LIFE CYCLE ASSESSMENT OF GREENHOUSE GAS EMISSIONS FROM DOMESTIC WOODHEATING

GREENHOUSE GAS EMISSIONS FROM FIREWOOD PRODUCTION SYSTEMS

BUSH FOR GREENHOUSE | SEPTEMBER 2003

Prepared for the Australian Greenhouse Office and Environment Australia
by CSIRO Forestry and Forest Products. Authors: Keryn Paul, Trevor Booth,
Anthony Elliott, Tom Jovanovic, Philip Polglase and Miko Kirschbaum.

September 2003

Australian Government
Department of the Environment and Heritage
Australian Greenhouse Office

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The authors thank:

- Joanne Halliday who managed the project for the Australian Greenhouse Office (AGO) and Annie Boutland, Denise White, and Elizabeth Dixon who managed the project for Department of the Environment and Heritage (DEH).
- Gary Richards (AGO) and David Evans (AGO) for providing access to the latest copies of the FullCAM program.
- Rob Waterworth (AGO) and Australian National University (ANU) and Cris Brack (ANU) for their guidance on the use of FullCAM.
- Julian Wall (National Parks and Wildlife Service, Coffs Harbour) who provided helpful comments to complement the very useful data included in his thesis.
- Liz Hamilton (Corangamite Farm Forestry Network) for a description of measurement of merchantable firewood volume.
- Fabiano Ximenes and David Gardner, State Forests of New South Wales (SFNSW) for information on recoveries of carbon following harvesting and milling operations.
- Doug Binns and John Fulton (SFNSW) for comments on the management of native forests and suggestions of useful information sources.
- Andrew Lang and Desmond Stackpole, Department of Natural Resources and Environment, Victoria (DNRE) and Peter Bulman (Farm Tree Systems) for information on sugar gum plantations.
- Greg Traegar (Adelaide Wholesale Landscape Supplies Pty Ltd) for data on fuel usage.
- Dan Wildy (University of Western Australia) for information on coppicing management practices and expected changes in growth rates with subsequent coppicing rotations.
- David Freudenberger and Margaret Cawsey (CSIRO Sustainable Ecosystems) for general background information on firewood use in Australia.
- Several of our colleagues at CSIRO Forestry and Forest Products, including Bob McCormack, Mike Connell, David Bush, John Raison, Peter Clinnick, Peter Snowdon and Paul Fung for useful information on a wide range of topics related to the project.
- John Raison (CSIRO Forestry and Forest Products) for providing comments on earlier drafts.

ONE

EXECUTIVE SUMMARY

Use of fossil fuels is the main cause of the increase in atmospheric CO_2, which in turn is a major cause of global warming. Sustainable firewood production systems have the potential to reduce fossil fuel use and attendant CO_2 emissions. Within a specified period of time, the net greenhouse gas (GHG) benefit of burning firewood to displace other forms of energy depends on:

(i) growth rate of the forest;

(ii) management system used;

(iii) quantity of fossil fuel required for processes such as establishment and harvesting of trees, and transporting the firewood to households, and;

(iv) efficiency with which the firewood is burnt.

The aim of this project was to use the AGO's FullCAM model to explore the effects of these factors on net CO_2 emissions from the following example firewood production systems within the 600–800 mm annual rainfall zone of eastern Australia:

(i) remnant woodland near Armidale, New South Wales that was dominated by *Eucalyptus melliodora* (yellow box) where periodic (i.e. every 5 years) collection of dead wood from the ground was contrasted to annual collection of both dead wood and dead trees;

(ii) sustainably managed native forest near Armidale, New South Wales that was dominated by *Eucalyptus laevopinea* (silvertop stringybark), where collection of harvest residues for firewood together with periodic (i.e. every 5 years) collection of dead wood from the ground was contrasted with collection of both harvest residues and the annual collection of dead wood and dead trees, and;

(iii) a new plantation of *Eucalyptus cladocalyx* (sugar gum) established on ex-farmland (i.e. afforestation) near Lismore in Victoria, where the use of thinnings and harvest residues (from a system managed primarily for sawlogs) was compared with a plantation grown using a coppice system solely for firewood production.

Comparisons of CO_2 emissions were made both within and between these systems. It was beyond the scope of this study to assess the effect of these ecosystems and their management on net emissions from other greenhouse gases, and on other environmental attributes such as biodiversity and land management for remediation of water quality and soil salinity and acidification.

The FullCAM model was used to calculate CO_2 emissions resulting from tree growth and decomposition of debris and products. In addition, emissions associated with establishment of trees and the harvest and transport of firewood were calculated. Transport distances ranging from 50 to 800 km were examined. As expected, emissions were reduced by commercial rather than small scale harvesting, and by short rather than long transporting distances.

Net emissions were calculated by adding together the net change in storage of carbon as a result of establishment of trees, changes in tree biomass, debris and harvested products, and emissions resulting from harvest and transport operations. Net emissions may be positive if less carbon is sequestered in biomass than is lost to decomposition and operations such as establishment, harvest and transport, but negative if more carbon is sequestered than lost. We calculated that when firewood was used for domestic heating, the net amount of greenhouse gas emitted per unit of heat energy produced was:

(i) 0.11 kg CO_2 $kWhr^{-1}$ when firewood was periodically collected from dead wood on the ground under woodlands;

(ii) 0.07 kg CO_2 $kWhr^{-1}$ when firewood was collected annually from both dead trees and dead wood on the ground under woodlands;

(iii) 0.03 kg CO_2 $kWhr^{-1}$ when firewood was collected from harvest residues and from the annual collection of both dead trees and dead wood on the ground under native forests;

(iv) 0.03 kg CO_2 $kWhr^{-1}$ when firewood was collected from harvest residues and from the periodic collection of dead wood on the ground under native forests;

(v) –0.06 kg CO_2 $kWhr^{-1}$ when firewood was collected from the harvested material in a coppiced plantation; and

(vi) –0.17 kg CO_2 $kWhr^{-1}$ when firewood was collected from the thinnings, slash and other material on the ground in a plantation grown for sawlog production.

It should be noted that given the many assumptions made when simulating these case studies, these results are only semi-quantitative, and as such simply provide a comparison of contrasting ecosystems and management options. However, these results do indicate that in terms of limiting net greenhouse gas emissions, firewood is generally more favourable for domestic heating than other sources of domestic heating such as gas and electricity (which generally produce at least 0.31 kg CO_2 $kWhr^{-1}$, excluding solar-, wind- or hydro- electricity), particularly when firewood was collected from the thinnings, slash and other residues of a commercially grown plantation.

However, sensitivity analysis indicated that it was quite possible that using firewood from woodlands could actually be less favourable than some other forms of domestic heating if growth rates were somewhat lower than assumed (i.e. by 30%), or if mortality of trees was slightly higher than assumed (i.e. 1.2% per year), or if the firewood was burnt in an open fireplace (with an efficiency of only 10%). Therefore it may not always be beneficial to utilise woodlands for firewood collection, particularly those woodlands that are valuable in terms of maintaining biodiversity.

