7 The dead-wood scenario

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7.1 Summary

This Section estimates the maximum, long-term sustainable supply of firewood available from the privately owned, native forests of the MDB under a "dead-wood scenario". This scenario involved firewood harvest only of the coarse woody debris. Such a scenario is relevant only to non-mallee forests of the MDB; where mallee forests are used as a source of firewood it is obtained by felling live trees.

It was estimated there are 12.3 million (M) hectares of non-mallee forest in the MDB suitable for harvesting under the dead-wood scenario. It was considered that an appropriate firewood harvest management regime for these forests would involve about 30 harvests of woody debris over the lifetime of any stand, at intervals of 5-10 years and with the first harvest occurring at 20-25 years of age. Over the next 100 years, it was estimated that the maximum annual sustainable supply of firewood (oven-dry biomass) from the MDB under this scenario would average 10 million tonnes per year (M t yr^{-1}), with a deviation in any year from this amount of no more than 1.1 million tonnes (M t). This is far more than the amount of firewood harvested presently from the MDB, which is believed to be within the range 2-2.5 M t yr^{-1}. It was estimated that as little as 3 M ha of the forests could be sufficient to meet the existing supply. If the maximum 10 M t yr^{-1} of firewood was harvested, it was estimated that the long-term average amount of woody debris which would remain in the forest after firewood harvesting would be 3 tonnes per hectare (t ha^{-1}), far less than the average 20 t ha^{-1} it was estimated that would remain if there was no firewood harvesting. This loss of woody debris might have consequences for the biodiversity of the region by reducing the availability of debris for floral, faunal and other ecosystem processes which contribute to sustainable landscape function.

7.2 Introduction

Based on information in Driscoll et al.(2000), it may be concluded that 2-2.5 M t yr^{-1} of firewood[3] are supplied annually at present from the privately owned native forests of the MDB (see Section 2, Figure 2.1). It is believed that most of this wood is harvested from the coarse woody debris (defined here as stem and branch wood of dead standing trees and pieces of fallen wood with length ≥0.5 m and mid-diameter ≥10 cm), although principally from fallen material rather than from dead standing trees. However, it is believed also that at least some firewood comes at present from felling live trees and some may come from trees removed in land clearing.

Concern was expressed in Driscoll et al's report that the removal of woody debris from these ecosystems may have important consequences for the biodiversity of the MDB. They suggested (page 3) that *"[o]f particular concern are probable effects on ecosystem processes such as nutrient cycling and plant establishment, because of the potential loss of highly specialised species of invertebrates and fungi."* As well, they suggested that loss of woody debris might deprive some faunal species of their necessary habitat.

[3] Note that all weights of firewood, coarse woody debris and plant biomass referred to in this report are oven-dry weights.

7.3 Sustainable yield prediction

The task of a manager responsible for a large area of forest is to determine how it should be managed to ensure a long-term, sustainable supply of the "products" obtained from that forest. The products may vary widely, from the commercial supply of timber to the maintenance of environmental qualities, such as biodiversity. In the context of this Section, the forest to be considered consists of the privately owned, non-mallee, native forests of the MDB and the products to be obtained from it are:

1. firewood, obtained by harvesting coarse woody debris; and
2. the woody debris remaining in the forest as a contributor to the maintenance of biodiversity.

Turner et al.(2002) summarised the issues faced and the approach generally taken by forest managers to achieve this management task in Australian forests. In general, the approach involves:

a) Development and application of a forest growth and yield model system to predict the amounts of the desired products available from any stand in the forest, at any time in the future, when any particular management regime is applied;

b) Determination of the total area of the forest and stratification of that area by those characteristics which are likely to affect its ability to supply the products (characteristics such as forest type or productive capacity);

c) Choice of a possible set of management regimes which could be applied to any stand in the forest to produce the products; and

d) Prediction of the long-term, sustainable supply of the products available (usually annually) from the entire forest area, under any management regime considered appropriate. This last step involves using the information determined in the three preceding steps. Further, determination of the sustainable supply of products often involves application of a mathematical programming system to determine what areas of which strata of the entire forest area should be managed with which of the possible management regimes which could be applied to any stratum.

This approach was used in the present Section. Section 6 describes the growth and yield model developed by this project to predict both firewood availability from coarse woody debris and the amount of residual woody debris in non-mallee forests of the MDB. The remaining three elements of the approach will be considered in turn below.

7.4 Forest area and stratification

The data for the scenario was derived using the GIS described in Section 4. Full details of the information available to this project on the area of privately owned native forests in the MDB and their stratification by the overall exploitation criteria (Section 3.1) are described in Sections 4.3.1 and 4.3.2. The additional exploitation criteria necessary to derive a final stratification of the forest suitable to apply for the dead-wood scenario are described in Section 3.2, and their application to the data to derive the final stratification are detailed in Sections 4.3.3 and 4.3.4. These considerations are summarised below.

The dead-wood scenario applies only to the non-mallee forest of the MDB. Hence, the first step in forest stratification for the dead-wood scenario was to separate mallee and non-mallee forest areas.

