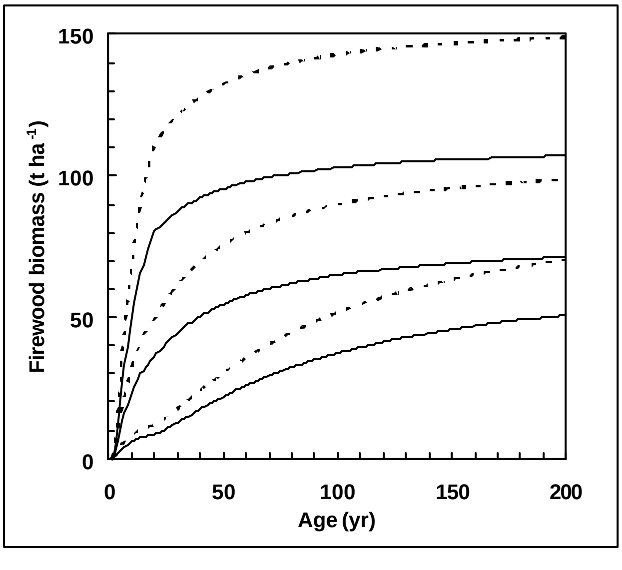

Figure 6.6. Predictions, from the complete model system developed here, for non-mallee forests of the MDB, of the change with age in the amounts of firewood biomass, in both live trees and coarse woody debris, in undisturbed stands from which no firewood is harvested. Results are shown for stands of NPP index 2 (lowest lines), 9 (middle lines) and 12 (upper lines) (t ha^{-1} yr^{-1}). For each case, the solid line shows live tree firewood (stem and branch material) and the corresponding dashed line (just above the solid line) shows live tree firewood plus coarse woody debris firewood, so the difference between the two is coarse woody debris firewood.

Figure 6.7 shows predictions from the model, for a stand of NPP index 12 t ha^{-1} yr^{-1}, of the firewood biomass remaining both in the live trees in the stand and the coarse woody debris when the stand was thinned by removal of 50% of the live tree above-ground biomass at 55 and 105 years of age and when all available coarse woody debris was harvested from the stand every 10 years between 20 and 150 years of age. The decline in firewood remaining in the stand after each thinning and coarse woody debris harvest is apparent. For this stand, the model estimated that 86 t ha^{-1} of firewood would have been harvested from the two thinnings and 177 t ha^{-1} of firewood would have been removed over the 14 coarse woody debris harvests.

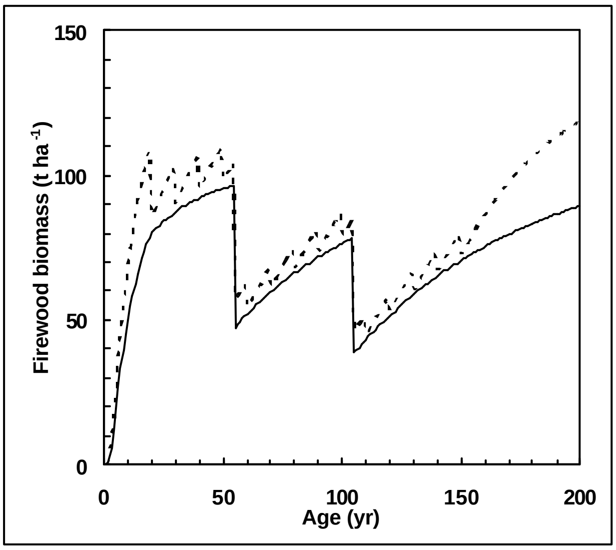

Figure 6.7. Predictions, from the complete model system, of the change with age in the amounts of firewood biomass remaining in both live trees and coarse woody debris in a stand, of NPP index 12 t ha^{-1} yr^{-1}, from which firewood was removed by thinning at 55 and 105 years of age and from coarse woody debris every 10 years between 20 and 150 years of age. The solid line shows live tree firewood (stem and branch material) and the dashed line shows live tree firewood plus coarse woody debris firewood, so the difference between the two is residual coarse woody debris firewood.

Because no data were measured here from stands which had been thinned, or for which the history of coarse wood debris removal was known, it is impossible to test, by formal comparison with observed data, the validity of results such as those shown in Figure 6.7. However, the structure of the complete model system is such that total production of biomass predicted by the model for such a stand is the same as it would be if the stand was unthinned and had no coarse woody debris removed from it at any age.

6.8 Growth and firewood yield of mallee forests

Mallee eucalypts have multiple stems which arise at ground level from a large lignotuber. They occur extensively in the drier parts of the MDB (National Forest Inventory 1998, page 49) and generally grow to only 2-10 m in height. Mallee forests in South Australia have been cut regularly for firewood for many years. Some mallee forests in Victoria and NSW are exploited for firewood and charcoal. Their growth habit is so different from that of the other forests of the MDB, that their growth and yield was considered here separately from that of non-mallee forests.

Neagle (1994) reported on the wood yields and management practices used in mallee forests in South Australia. A simple, clear-felling system is used to manage mallee forests for firewood production. Regeneration from lignotubers is usually satisfactory following the clear-felling. Clear-felling seems to be restricted generally to stands aged in the range 20-100 years. Figure 6.8 shows a scatter plot of firewood biomass yields for mallee forests in relation to stand age as reported by Neagle (1994). For the present work, it was found that a suitable model system to predict those yields would be:

$$B_F(A) = 8.91 + 0.274A \qquad \text{(if } A<59\text{)} \qquad (6.23a)$$

and:

$$B_F(A) = 25.1 \quad \text{if } A \geq 59 \qquad (6.23b)$$

where $B_F(A)$ is stand biomass of firewood (t ha^{-1}) at age A (years). The fit to the data of this model is shown on Figure 6.8.

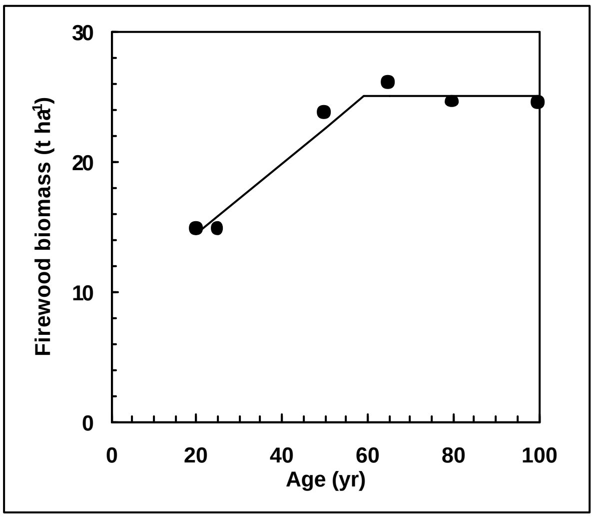

Figure 6.8. Yields of firewood (●) obtained from clear-felling mallee forests of different ages in South Australia, as reported by Neagle (1994). The fit to the data of model (6.23a,b) is shown also (———).

6.9 Model Applications

The application of these models of forest growth and yield to the scenarios is described in subsequent sections of this report. Sections 7 and 8 describes the application of the models to the dead-wood and green-wood scenarios respectively. Section 10 describes the application of a previously published model to predict the areas of the MDB that would need to be put under native hardwood plantation to meet the demand for firewood from the MDB.