In contrast, there is generally little CO_2 produced per unit of energy from burning firewood collected from harvest residues and other material from beneath a native forest, while there is actually a net sequestration of carbon per unit of energy produced from burning firewood collected from a coppiced plantation. However, collecting firewood from the thinnings, harvest residues and other material from beneath a plantation grown for sawlog production provided the greatest benefits in terms of carbon sequestered per unit of energy produced.

BACKGROUND: TERMS OF REFERENCE

Although we have an understanding of the environmental effects of unsustainable firewood collection practices, and what actions need to be taken to facilitate a more sustainable approach (ANZECC 2001), we do not have a good understanding of the greenhouse implications of different firewood collection methods. There is interest from both consumers and forest growers to know more about the greenhouse effects of growing, collecting and burning firewood.

The Australian Greenhouse Office (AGO) and the Department of the Environment and Heritage (DEH) contracted CSIRO Forestry and Forest Products to undertake a comparative life cycle analysis (LCA) of greenhouse gas emissions from wood collected in different ways and burned for domestic heating.

The specific objectives of the project were to:

(i) demonstrate the differences in net greenhouse gas emissions between collecting firewood from a remnant woodland, a sustainably managed forest and a new plantation;

(ii) describe the different effects of a range of management and harvesting practices on greenhouse gas emissions; and

(iii) assist in formulating policy within the AGO and DEH in relation to domestic firewood and firewood plantations as greenhouse sinks, and provide an improved knowledge base to encourage sustainable firewood collection practices, which could be promoted to the public.

The FullCAM model for forest carbon balances was used since this model could simulate carbon flows in tree biomass, debris, soil and products for a range of forest ecosystems and take into account different management practices.

CSIRO Forestry and Forest Products (FFP) provided multi-disciplinary expertise in modelling, growth analysis, and assessment of energy and carbon flows in industrial environments, to deliver a life cycle assessment of greenhouse gas emissions from domestic woodheating. The team from FFP who undertook this study, and their associated expertise, comprised:

Dr Keryn Paul – Research Scientist: soils, greenhouse science, and modelling

Dr Trevor Booth – Senior Principal Research Scientist: forest growth and modelling

Dr Anthony Elliott – Research Engineer: quantifying energy flows

Mr Tom Jovanovic – Experimental Scientist: forest growth

Dr Philip Polglase – Principal Research Scientist: soils, forest ecology and modelling

Dr Miko Kirschbaum – Principal Research Scientist: greenhouse science

THREE

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has identified increasing levels of atmospheric carbon dioxide (CO_2) as one of the major causes of global warming. The use of fossil fuels results in the release of CO_2 to the atmosphere at rates that vary from about 0.41 kg CO_2 $kWhr^{-1}$ for electricity produced from brown coal in Victoria, to about 0.21 kg CO_2 $kWhr^{-1}$ for electricity production from natural gas in the same area (URS 2001). Although the use of firewood also results in the release of CO_2 to the atmosphere, these emissions can be offset by the uptake of CO_2 when forests are re-grown. Therefore, sustainable firewood production systems have the potential to reduce CO_2 emissions.

Between 4.5 and 5.0 million tonnes of firewood are burned for domestic purposes in Australia every year (Driscoll *et al.* 2000). Driscoll *et al.* (2000) reported that nationally, about 23% of households use firewood, two-thirds of which are located in rural and regional areas. Furthermore, 72% of the locations from which merchants source firewood are in low rainfall forests (Driscoll *et al.* 2000).

In a review of the firewood industry in Australia, Driscoll *et al.* (2000) found that about half of the firewood used annually was collected by private individuals, mainly from private property (84%), but also from State forests (9.5%), roadsides (2.9%) and other sources (3.8%). These findings indicate that remnant woodlands on private land are perhaps the major source of timber for domestic firewood in Australia. Of the firewood that is purchased from small-scale suppliers and wood merchants, most also comes from woodlands. For example, a survey of firewood merchants in 2000 indicated that woodland was the major vegetation type given as a source of firewood after riverine forest (Driscoll *et al.* 2000). Some common woodland tree species in south-eastern Australia are *E. melliodora* (yellow box), *E. albens* (white box), *E. polyanthemos* (red box) and *E. sideroxylon* (red ironbark). Approximately 85% of such box-ironbark woodlands have been cleared since European settlement (Traill 1993), and because these trees are preferred firewood species, it is estimated that 33% of Australia's annual firewood supply is removed from the remaining stands each year (Mussared 1992). On-going high rates of removal of firewood from woodlands in Australia may have detrimental effects on biodiversity through reduction in the diversity of tree species, sizes and age-classes and thereby loss of habitat and food resources for native fauna. This is particularly a problem when dead trees and wood are removed for firewood since they often contain habitat hollows (Driscoll *et al.* 2000).

Although woodlands (and mallee) are the dominant forest type in Australia (occupying a total of about 122 million hectares) and are the most common source of firewood, there is also 42 million hectares of higher productivity native forest (80% of which are dominated by eucalypts) in Australia (AFFA 2003). Such forests on state and private land are generally utilised for sawlog, woodchips or pulpwood production. However, it is possible that firewood could be collected from fallen timber, from slash following harvesting, and from mill residues.

There are more than 1.3 million hectares of plantations in Australia (AFFA 2003). Although some of these are pine plantations (which produce poor firewood), about 0.4 million hectares are eucalypt plantations that could be utilised, at least in part, for firewood production. Parlane and Clarke (2000) estimated that 14 million tonnes of firewood could be produced as part of normal forestry operations from the 1.1 million hectares of plantations in southern Australia. Utilising residues from thinning and harvesting of eucalypt plantations grown for pulp or sawlogs in higher rainfall zones may offer the best potential source of sustainably produced firewood. However, eucalypt plantations grown for the purpose of firewood production could also be established where the rainfall is too low for pulpwood plantations. It is estimated that to supply Australia's 6 million tonnes of annual consumption of firewood from low rainfall plantations, 4 million hectares would need to be planted (Chudleigh and Zoretto 1999). The establishment of new plantations for firewood has the potential to increase Australia's greenhouse sink capacity, particularly in low rainfall areas (ANZECC 2001).

The aim of this project was to produce a LCA of greenhouse gas emissions associated with domestic woodheating, including the establishment and growth of trees, the subsequent harvest and transport of firewood, and conversion to energy. In particular the objectives were to:

(i) demonstrate the differences in net greenhouse gas emissions between collecting firewood from remnant woodland, a sustainably managed native forest and a new plantation;

(ii) describe the effects of a range of management and harvesting practices on greenhouse gas emissions; and

(iii) provide information that will assist in formulating policy within the AGO and DEH in relation to domestic firewood and firewood plantations as greenhouse sinks, and provide an improved knowledge base to encourage sustainable firewood collection practices, which could be promoted to the public.