Secondly, the dead-wood scenario was confined to native hardwood forests which were not plantations (Section 3.2, exploitation criteria 4 and 5) of the MDB (Section 3.1, exploitation criterion 1) on private land (exploitation criterion 3) located within 500 km of a capital city (Section 3.1, exploitation criterion 2); it was assumed that it was not economically feasible to transport firewood further than this. Using the GIS system described in Section 4, there were found to be 12.3 M ha of such forest (Sections 4.3.3 and 4.3.4, Table 4.7 and Table 7.1).

Thirdly, this 12.3 M ha of forest was stratified by site productive capacity (Sections 4.3.3 and 4.3.4), as defined by the net primary productivity (NPP) index of Barrett (2002) (expressed as tonnes of plant biomass/hectare/year: t ha^{-1} yr^{-1}). This index has been described and discussed in detail in Section 6.4 and Appendix 5. The stratification method is described in Section 4.3.3 and the complete stratified dataset is presented in Appendix 6, Table 8. Figure 7.1 shows the distribution of the 12.3 M ha of forest in relation to site productive capacity.

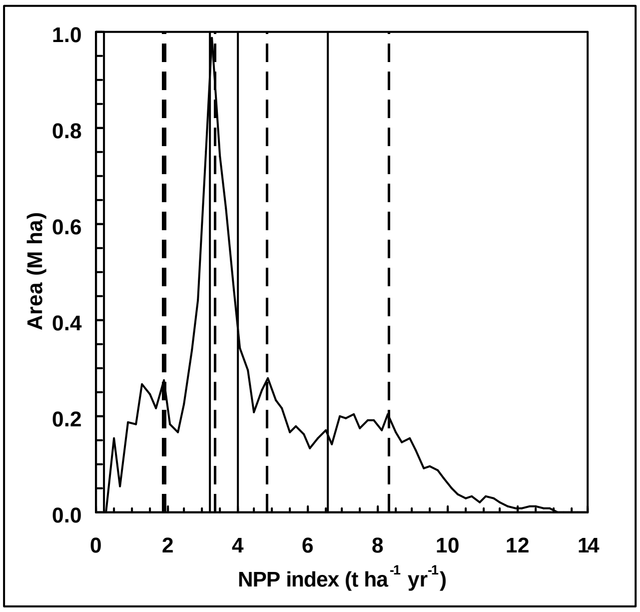

Figure 7.1. Distribution of the 12.3 M ha of forest considered eligible for firewood harvest under the dead-wood scenario in relation to site productive capacity (net primary productivity index). The ranges of the four productivity classes, defined later in this Section, are shown (——), together with their weighted average productive capacities (- - - -) (see Table 7.1).

The fourth step in the stratification was to split the 12.3 M ha of forest into four classes of site productive capacity of roughly equal forest area. It was decided to restrict the number of classes to four principally to reduce the amount of computation necessary subsequently to determine firewood yields from these forests. The weighted average (weighted by the areas within each class of different productive capacities) site productive capacity of each of these four classes was then determined. The results are shown in Table 7.1. The area of those classes and their weighted average productivities are indicated also on Figure 7.1.

Table 7.1. The site productive capacity classes (based on NPP index) defined here are shown, together with their areas and their weighted average productive capacities For forest eligible for the dead-wood scenario,.

Productivity Class	**NPP index class ($t\ ha^{-1}\ yr^{-1}$)**	**Area (M ha)**	**Weighted average NPP index ($t\ ha^{-1}\ yr^{-1}$)**
1	0.2 - 3.2	2.95	1.9
2	3.2 - 4.0	3.12	3.4
3	4.0 - 6.6	3.09	4.9
4	6.6 - 14.0	3.12	8.3

The sixth and final step in the stratification was to consider the age-class distribution of the forests (age of a stand being defined as the time elapsed since its regeneration from bare ground). Age stratification was necessary to allow application of the growth and yield model. Little information was available to do this reliably. However, it is believed (Turland 2003) that a large proportion of the forests of the MDB regenerated around the turn of the 20th century, when several mild summers occurred following wet winters, coupled with removal of grazing pressure following drought in the 1870s and the rural depression of the 1880s. There was a second period of regeneration in the 1950s following eradication of rabbits. Given this, and from observations by the authors of this report of the forests of the MDB, it was assumed that in 2004, 40% of their area would be aged 50-60 yr, 50% would be 100-120 years and 10% would be 150-178 yr. Further, it was assumed that forest areas were distributed evenly in each annual age-class across these periods.

This stratification process led to subdivision of the 12.3 M ha of forest deemed appropriate to harvest for firewood in the dead-wood scenario into a total of 244 strata. Appendix 10 lists the area of each of those strata. Map 26 (Appendix 4) shows the distribution across the MDB of the 12.3 M ha of non-mallee forests of the MDB deemed suitable for firewood harvest under the dead-wood scenario. The area has been stratified by site productive capacity class as defined in Table 7.1.

7.5 Firewood harvest management regimes

Firewood collection from coarse woody debris is a relatively benign harvest practice. It causes only minor site disturbance from vehicle access. It has no effect on the subsequent growth behaviour of the live trees in the forest. However, it does affect the amount of woody debris remaining in the forest for maintenance of biodiversity, which is of concern in the present project.