The study used the CAMFor model that is included as an option within FullCAM (Richards 2001). CAMFor within FullCAM is hereafter referred to simply as FullCAM. The model was developed to track carbon flows in a range of ecosystems. Although empirical, it is suitable as a basis for LCA because it is a comprehensive model that accounts for changes in carbon in all forest pools including vegetation (above-ground and roots), litter, soils, and in carbon taken off-site in wood products. It also incorporates the effects of forest management such as thinning and harvesting.

In brief, FullCAM tracks net carbon change in tree biomass, debris, soil, and product pools given a user specified series of management events (Fig. 1). It takes input data for annual increments in stem volume or above-ground biomass, and uses a series of default (or system specific calibration) parameters to calculate the biomass of tree components (stem, branches, bark, foliage, coarse and fine roots). Default values for litterfall, root slough, and decomposition are also required to estimate carbon within the pools of debris and soil, while defaults for decomposition of harvested products are used to estimate the carbon stored in these products.

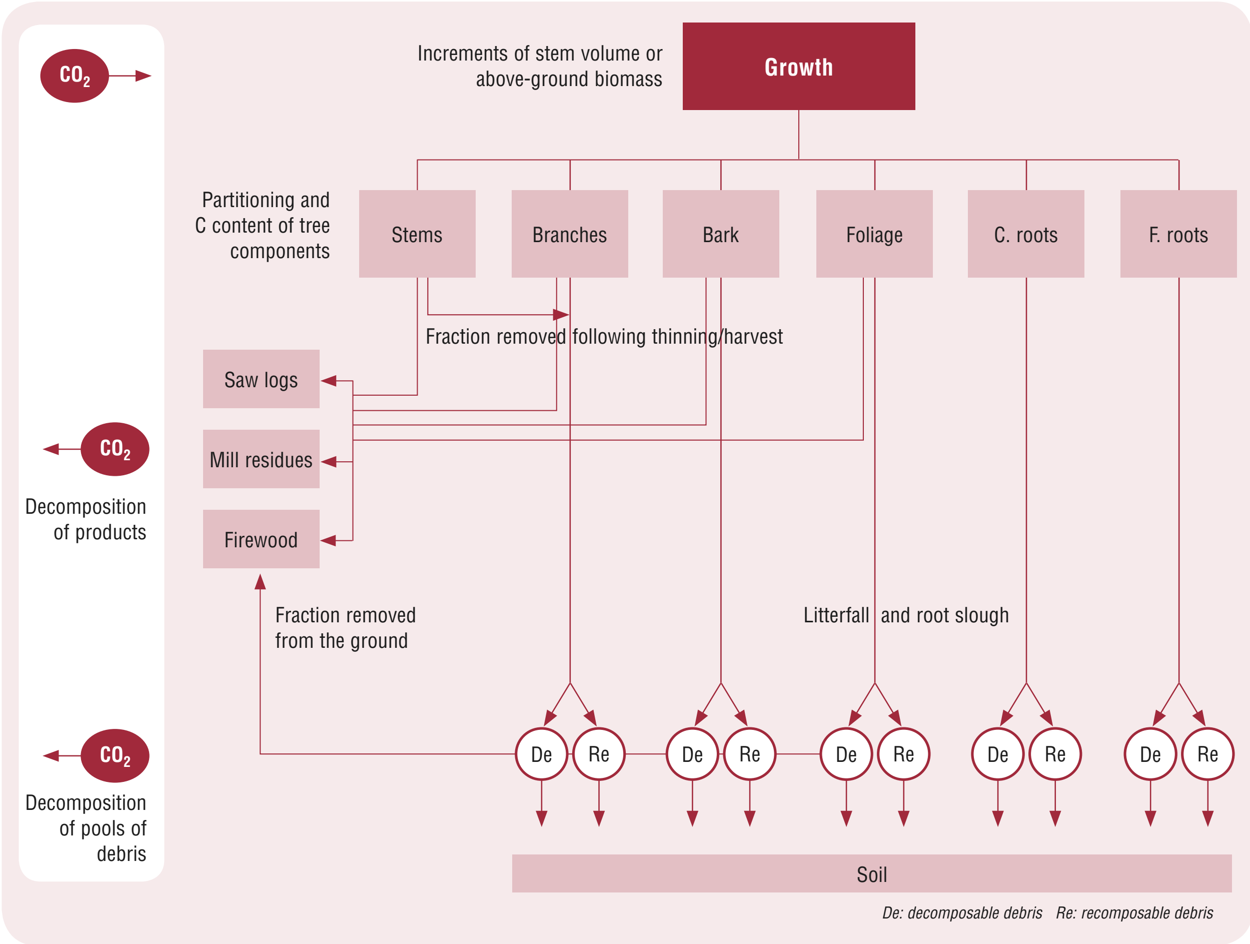

Figure 1: Diagrammatic representation of FullCAM

Net carbon sequestered by a given ecosystem was predicted using FullCAM. The model can simulate plots of trees (defined on a per hectare basis) in which there is a given growth rate, partitioning between tree components, turnover of these components, decomposition, management regime, and use of products (Richards 2001). As discussed below, some of these were assumed to be common between all the systems that were simulated.

FOUR

METHODS

Here we briefly describe the case studies used, and discuss the assumptions made in estimating the contribution of (i) establishment, (ii) growth, and (iii) harvest, transport and the use of firewood, on the net greenhouse gas emissions from remnant woodlands, native forests and plantations. The methodology used to assess the impact of uncertainty in management factors on carbon storage in each ecosystem is described.

4.1 OUTLINE OF THE CASE STUDIES

Three ecosystems were investigated: woodlands, native forests and plantations. These ecosystems had vastly different rates of growth (and of replacement after harvesting), and therefore attain their maximum carbon storage after varying time periods. To enable each of the three ecosystems to be compared on a uniform basis the growth of all stands was simulated for 100 years.

There are large difference in management regimes and growth rates for woodlands, native forests and plantations in the 400–800 mm rainfall zones of Australia. It was therefore difficult to choose management regimes and growth rates for our case studies that were typical for these ecosystems. As discussed below, our case studies were modelled on sites where data were available on management and growth, and as such, they are simply illustrative examples of the various ecosystems.

4.1.1 Woodlands

Remnant woodlands are composed of many different species. There are clearly many different ecological classes found within the 400–800 mm rainfall zone where firewood is often collected (see, for example, the box-ironbark study by ECC 2001). Not only were woodlands in these low-medium rainfall areas originally highly diverse, but they have also been extensively modified. For instance, about 83% of the forests and woodland in the box-ironbark study area have been cleared to a greater or lesser extent for agriculture (ECC 2001). In many of these areas some trees have been retained to provide shade and shelter, but the numbers of trees remaining is highly variable. The year in which land was cleared for agriculture also has an important effect on the remnant woodlands. Tree seedlings are often grazed in remnant woodlands, so the older trees are often not replaced and this has implications for the growth rate and survival of the remaining trees.

One of the greatest problems for simulating remnant woodlands is the general lack of information about key characteristics for carbon balance, such as total volume growth and proportions in stem, bark, branches and foliage. The original intention was to use a stand from the 400–600 mm rainfall zone of the Murray Darling Basin as the example of remnant woodland, but there is a general lack of detailed information about such ecosystems. Wall (1997) carried out a detailed study of yellow box (*E. melliodora*) dominated woodlands used for firewood collection in the somewhat wetter region of the Northern Tablelands of New South Wale (mean annual rainfall 793 mm). This ecosystem was chosen as our example woodland system. The choice of this species is appropriate as *E. melliodora* is a species of wide significance for the firewood industry in southern Australia (Driscoll *et al.* 2000).

Wall (1997) describes how clearing of land for agriculture and subsequent grazing has left scattered aging trees in many woodland areas. Based on Wall (1997), it was assumed that the average age of the woodland was about 95 years, and that 0.7% of the trees die each year without replacement. We also assumed that carbon storage within pasture under the trees in the woodlands remained unchanged during the simulation period.

Three case studies of remnant woodlands were simulated. In the first it was assumed that dead wood resulting from tree death and litterfall were left on the ground to decompose and that no firewood was collected.

In the second case study it was assumed that fallen timber was manually collected from the ground every five years. It was assumed that 80% of this fallen material was suitable for firewood, the remainder being left on the ground to decompose. This case study was based on the estimations of Driscoll *et al.* (2000) that 76% of the people collecting firewood in Australia target dead fallen timber.

In the third case study it was assumed that each year, both dead trees (i.e. the 0.7% that were assumed to die each year) and fallen timber were collected. Again, it was assumed that 80% of this material was suitable for firewood and that the rest was left to decompose. As there is a strong preference for dry rather than green wood (Wall 1997; Driscoll *et al.* 2000), we assumed that no live trees were felled for the purpose of firewood collection. In practice, trees in woodlands are often felled and then left for a year to dry out before they are collected for firewood.

4.1.2 Managed Native Forest

Information for the managed forest analysis was taken from the Wall (1997) thesis (site 64), which provided detailed information on stand composition and growth (see also Baldwin 1994). This was a closed forest of high site quality located in the Northern Tablelands of New South Wales where the mean annual rainfall was about 718 mm. The site was composed mainly of *E. laevopinea* (silvertop stringybark) with some of the closely related *E. youmanii* (Youman's stringybark) also being present. However, for the purposes of simulation both species were assumed to grow at the same rate.

Wall (1997) observed that 7 out of 15 trees were over 60 years old in the native forest site 64, and that mean age of the trees over 15 cm diameter at breast height (DBH) was 73 years. We therefore assumed that although the stand was of mixed aged, the average age of the native forest was about 75 years. It was also assumed that 0.2% of the trees died each year. Indeed, Wall (1997) observed that about 10% of the standing stringybark trees were dead.

Information on previous silviculture of the native forest investigated by Wall (1997) was not available as it is on freehold land and records have not been kept. It is likely that there has been some selective logging in the past. Appropriate silviculture was discussed with Doug Binns and John Fulton (SFNSW). Detailed management prescriptions have been developed for the high rainfall native forests in coastal areas of northern New South Wales, but are not available for sites in the drier inland forests as examined here. However, the general principles of silvicultural management are outlined in the Native Forest Silviculture Manual (SFNSW 2000). In the New England region, selective logging is favoured over clearcutting because selective logging reduces the risk of frost damage and allows the larger trees (>60 cm DBH, that are undesirable for processing) to be left *in situ* (Wall 1997, p 186). We therefore assumed that the managed native forest was selectively logged, but sustainably managed so that its growth rate was maintained after each logging event. To achieve this, as well as maintaining realistic growth rates (Section 3.2), we needed to assume that 38% of the tree stems were cut in a selective logging operation every 25 years.

There were three case studies simulated. In the first case study, it was assumed that of the 38% of the biomass of trees that were logged during each logging event, 50% remained on site as slash, while 37% ended up as mill residues and only 13% ended up as sawlogs. Indeed, in the absence of a market for pulp (such as in these case studies), up to 44 to 55% of harvested stems may remain on site as slash (Grierson, *et al* 1991; Snowdon *et al.* 2000 and J. Turland, F. Ximenes and D. Gardner of SFNSW pers. comm.). Others have found that saw timber recoveries are generally about 35 to 37% for hardwood native forests (Fung *et al.* 2002; F. Ximenes and D. Gardner (SFNSW) pers. comm.), so only about 13 to 20% of the carbon in the logged trees ends up in sawlogs.

The second case study was similar to the first, but rather than assuming all of the slash was left on the ground to decompose, we assumed that 80% of stems, branches and bark slash were used for firewood, the rest remaining on-site to decompose. In addition, we assumed that 80% of the fallen timber was manually collected every five years. The remaining 20% of this material was deemed to be unsuitable for firewood due to its size, form or inaccessibility.

The third case study was similar to the second case study with the exceptions that: (i) rather than collecting firewood from 80% of the material on the forest floor every five years, it was collected each year, and (ii) rather than letting trees that have died fall to the ground and decompose, it was assumed that 80% of all stem, bark and branch material from dead trees (i.e. the 0.2% that were assumed to have died each year) were harvested each year.

4.1.3 New Plantation

Several reports have been written in recent years on the potential of *E.cladocalyx* (sugar gum) as a species for both sawlog and firewood production (e.g. Hamilton 2000; Holloway 2000). It is a species with potential for the 400–600 mm rainfall zone, with a moderately fast growth rate, and good coppicing ability (CAB International, 2001). Sugar gum firewood is popular because it is easy to split, has a high density, and has a 15% higher relative heat output than red gum (Hamilton 2000). *E.cladocalyx* (sugar gum) was therefore chosen as an example of a plantation established in a low rainfall region. It was assumed that plantations were established at the commencement of the simulation period in 2000 on ex-pastoral land and were therefore sinks for carbon.

Again there were three case studies investigated. In the first it was assumed that the plantation was established for the sole purpose of sawlog production. Wood of *E. cladocalyx* is often used for telephone poles and fence posts, and is also used in heavy and general construction and in cabinet making (CAB International, 2001). We assumed that the rotation length was 35 years and there were two thinnings in each rotation, the first was 40% of the stems at age 7 years, and the second was 50% of the remaining stems at age 18 years. All of the slash from both thinning and harvest were left onsite to decompose. The silviculture was based on a description provided by Andrew Lang, who is both a farm forester and project officer for the Corangamite farm forestry project (Hopkins 2002). For 600 mm rainfall sites on reasonable soil he anticipated 30–40 year rotations would be required. The plantation would be established at 900 stems per hectare (sph) with 250 sph remaining after two thinnings. Hamilton (2000) and R. Washusen (pers. comm.) also suggested that for *E.cladocalyx*, a 30–45 year rotation was suitable for the 600 mm rainfall zone. R. Washusen (pers. comm.) thought that although most existing stands have not been thinned (as they should have been) to maintain form, thinning of about 31% at age 10 and then 67% of the remaining stems at 18–20 years would be reasonable. Sawlogs were the final product from harvesting (R. Washusen pers. comm.).