For the present Section, it was felt, somewhat arbitrarily, that the only constraints which needed to be applied to harvest management for firewood collection from coarse woody debris were:

a) any one harvest in any stand would not be worth undertaking unless it yielded at least 1.5 t ha^{-1} of firewood; this was considered the minimum amount that it would be worthwhile collecting commercially. Furthermore, it was assumed that as much as possible of the firewood available from coarse woody debris would be removed at any harvest;
b) the first harvest in any stand would usually take place around 20-25 years of age, by which time the stand would be well developed;
c) to avoid too frequent intervention in a stand, subsequent harvests would be done at intervals of 5-10 years or delayed further until 1.5 t ha^{-1} of firewood became available; and
d) no harvests would take place after 178 years of age, the age which Barrett (2002) determined was the average life-span of forests of the region.

This will be termed the “standard regime” for firewood harvest from coarse woody debris.

Using the growth and yield model for non-mallee forests (Section 6), it was found that stands of the weighted average net primary productivity indices for productivity classes 1-4 (Table 7.1) would yield, at most, about 106, 135, 145 and 180 t ha^{-1} of firewood, respectively, when woody debris was harvested from them over their lifetime using this standard regime. In each case, this involved about 30 harvests over the lifetime of each stand.

7.6 Long-term firewood yields

7.6.1 Method of determining yields

Given the considerations of Sections 7.4 and 7.4, attempts were made to estimate the availability of firewood from, and residual amounts of coarse woody debris in the MDB under the dead-wood scenario, in any calendar year from 2004 on. This was done as follows:

- Any one of the strata defined in Appendix 10 was considered.
- With the growth and yield model, annual predictions were made of (a) the coarse woody debris firewood yields available per unit area from a stand in that stratum, under any desired firewood harvest management regime; and (b) the amounts of woody debris remaining in the stand at any age. In doing so, it was assumed the stand had a site productive capacity equal to the weighted average site productive capacity for the stratum (Table 7.1). In making these yield predictions, it was assumed that stands in the MDB have an average life-span of 178 years (Barrett 2002), after which they were assumed to be destroyed (perhaps by fire or a violent storm) and then regenerate. Of course, stand destruction and renewal is a chance event and it is not to be expected that any stand will be destroyed and renewed at exactly 178 years of age. To allow for this, the age to which any stand was grown was chosen at random within the range 165-191 yr, a range chosen arbitrarily for the present work.
- Given the age of the stratum in 2004, the firewood harvest yields and residual woody debris amounts per unit area for a stand in that stratum in any calendar year from 2004 on were determined. In doing so, consideration had to be given to the life of a stand beyond the age that it was assumed to be destroyed and regenerated. For example, a stand aged 110 years in 2004 would, if it survived to 178 years of age, be destroyed in 2072 and then regenerate. Where this occurred, it was assumed that the regenerated stand was entering a second "rotation" when it was 1 year of age in 2073. It would then continue to be grown, assuming that the firewood harvest management regime which applied in the first rotation was applied also in the second rotation. The age for destruction of the second rotation was chosen randomly, again in the range 165-191 yr. This process was repeated for as many rotations as desired. It was assumed that any residual woody debris present in a stand at the time of its destruction was lost before its second rotation started.
- It was assumed that the weighted average site productive capacity assigned to the stratum applied to the entire area of that stratum. Firewood yields from coarse woody debris and residual woody debris amounts in any calendar year from 2004 on were determined for the whole stratum by multiplying the unit area stand amounts by the stratum area.
- This process was repeated for all 244 strata and the results were summed across all strata to obtain the total firewood yield and residual woody debris amounts for the entire MDB, in any calendar year from 2004 on.

7.6.2 Woody debris remaining after firewood harvest

Given the process described in the preceding section, estimates were made of the amount of coarse woody debris which would remain, over each of the next 400 years, in the 12.3 M ha of the forests of the MDB deemed appropriate for the dead-wood scenario, with or without firewood harvest. The upper line in Figure 7.2 shows the results if there was no harvest of firewood and the lower line shows the results if harvests were done using the standard regime defined above. Note that the results are shown as unit area amounts of woody debris, averaged over the entire 12.3 M ha.