The second case study was the same as above except that: (i) fallen timber was collected periodically, (ii) 80% of the stems, bark and branches material cut during thinning or harvest were used for firewood, and (iii) at each thinning and harvest event, 80% of the dead wood and other litter on the forest floor was collected for firewood. This case study was based on the opinion that at least the first thinning of a *E.cladocalyx* plantation would be used for firewood (Hopkins 2002; R. Washusen, pers. comm.).

The third case study was a coppiced plantation grown solely for the purpose of firewood production on a 15 year rotation (based on Holloway 2000). It was assumed that there were three coppiced rotations, the stand being re-planted for the fourth rotation. Consistent with Holloway (2000), we assumed that (i) following coppicing, 40% of the roots survived, and (ii) 80% of the stems, branches and bark were collected for firewood. Also, 80% of the dead wood and other litter material on the ground were collected for firewood at each harvesting event. It should be noted that although this case study is a useful comparison, it is unlikely to be economically viable since the value of dried sawn wood is much greater than firewood (R. Washusen pers. comm.). Current *E.cladocalyx* firewood prices paid to farmers may be as low as $8 per tonne, whilst sawlogs are worth about $30–60 per tonne on the stump or about $100–$150 per cubic metre delivered to the mill. Sawn and kiln-dried *E.cladocalyx* timber is worth $1800–$2000 per cubic metre (Hopkins 2002).

4.2 ESTABLISHMENT

As discussed above, we have assumed that the woodland and native forests were already established at the commencement of simulation. For both ecosystems, the initial biomass of tree components and amount of carbon in the various pools of debris were assumed values that were based on available data (Section 4.3). In contrast, the initial mass of tree and debris components were assumed to be zero in the plantation case studies since the plantation was newly established at the commencement of simulation in the year 2000.

Carbon released as a result of plantation establishment was estimated using energy costs prepared by Wells (1985). He assessed the energy costs for site preparation, nursery and planting in *Pinus radiata (*radiata pine) plantations around Tumut, New South Wales. His estimates for site preparation were reduced by 60% as he was estimating for areas where native forest had to be cleared. New firewood plantations would be established on cleared agricultural land, but otherwise the energy costs for *E. cladocalyx* plantations should be similar. Estimates made by Wells (1985) were converted from MJ ha^{-1} assuming a carbon content per unit of energy of 0.26 kg CO_2 $kWhr^{-1}$, which is a rate appropriate for diesel fuel.

4.3 BIOMASS OF TREES

Net carbon sequestered by a given ecosystem as a result of tree growth was predicted using FullCAM. The FullCAM model can simulate plots of trees (defined on a per hectare basis) in which there is a given growth rate, partitioning between tree components, and carbon content of these components.

It should be noted that there is a general lack of quantitative data on the growth, litter accumulation and management of firewood production systems within the 600–800 mm rainfall zone, and so it was difficult to assess how representative examples are of generic categories of woodland, native forest and plantations. Despite the considerable uncertainties about many of the factors used in the models there will usually be significant productivity differences between woodlands, managed native forests and plantations. For example, it matters little whether the actual mean annual increment (MAI) of a particular piece of remnant woodland is 0.50 or 0.75 m^3 ha^{-1} yr^{-1}, its carbon balance will be distinctly different from those of most managed forests and virtually all plantations.

4.3.1 Growth increments

For each year of simulation, tree growth is driven by a user-entered input of growth increment. This can be either increments in stem volume or aboveground biomass. Below we describe how these annual increments of growth were determined for each ecosystem.

Wall (1997) presents both the current annual increment (CAI) and MAI curves of total firewood volume rather than merchantable stem volume (see Appendix 1) for an open *E. melliodora* forest site (site 65). Wall (1997) found that the CAI of the *E. melliodora* forest at age 150 years was about 86% of MAI and declined by about 5% per year (Fig. 2). For the purposes of growth modelling the CAI curve was reduced in proportion to the ratio of the observed basal area of the *E. melliodora* woodland to that of the forest (i.e. 5.7:20.0 or a ratio of 0.29). It was therefore assumed that the CAI for woodland stands was 0.78 m^3 $ha^{-1}yr^{-1}$ at the start of simulation when the average age was assumed to be 95 years, declining by 0.75% per year. Assuming that the stem wood represented 63% of the firewood (Appendix 1), we assumed that the CAI of the woodland case studies was initially 0.49 m^3 $ha^{-1}yr^{-1}$, and declined to 0.23 m^3 $ha^{-1}yr^{-1}$ after 100 years of simulation. These estimates were discussed with Julian Wall who confirmed that they were within reasonable limits.

Figure 2: Dry-weight CAI curve for firewood taken from an open forest of *E. melliodora* grown in southern New England (Wall 1997).

It was assumed that the selectively logged *E. laevopinea* forest was of mixed age and was in a state of equilibrium with respect to its annual growth increment during the 100 year simulation period. Wall (1997) found that *E. laevopinea* forests (mean age of 73 years) had an average MAI for firewood of between 3.2 and 3.7 m^3 ha^{-1} yr^{-1}. This was equivalent to a merchantable stem volume MAI of between 2.0 and 2.3 m^3 ha^{-1} yr^{-1}. Allowing for improvements in stand management, we assumed that the annual growth increment of stem volume was 3.4 m^3 ha^{-1} yr^{-1} since this gave us a predicted merchant MAI of 2.77 m^3 ha^{-1} yr^{-1}. This assumed growth increment also allowed us to predict aboveground biomass and stem volumes that were in the range of that expected for this ecosystem (see Chapter 5).

The pattern of growth of the plantation case studies was based on aboveground biomass growth data derived from measurements of *E. cladocalyx* at sites in the 400–500 mm rainfall zones in western Victoria (Hassall & Associates, 1998, Fig. 3). However, the MAI was only about 5.3 m^{-3} $ha^{-1}yr^{-1}$, and this was considered to be comparatively low not only due to low rainfall, but also to stands being moribund and overstocked (D. Bush, pers. comm.). We therefore multiplied the aboveground biomass data in Figure 3 by a factor of 2.4 as this enabled us to predict stem volume, MAI and aboveground biomass that had been observed for *E. cladocalyx* plantations in a 600–800 mm annual rainfall zone (see Chapter 5).

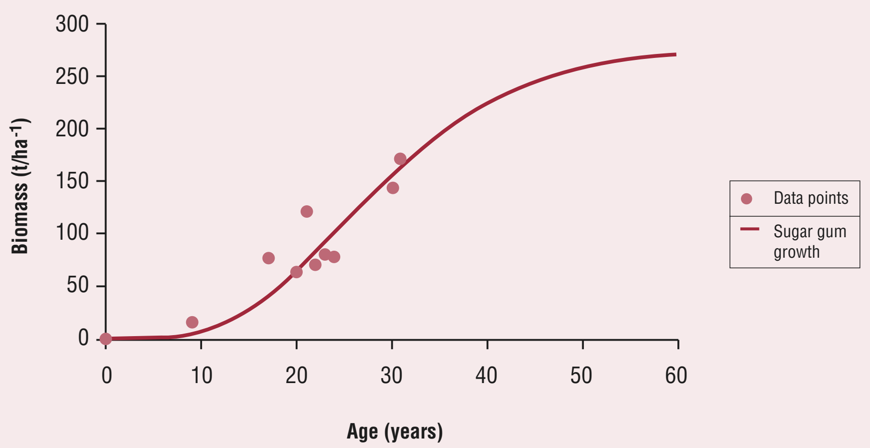

Figure 3: *E. cladocalyx* aboveground biomass measured in Hassall & Associates (1998) study

The third case study of plantations was a coppiced stand. Coppicing utilises the ability of the stem and root system of certain species to produce successive crops of above-ground biomass after the previous crop has been harvested. The first rotation coppiced shoots are faster growing than the original trees because established roots already have access to soil water and nutrients, and contain stored energy in the form of carbohydrates (Steinbeck 1982). However, growth rates do eventually decline after successive coppice rotations. We could find no records of observed changes in growth rates during successive rotations of coppiced *E. cladocalyx* plantations managed on a 15 year cycle. We assumed that during the first rotation, growth rates were 100% of those predicted for *E. cladocalyx* (see above), while in the second rotation (first coppice) growth rates would increase to 110% , and then decline in the third and fourth rotation (second and third coppice) to 90% and 75%, respectively (D. Wildy, pers. comm.) We then assumed that trees were replanted and the cycle started again.

4.3.2 Stem wood density

Ilic *et al.* (2000) have reviewed wood density data for 590 Australian tree species and include estimates of both basic and air-dried density for *E. melliodora*. They found that the basic and air-dried density measurements averaged 0.899 t m^{-3} and 1.082 t m^{-3}, respectively. This gave a ratio of basic to air-dry density of 0.83. Groves and Chivuya (1989) estimated the mean air dried wood density of 12 samples of *E. melliodora* taken from trees of around 23 cm dbh over bark as 0.977 t m^{-3}, which was equivalent to a basic density of 0.811 t m^{-3} (using the weighted ratio of basic to air-dry density). Wall (1997) measured mean air-dried density from 46 samples taken from the open *E. melliodora* forest (site 65) as 0.957 t m^{-3}, which was equivalent to a basic density of 0.792 t m^{-3}. We chose 0.792 t m^{-3} as the wood density used in the woodland case studies.

Air-dried density of *E. laevopinea* was found to be 0.860 t m^{-3} (Ilic *et al.* 2000). Wall (1997) measured mean air-dried density from 67 samples taken from the open *E. laevopinea* forest (site 65) as 0.784 t m^{-3}. No ratios between air-dried and oven dried samples were available for *E. laevopinea*, so the same ratio used for E. *melliodora* was applied producing an estimated basic density of 0.649 t m^{-3}.

Basic density of *E. cladocalyx* was 0.758 t m^{-3} (mean of 10 samples, Ilic *et al.* 2000), and so this was the wood density used in the plantation case studies. This is consistent with the measures of wood density of *E. cladocalyx* observed by Hassall and Associates (1998, 1999) of 0.700 to 0.770 t m^{-3}.

4.3.3 Partitioning between tree components

FullCAM partitions between tree components by first calculating the increment of stem mass for each year of simulation, and then multiplying these increments by the assumed increment in mass of the other tree components (i.e. branches, bark, foliage, coarse roots and fine roots) relative to that of the stem for each year of simulation.

There are few data on the mass of tree components at various ages of plantations, let alone woodlands and native forests. However, Polglase *et al*. (2002) developed default values for partitioning of carbon between components (i.e. stems, branches, bark and foliage) of *E. globulus* (Tasmanian bluegum) simulated using the FullCAM model. These workers determined partitioning by reviewing the literature on the mass of stems, branches, bark and foliage of *E. globulus* and then developing linear and non-linear relationships between: (i) the mass of stem wood and stem bark, which are then combined to give the mass of the stem wood+bark component, (ii) mass of stem wood+bark and mass of branches (sum of live and dead), and (iii) mass of stem wood+bark and mass of leaves. For example, they used data from 18 sites covering India, South Africa, Portugal and Australia to estimate a relationship between the mass of foliage and that of the stem wood+bark of *E. globulus*. They found that the relationship accounted for 85% of variance. Polglase *et al*. (2002) also estimated partitioning of carbon to coarse and fine roots of a *E. globulus* plantation grown in a low rainfall region. We utilised the partitioning estimates for this site (run over a period of 100 years) as a basis for obtaining the expected partitioning of carbon in our case studies.

Since we assumed that the woodland and forest were mixed aged stands with an average age of 95 and 75 years, respectively, partitioning in these stands was assumed to remain fairly constant over the 100 year simulation period. Therefore partitioning fractions to each tree component were assumed to be the average value observed for *E. globulus* plantations (Polglase *et al.* 2002) in the first 95 years (for woodlands) or 75 years (for forests) after establishment (Table 1). Then, foliage and branch mass were multiplied by a factor of 1.35 for the woodlands case studies since, where the tree spacing is relatively sparse, it is expected the foliage and crown mass may be a little larger than in closed forests. Indeed, Wall (1997) observed that relative to *E. laevopinea*, *E. melliodora*, had a lower stem:branch ratio.

We also used the average partitioning of carbon to tree components that Polglase et al. (2002) observed for *E. globulus* plantations to the *E. cladocalyx* plantation case studies. However, branch and foliage mass were assumed to be reduced by 65% of the values predicted for *E. globulus* to allow for the lower foliage mass of *E. cladocalyx* (A. Boutland and D. Bush, pers. comm.) (Table 1). Also, a different approach was required for the coppiced plantation. It is known that coarse root growth is suppressed for the first few years following coppicing (D. Wildy, pers. comm.). Therefore, we assumed that the growth of coarse roots relative to the stem declined during the four coppiced rotations from 0.30 to 0.02.

Table 1: Annual increment of mass of each tree component due to the growth expressed relative to the annual increment in stem mass for the woodland, native forest and plantation ecosystem.