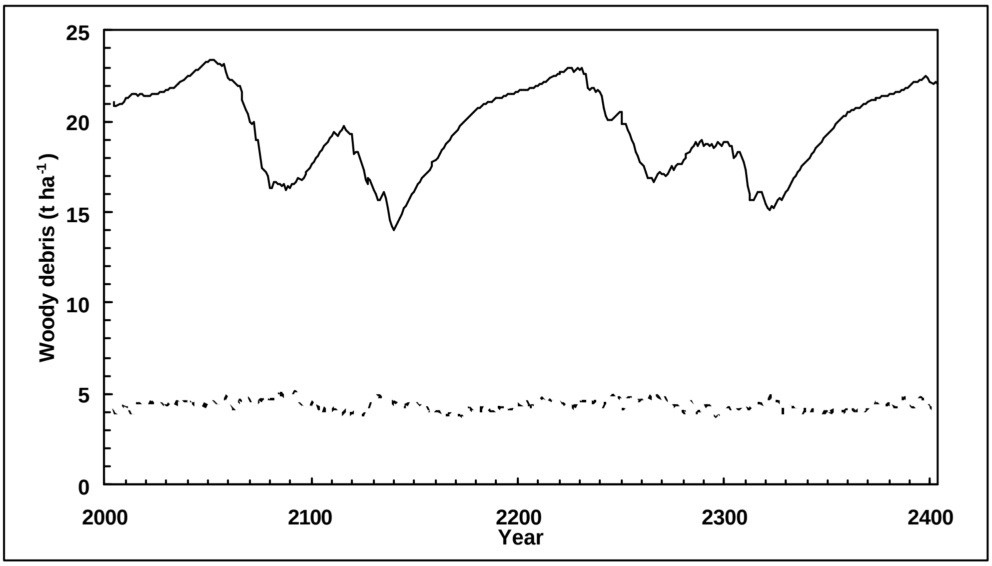

Figure 7.2. Estimates of the amounts of coarse woody debris remaining in the forest, annually over 2004-2403, averaged over the 12.3 M ha of the MDB considered for firewood harvesting under the dead-wood scenario. The graph shows the results where there was no harvesting of firewood from woody debris (______) and where firewood was harvested using the standard harvest regime described in the text (- - - -).

The results show that, without firewood harvesting, the amount of residual woody debris would vary widely over the next 400 years in a cyclic fashion. The amounts would vary from just over 21 t ha^{-1} in 2004, to maxima of about 23 t ha^{-1} in 2053 and 2230 and minima of about 14-15 t ha^{-1} in 2140 and 2321. The average over the 400 years would be 20 t ha^{-1}. This cyclical rise and fall reflects the assumed distribution of age-classes of the forest of the MDB. Of course, natural or man-induced events over the next 400 years will undoubtedly lead to changes in the distribution of age-classes, with consequent changes in the cycles of the amounts of woody debris remaining in the forest. However, the results illustrate that the uneven age-class distribution of the forests will lead to substantial variation in the availability of woody debris for maintenance of biodiversity and landscape function from time to time in the future.

With firewood harvesting under the standard harvest regime, the results of Figure 7.2 show there would still be a cyclic variation in the amount of woody debris remaining, as was the case without firewood harvest. However, the variation would be much less, from maxima of about 5 t ha^{-1} to minima of just over 3.5 t ha^{-1}. The average over the 400 years would be 4.4 t ha^{-1}. These results make clear the extent to which the removal of firewood from the entire 12.3 M ha would affect the amount woody debris left in the MDB for the maintenance of biodiversity and landscape function.

It is of interest also that the amounts of woody debris remaining in the forests would differ substantially between the different productivity classes. Table 7.2 illustrates this. It shows estimates of the minimum and maximum values of woody debris which would remain, with and without firewood harvest, at any time over the next 400 years, together with the average over the entire 400 years. The last row of the table shows results averaged across the entire 12.3 M ha of forest and is taken directly from the information in Figure 7.2. Similar results are shown for the areas of forest of different productive capacity. The steadily increasing amounts of woody debris present in more productive forest are seen clearly in the table.

Table 7.2. The minimum-average-maximum amounts of coarse woody debris (t ha^{-1}) remaining, without and with firewood harvesting of woody debris, over the next 400 years in the 12.3 M ha of the MDB considered for firewood harvesting under the dead-wood scenario. Results are shown separately for forests of different productivity classes and for the entire forest area.

Productivity class	Unharvested	Harvested
1	9 - 14 - 17	2 - 3 - 4
2	12 - 18 - 23	3 - 4 - 5
3	14 - 20 - 24	3 - 4 - 6
4	19 - 25 - 29	4 - 6 - 8
All Classes	**14 - 20 - 23**	**4 - 4 - 5**

7.6.3 Firewood harvest yields

Figure 7.3 shows estimates of the annual harvest of firewood, from the entire 12.3 M ha of forest, under the standard harvest regime. The corresponding (unit area) amounts of woody debris that would remain in the forest after this harvesting were given by the dashed line in Figure 7.2.

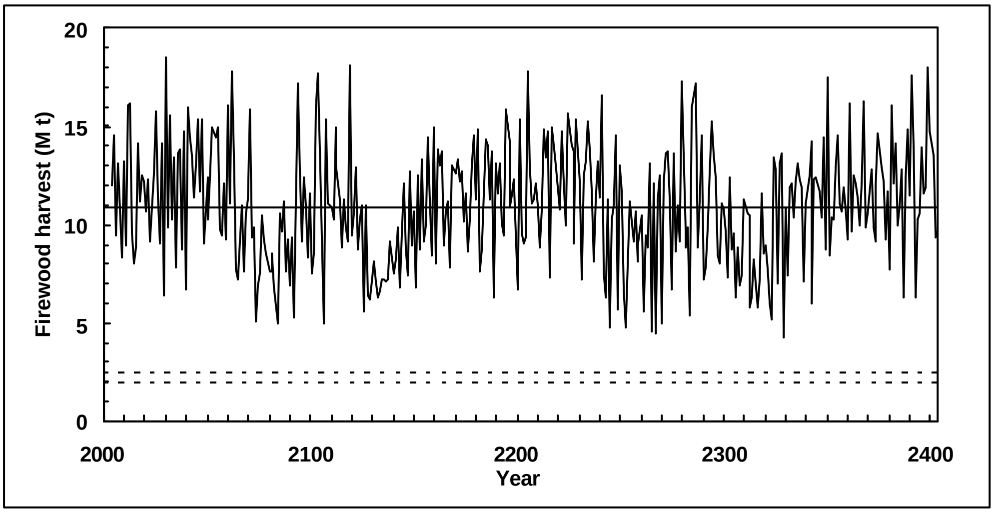

Figure 7.3. Estimates of the amounts of firewood which could be harvested from coarse woody debris, annually over 2004-2403, from the 12.3 M ha of the MDB deemed suitable for firewood harvesting under the dead-wood scenario. The results assume that the entire area was harvested using the standard harvest regime. The two horizontal dashed lines indicate the range of the estimated amount of firewood currently harvested from the MDB. The solid horizontal line is the average of all the annual estimates.