Ecosystem	Age (yr)	Branches	Bark	Foliage	Coarse roots	Fine roots
Woodland	95	0.04	0.03	0.03	0.24	0.03
Forest	75	0.05	0.03	0.04	0.24	0.03
Plantation	1	0.35	0.16	0.21	0.30	0.20
	2	0.32	0.16	0.19	0.30	0.15
	3	0.29	0.15	0.17	0.30	0.06
	4	0.24	0.15	0.15	0.30	0.04
	5	0.20	0.15	0.12	0.30	0.03
	6	0.16	0.14	0.10	0.30	0.03
	7	0.12	0.14	0.08	0.30	0.03
	8	0.08	0.13	0.07	0.30	0.02
	9	0.06	0.12	0.05	0.30	0.02
	10	0.04	0.12	0.05	0.30	0.02
	11	0.03	0.12	0.04	0.30	0.02
	12	0.02	0.12	0.04	0.30	0.02
	13	0.01	0.12	0.03	0.30	0.02
	14	0.01	0.12	0.03	0.30	0.02
	15	0.00	0.12	0.02	0.30	0.02
	16	0.00	0.12	0.02	0.30	0.02
	17	0.00	0.12	0.02	0.30	0.02
	18	0.00	0.12	0.02	0.30	0.02
	19	0.00	0.12	0.01	0.30	0.02
	20	0.00	0.12	0.01	0.30	0.02
	21	0.00	0.12	0.01	0.30	0.02
	22	0.00	0.12	0.01	0.30	0.02
	23	0.00	0.12	0.01	0.30	0.02
	24	0.00	0.12	0.01	0.30	0.02
	25	0.00	0.12	0.01	0.30	0.02
	26	0.00	0.12	0.01	0.30	0.02
	27	0.00	0.12	0.01	0.30	0.02
	28	0.00	0.12	0.01	0.30	0.02
	29	0.00	0.12	0.00	0.30	0.02
	30 to 35	0.00	0.12	0.00	0.30	0.02

Concentrations of carbon in each tree component are multiplied by the predicted mass of these components to calculate the carbon contents and hence annual sequestration. Carbon fractions of tree components were taken from Gifford (2000) (Table 2).

Table 2: Assumed carbon contents of tree components.

Tree component	Carbon content (%)	Tree component	Carbon content (%)
Stems	52	Leaves and twigs	52
Branches	47	Coarse roots	49
Bark	49	Fine roots	46

4.4 MATERIAL ON THE GROUND

Carbon storage on the ground as litter or coarse woody debris was predicted using FullCAM. As discussed above, the FullCAM model first simulates growth of each tree component, then based on user-defined inputs, the model simulates the turnover of these components and their decomposition (Richards 2001). These rates of turnover and decomposition were assumed to be defaults that were common between all three ecosystems simulated.

4.4.1 Turnover of tree components

Using FullCAM, litterfall and root slough are simulated by user-defined rates of turnover of tree components. Rates of turnover used in the simulations for this study were based on previous calibrations of the FullCAM model for litterfall, litter mass and soil carbon (Paul *et al.* 2003) using data from effluent-irrigated eucalypt trials at Wagga Wagga (Myers *et al.* 1996) (Table 3). This study had data on growth, litterfall and accumulation of litter, allowing for calibration of turnover rates of tree components. Although rates of turnover of tree components may vary between species and with management, there is currently no data available to indicate the magnitude of these effects.

Table 3: Assumed turnover rates of tree components, expressed as a percentage of standing biomass lost to litterfall or root slough.

Tree component	Turnover (% yr^{-1})	Tree component	Turnover (% yr^{-1})
Branches	4.90	Coarse roots	10.2
Bark	6.70	Fine roots	95.0
Leaves and twigs	50.4		

4.4.1 Decomposition of debris and soil carbon

In FullCAM, fallen litter (i.e. dead wood, bark and foliage) and coarse and fine dead roots are each assumed to be composed of two pools: a small pool that has a fast rate of decomposition, and a larger pool that has a slow rate of decomposition. After reviewing the global literature on studies of decomposition, Paul *et al.* (2003) calibrated FullCAM for decomposition of litter under eucalypts. The defaults they found for rates of decomposition and the fraction of litter components that were resistant were used in this study and are shown in Table 4.

Table 4: Assumed rates of breakdown and the proportion of resistant components of debris material under eucalypts.

Tree component	Rate of breakdown (% yr^{-1})		Resistant component (%)
	Decomposable	Resistant	
Dead wood	100	12	100
Bark litter	100	20	100
Foliage litter	100	30	80
Coarse dead roots	100	20	100
Fine dead roots	100	30	62

On the basis of previous studies (Paul *et al.* 2002), that have shown that changes in soil carbon are generally insignificant compared to changes in the carbon within biomass and debris pools, we assumed in this study that soil carbon was unchanged over the period of simulation.

4.5 PRODUCTS

In FullCAM, user-defined rates of decomposition of products (i.e. sawlogs, mill residues and firewood etc.) are required to calculate the net carbon stored in products over the period of simulation. Product decomposition rates were taken from Jaakko Poyry (1999), where it was assumed rates of decomposition were 50% yr^{-1} for firewood, 2% yr^{-1} for sawn timber and 100% yr^{-1} for mill residues.

4.6 HARVEST AND TRANSPORT

We reviewed the literature and consulted people in the firewood industry to determine the CO_2 emissions relating to:

(i) production and combustion of fossil fuel used;

(ii) harvesting, or cutting the trees down (if they had not already died and fallen to the ground), collecting the timber, loading it for transport to the wood yard, splitting the timber (either on-site or at the woodyard); and

(iii) transporting it to the consumer.

4.6.1 Production and combustion of fossil fuels

The greenhouse gas emissions from the combustion of fossil fuels have been estimated by a number of authors including Beer (2002), Athanassiadis (2000) and AGO (2001). The total emissions from combustion of diesel fuel include the emissions that arise from producing the fuel as well as those from its combustion (Table 5).

Table 5: Summary of CO_2 emissions from diesel production and combustion.

	Production (kg CO_2 L^{-1})	Combustion (kg CO_2 L^{-1})	Total (kg CO_2 L^{-1})
Complete combustion of $C_{14}H_{30}$		2.62	
Beer (2002)	0.45	2.59	3.0
AGO current (2001)	0.46	2.69	3.2
AGO low S (2001)	0.50	2.69	3.2
AGO ultra low S (2001)	0.55	2.69	3.2
Average	0.49	2.66	3.1

4.6.2 Harvesting firewood

Clearly emissions of CO_2 resulting from harvesting and transport will depend on whether the firewood was collected by private users or small commercial suppliers or collected as part of a commercial forestry operation. Cutting and collection of firewood by private users or small commercial suppliers generally involves cutting with a chain saw, manual log splitting and local transportation. There were some data on expected emissions of CO_2 resulting from these processes. However, collection of residues and thinnings from commercial forestry processes is a fairly new concept and there are limited data on the types of equipment that may be used for this specific purpose. We therefore assessed the impact by considering fuel usage as for the commercial timber harvesting.