Several things are apparent from Figure 7.3. Firstly, the amount of firewood which could be harvested annually would vary in a cyclic fashion, as a consequence of the uneven age-class distribution of the forests of the MDB. The periods of greater and lesser availability of firewood correspond to the cyclic trends apparent for the residual woody debris shown in Figure 7.3.

Secondly, superimposed on this cyclic change in firewood harvest is a high degree of year-to-year variation in the amount of firewood harvested. This represents chance variation in the years it was chosen that harvests should occur in any one stratum; in deriving these estimates, decisions were made randomly as to which year within the 20-25 years age range the first harvest was made in a stand and when within the 5-10 years range each subsequent harvest occurred. Such an irregular supply from year to year would be inappropriate for the firewood industry, which would expect to supply more or less the same amount from year to year. Attempts to determine how the forests of the MDB should be managed to achieve this smoothing of the annual supply are described in the next Section.

Thirdly, it appears there would be no difficulty in supplying the 2-2.5 M t that previous work (Driscoll et al.2000) has suggested is consumed annually at present from the MDB. The average annual supply determined from the data in Figure 7.3 is 10.9 M t yr^{-1}.

7.7 Sustainable firewood supply over the next 100 years

The previous section has determined the annual supply of firewood which might be obtained, over the next 400 years, from the MDB under the dead-wood scenario under the standard harvest regime (Figure 7.3).

The results of Figure 7.3 suggest the supply would vary greatly from year to year, for reasons discussed in the previous section. In practical terms, the firewood industry would expect to supply a more or less constant amount of firewood annually from the MDB, to meet customer demand. Furthermore, the previous results were calculated annually for the next 400 years. Again in practical terms, the firewood industry would be unlikely to consider its future this far ahead. As well, social and natural events will inevitably alter substantially the circumstances of the forests of the MDB over a period this long.

With these practical considerations in mind, an attempt was made to determine the maximum, constant annual supply of firewood from the MDB under the dead-wood scenario for the next 100 years. This is still quite a long planning period, but at least it is reasonably foreseeable in human terms; forest managers of the MDB would be likely to reassess the results obtained here from time to time as both the firewood industry changes with time and as the circumstances of the forests of the MDB change. Figure 7.4 shows the results of annual firewood harvest yields from the MDB as in Figure 7.3, but only for the next 100 years.

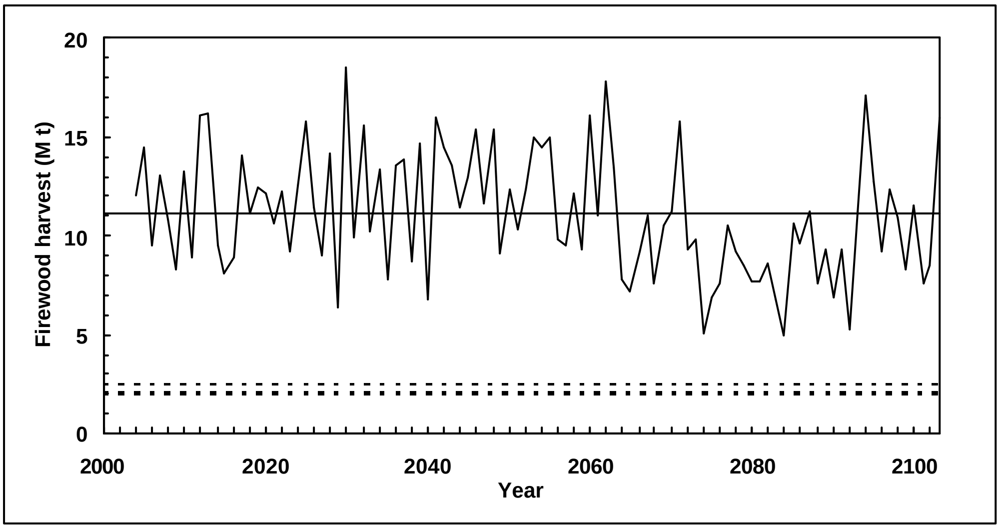

Figure 7.4. Estimates of the amounts of firewood which could be harvested from woody debris, annually over 2004-2103, of the 12.3 M ha of the MDB considered for firewood harvesting under the dead-wood scenario. The entire area was harvested using the standard harvest regime described earlier in the text. The two horizontal dashed lines indicate the range of the estimated amount of firewood currently harvested from the MDB. The solid horizontal line is the average of all the annual estimates of yield.

The average annual harvest of the results in Figure 7.4 is 11.1 M t yr^{-1}, but with variation from year to year over the range 5-18 M t yr^{-1}. Much of this year-to-year variation simply reflects chance selections of which year a harvest was carried out in any particular stratum of the forest. To smooth this annual variation will require that options be considered for the harvest times in different parts of any stratum.

It is also apparent from Figure 7.4 that harvests tend to be below average in the later part of the 100 year period, say over 2071-2093, and above average over the mid-part of the period, say over 2046-2064; these trends correspond to the cyclic trends apparent in Figure 7.3. To smooth this longer term variation will require that options be considered for delaying some of the harvests in the mid-part of the period to the later part.

Smoothing annual variations in harvest flows is a common problem faced by forest managers responsible for a large forest resource. The smoothing is usually achieved by considering, for each stratum of the forest, a number of options for the management of that stratum. These options allow variation both in the timing of harvests from the stratum and the amount of wood which is removed at each harvest. For any one stratum, different parts of its total area might then be managed using each of these options, so that, over all the strata, a smooth annual wood flow is achieved from the entire forest area. This is usually a crucial part of the process of ensuring that long-term management of forests produces a sustainable supply of the products obtained from them.

Of course there is an almost infinite number of harvest management options that could be considered as possibilities to apply in any stratum of the forest. Further, it is obviously very complex to determine which of those options should be applied to what proportion of the total area of each stratum, to achieve the required smoothing of supply. Usually, these issues are dealt with in forestry by applying a mathematical programming system. Such a system was developed here to attempt to determine how the forests of the MDB should be managed to achieve a smooth annual firewood supply over the next 100 years, under the dead-wood scenario. The system is described in the next section.

7.7.1 Mathematical programming system

A linear mathematical programming system was developed as follows. Table 7.3 lists the symbols used in this system and their meanings.

Table 7.3. Symbols used in the linear programming system and their meanings.

Symbol	Units	Meaning
A_i	ha	Area of the i^{th} (i=1...s) stratum of the forest.
A_{ik}	ha	Area of the i^{th} (i=1...s) stratum which is managed with the k^{th} (k=1...r_i) of the firewood harvest management regimes considered as possibilities to apply in that stratum over the planning horizon.
F_{ijk}	t ha^{-1}	Weight of firewood removed at harvest from the area of the i^{th} (i=1...s) stratum which is managed with the k^{th} (k=1...r_i) of the firewood harvest management regimes, considered as possibilities to apply in that stratum, during the j^{th} (j=1...h) year of the planning horizon.
h	yr	Length of the planning horizon (=Y_H-Y_I+1).
r_i	-	The number of firewood harvest management regimes considered as possibilities to apply in the i^{th} (i=1...s) stratum.
S	t	The total weight of firewood to be supplied annually from the entire forest area by firewood harvest.

Symbol	Units	Meaning
s	-	The number of strata into which the total forest area has been divided.
Y_I	-	The calendar year of the start of the planning horizon (assumed to start on 1st January of this year).
Y_H	-	The calendar year of the end of the planning horizon (assumed to end on 31st December of this year).
ρ	-	The proportion by which the supply of firewood from the entire forest area may vary from year to year over the planning horizon.

Suppose that the annual firewood supply from the MDB is to be considered over some planning horizon of length h year. For the present case, h=100 years, extending from the 1st of January of calendar year Y_I (=2004) until the 31st December of calendar year Y_H (=2103). Suppose the total area of forest to be harvested for firewood was subdivided into s strata and the area (ha) of the i^{th} stratum (i=1...s) was A_i (ha). For the present case, s=244 and the values of the A_i are given in Appendix 7.1.

Now, suppose that r_i firewood harvest management regime options were considered as possibilities to apply to all or part of the i^{th} stratum and that an area A_{ik} (ha) of that stratum was then actually harvested with the k^{th} (k=1...r_i) of those options. Suppose further that the weight (t ha^{-1}) of firewood which was harvested from a stand in the i^{th} stratum (i=1...s) during the j^{th} year of the planning horizon (j=1...h), if treated with the k^{th} management regime (k=1...r_i), was F_{ijk} (t ha^{-1}).

The objective of the linear programming system was then to determine what area of each stratum should be treated with which of the possible management regimes for that stratum to achieve the maximum possible supply of firewood from the MDB over the entire planning horizon. That is, the objective function of the system was,

$$\text{Maximise} \quad \sum_i \sum_k [A_{ik}(\sum_j F_{ijk})] \qquad (7.1)$$

where the A_{ik} are the unknowns to be determined by the system. Note that the summations in expression (7.1) and in the equations below are for i=1...s, j=1...h and k=1...r_i.

However, this maximum firewood supply would be limited by two constraints as follows:

a). The sum of the areas treated with the various possible management regimes in any stratum must equal the total area of that stratum. That is, there are s constraints of the form:

$$\sum_k Aik = Ai \qquad (i=1...s) \qquad (7.2)$$

b). To ensure a more or less constant supply of harvested firewood from the entire MDB annually, it was assumed that the supply in any year should be within some proportion (ρ) of a constant amount S (t). This led to h constraints in the system of the form:

$$(1+\rho)S \geq \sum_i \sum_k (Aik\ Fijk) \geq (1-\rho)S \qquad (j=1...h) \qquad (7.3)$$

The next stage in developing the system was to choose the management regime options for each stratum. Varying the number and timing of harvests in a simple fashion in any stratum, consistent with the variation allowed in the definition of the standard regime, would permit satisfactory solutions to be obtained by the linear programming system. Accordingly, eight possible harvest management regimes were selected as possibilities for each stratum (that is, r_i=8 for all i=1...244).

The first possibility was that there was no firewood harvest at all from the stratum over the entire planning horizon. Each of the remaining seven possibilities was based on the standard harvest regime. The length of each rotation of the stratum was selected randomly with the range 161-195 years of age. The age at which the first harvest was done in each rotation was chosen randomly from within the range 20-25 years of age. The number of harvests to be done in each rotation was then chosen randomly within the range 20-40, with no harvest being allowed to occur after 178 years of age if the rotation lasted that long. The harvests were then spaced approximately equally over the chosen harvest period. However, the exact timing of any harvest was chosen randomly within ±1 year of the time of exactly equal spacing of harvests, subject only to delaying any harvest until at least 1.5 t ha^{-1} of firewood was available from it.

Firewood harvest yields for any of those regimes in any stratum (the F_{ijk} in the linear programming system) were then estimated using the growth and yield model (Section 6). Many more than eight options could have been used in any stratum. The more options available, the more likely it is that the linear programming system will be able to solve the system successfully and determine the maximum possible supply of firewood available from the MDB. However, as more options are considered, the larger becomes the problem to be solved, until the limits of computer resources are reached, in terms of both the amount of memory required and the computation time. For this project, the choice of eight regime options was found to lead to what appeared to be reasonable solutions to the system, with reasonable computing effort. This is not to say that better solutions than those achieved here could not be obtained by enlarging the number of management options available for each stratum.

Solutions to the linear programming system were obtained using the simplex method, as implemented in the MINOS suite of computer programs for solving large, complex mathematical programming problems (Murtagh and Saunders 1978, 1983).

7.7.2 Sustainable firewood supply

The linear programming system was applied with a number of different values of S (the annual yield of firewood from the entire MDB) and ρ (the proportion about S by which the yield in any year was permitted to vary). If S is too large, then the MDB may not contain sufficient forest area to yield that amount of wood annually and no solution will exist to the linear programming problem. If ρ is too small, then the linear programming system may be unable to find a solution to achieve that degree of smoothing of the annual supply.

After many runs of the system, it was found that with ρ=0.1 (that is the annual supply did not differ by more than ±10% in any year), a solution to the linear programming system could be obtained only when S was no larger than 9.9 M t yr^{-1}. The annual supply of firewood from the MDB, with this solution, is shown in Figure 7.5. Those results may be compared directly with those of Figure 7.4, where no smoothing of the annual supply was attempted.

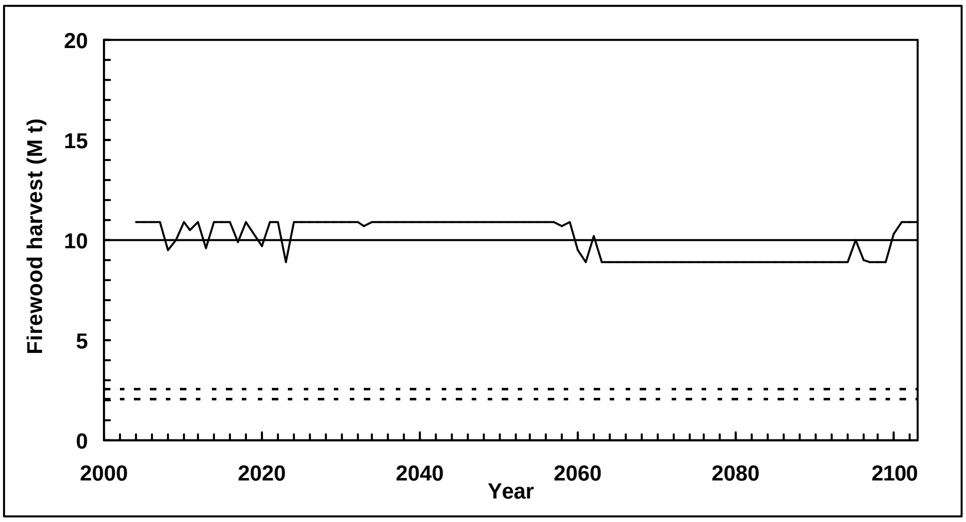

Figure 7.5. Estimates of the maximum amounts of firewood which could be harvested from woody debris, annually over 2004-2103, of the 12.3 M ha of the MDB deemed suitable for firewood harvesting under the dead-wood scenario. The graph shows the results where the annual firewood supply from the MDB was kept more or less constant from year to year. The two horizontal dashed lines indicate the range of the estimated amount of firewood currently harvested from the MDB. The solid horizontal line is the average of all the annual estimates of yield.

The average annual supply for the results in Figure 7.5 was 10.0 M t yr^{-1}. The smoothing constraints included in the linear programming system ensured that the annual amount never varied outside the range 8.9-10.9 M t yr^{-1}. There is little point in showing here the extremely lengthy details of the solution to the linear programming problem (i.e. the detail of exactly how much of the area of each of the 244 strata should be treated with exactly which harvest management regime). However, the solution found that none of the entire 12.3 M ha would be unharvested and 5.3 M ha would have been part of strata in which more than one of the possible management regimes would need to have been applied to achieve the smoothing of the annual yield. It is of interest also to compare the proportions of the firewood supply derived from forests of different productive capacity classes. Of the annual average of 10.0 M t yr^{-1}, about 1.8, 2.4, 2.6 and 3.2 M t yr^{-1} were obtained from forest of productivity classes 1-4, respectively.

7.7.3 Residual woody debris

Figure 7.6 shows estimates of the unit area amounts of woody debris remaining in the forest, annually over 2004-2103, with the firewood harvesting done to obtain the solution to the linear programming system. Also shown are the results if firewood harvesting was done using the standard harvest regime, without smoothing of the annual supply of firewood; these latter results are those for the first 100 years shown in Figure 7.3.

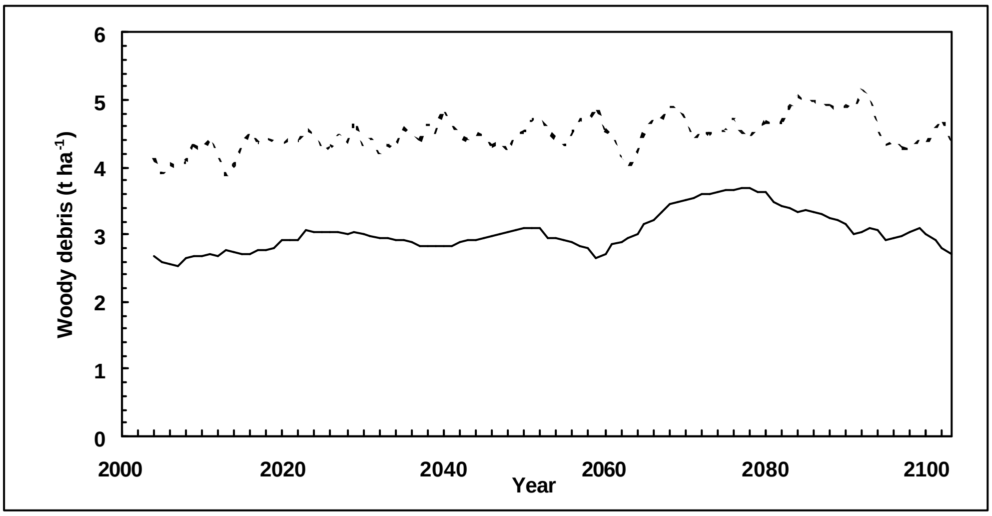

Figure 7.6. Estimates of the amounts of woody debris remaining in the forest, annually over 2004-2103, averaged over the 12.3 M ha of the MDB considered for firewood harvesting under the dead-wood scenario. The graph shows the results where the annual firewood supply from the MDB was kept more or less constant from year to (________) and where firewood was harvested using the standard harvest regime without any smoothing of the annual supply (- - - -).

The average residual woody debris over the 100 years in the data of Figure 7.6 is 3.0 t ha^{-1} (varying from year to year in the range 2.5-3.7 t ha^{-1}) with smoothing of the annual supply and 4.5 t ha^{-1} (varying in the range 3.9-5.2 t ha^{-1}) without smoothing. These results suggest that the more regular harvesting involved with the smoothed supply allows less accumulation, on average, of woody debris between harvests. These averages are both far less than the corresponding average of 20 t ha^{-1} (varying in the range 16-23 t ha^{-1}) for unharvested stands, over the first 100 years of the data shown in Figure 7.3.

7.8 Discussion and conclusions

The purpose of the dead-wood scenario was to estimate the maximum, long-term sustainable supply of firewood available from the privately owned, native forests of the MDB. We wished to examine the long-term feasibility of a continued reliance on coarse woody debris as the sole source of firewood to meet the current demand of 2-2.5 M t yr^{-1} from the MDB. We estimated that the long term supply from coarse woody debris (10 M t yr^{-1}) of far exceeds current demand. However, our model also indicates that harvesting coarse woody debris greatly depletes this important component of forest and woodland ecosystems. If the maximum 10 M t yr^{-1} of firewood was harvested, we estimated that the long-term average amount of woody debris remaining in forests after firewood harvesting would be 3 t ha^{-1}, far less than the average 20 t ha^{-1} that would remain if there was no firewood harvesting.

The ecological implications of depleting levels of coarse woody debris are discussed in detail in Section 9. Our model system (Section 6) provides, for the first time, the capability to estimate maximum levels of coarse woody debris expected in the absence of harvesting of any broad vegetation type with any given net productivity potential within the MDB. Estimating potential levels of coarse woody debris is a critical first step in assessing the ecological impacts of harvesting this important component of any forest or woodland.

Because the maximum sustainable supply estimated by our model system is much greater than current demand, it is unnecessary to use the entire 12.3 M ha of forest within 500 km of capital cities to obtain the present supply sourced from the MDB. In fact, it was found that the current demand of 2.5 M t yr^{-1} could be obtained by harvesting only the 3.1 M ha of the most productive forests in the MDB (as defined in Table 7.1 and shown in Figure 7.2). There is clearly potential to exclude large areas of the MDB from harvesting of coarse woody debris while still meeting current demand. Conversely, rather less than all the firewood available at any one harvest could be removed in order to provide the present firewood supply. The policy implications of this dead-wood scenario modelling are discussed further in Section 11.