Fuel use by private/small scale collectors

Based on discussions with retail firewood operators in the USA, Hinkel (1989) found that chainsaw fuel usage for cross cutting is approximately 2.5 L t^{-1} of dry firewood. The paper assumed that all necessary log-splitting was done manually.

The Department of Natural Resources and Environment (DNRE) (A. Lang, pers. comm.) provided contacts for several small firewood operators in south western Victoria. These operators harvest and transport *E. cladocalyx* as firewood to local regional customers. One of these operators (M. Hampson, pers. comm.) uses a chainsaw for harvesting the trees, and estimated that the fuel consumption for this operation was approximately 0.5 L t^{-1} assuming an average density of 0.73 t m^{-3} of green wood (average of the basic densities for *E. cladocalyx* 0.75 t DM m^{-3} green wood (Ilic *et. al.*, 2000), *E. laevopina* 0.53 t DM m^{-3} green wood (Bootle, 1983) and *E. melliodora* 0.90 t DM m^{-3} green wood (Ilic *et. al.*, 2000)). An excavator with a processing head (an inbuilt circular saw) is used to dock the logs to foot blocks, and a petrol engine splitter and elevator are used to prepare and stack the blocks. The fuel consumption for the processing of the firewood was estimated as 6.6 L t^{-1}

Fuel use for commercial scale collection

A Forestry Tasmania paper (Fitzpatrick 2001) estimated diesel usage rate for post harvest recovery of residues for fuel. He recognised that at present there is no industrial scale recovery of post harvest residues, and so has based his study on normal commercial timber harvesting practices for a typical Tasmanian native forest operation. It was anticipated that this method would underestimate the consumption as more effort would be required to move and load residues, due to their dis-aggregated nature, and overestimate the consumption due to the potential to piggy back the operation off commercial timber collection. The estimates of fuel consumption from the Forestry Tasmania operations were also compared to international estimates for similar operations.

Forestry Tasmania (Fitzpatrick 2001) identified that the fuel usage rates for personnel transport and chainsaw operation are negligible. Fuel consumption was estimated in three main areas, harvesting, transport and comminution (i.e. reduction to small fragments). The fuel consumption for harvesting assumed the operation of a skidder, an excavator at the landing and an excavator at the working front in the coupe. This provided an estimate of 2.6 to 4.1 L t^{-1} of green timber loaded onto a truck. The study considered the comminution of the residues to chips for delivery to commercial timber mills or power stations and estimated a fuel consumption of 1 to 2 L t^{-1} green timber. However, as this study investigated the collection of residues for domestic firewood, this step is not relevant.

Korpilahti (1998) estimated for Finnish operations, that the total fuel consumption for harvesting logging residues from regeneration thinnings, including chipping and delivery to a heat and power plant were 10 to 14 L t^{-1} green wood assuming an average density of 0.65 t m^{-3} of green wood. This compares to the 5.5 to 9.8 L t^{-1} estimated by Forestry Tasmania for commercial timber operations, including comminution and delivery, which supports the hypothesis that using the fuel consumption data from typical commercial forestry operations would underestimate the impact for the more intensive collection of firewood.

The fuel consumption in the commercial harvesting of timber estimated by Forestry Tasmania was also compared to other international estimates. Athanassiadis (2000) estimated that fuel consumption from timber harvesting operations in Sweden were approximately 2.9 L t^{-1} of dry wood assuming the operation of forwarders and single and two-grip harvesters. Berg (1995) independently estimated a figure of 2.7 L t^{-1} dry wood for Sweden. Sambo (1997) provided a figure of 5.1 L t^{-1} dry wood for clear cut loader/forwarder operation in typical coastal British Columbia forest operations. All of these values are consistent with the Forestry Tasmania assessment of 2.6 to 4.1 L t^{-1}, and all of these estimates assume an average density of wood of 0.73 t DM m^{-3} green wood.

Table 6: Fuel consumption (from harvest, comminution and transport operations) when firewood is collected either privately or by small business on a small-to-medium scale, or by commercial timber operations on a larger scale.

	Efficient harvest	Less efficient harvest	Comminution	Transport return
	(L t^{-1})	(L t^{-1})	(L t^{-1})	(L km^{-1}
Small/medium scale collection				
M. Hampson pers. comm. (2002)	7.1	–	–	0.07
Commercial timber operation				
Fitzpatrick (2001)	2.6	4.1	2.0	0.02
Sambo (1997)	5.1	5.1	–	–
Athanassiadis (2000)	2.9	2.9	–	–
Berg (1995)	2.7	2.7	–	–
Korpilahti (1998)	2.1	2.4	6.9	–
Adelaide Wholesale Landscape Supplies pers. comm. (2002)	–	–	–	0.02
Average	*3.1*	*3.4*	*4.4*	*0.02*

4.6.3 Transport of firewood

Fuel use by private/small scale collectors

Small firewood operators in south western Victoria use a diesel tractor and truck to transport the wood direct to customers in Ballarat. The fuel consumption for the processing operations was estimated to be 7.1 L t^{-1} (M. Hampson, pers. comm.). The firewood is normally transported in 10 m^3 loads to customers approximately 50 km from the source of the wood and the operator estimated that he uses approximately 1.9 km L^{-1} on the 100 km round trip. This gives a fuel consumption of 0.07 L km^{-1} t^{-1} of dry firewood (Table 6).

Fuel use for commercial scale collection

Wall (1997) estimated that private collectors in Armidale travelled 432,080 km in 1996 to collect 6,920 t of firewood. A vehicle efficiency of 7 km L^{-1} was assumed yielding a figure of 8.9 L t^{-1} of dry firewood.

Adelaide Wholesale Landscape Supplies Pty Ltd (G. Traeger, pers. comm.), one of the major firewood retailers in South Australia, estimate that the fuel consumption required to deliver 30 tonne loads of firewood from sites in New South Wales to Adelaide in semi-trailers is approximately 2 km L^{-1} over return trips of 1400 km. This yields a fuel consumption of 0.02 L km^{-1} t^{-1} (Table 6).

Forestry Tasmania (Fitzpatrick 2001) estimated that the fuel consumption from transporting the forest residues in a typical tri-axle unit was 1.4 km L^{-1} fully loaded to 3.0 km L^{-1} empty. For the purposes of this study a haulage distance of 50–100 km was assumed for loads of 28 t, which gave a fuel consumption of 0.02 L km^{-1} t^{-1}.

The estimates of total emissions from firewood harvesting and transport presented in this report are based on a combination of the most appropriate assessment of fuel usage during harvesting and transport combined with the average emission factors. A discussion is provided for each scenario for the most appropriate reference of fuel usage, and the respective transportation distances related to each scenario. A summary of the factors used is presented in Table 7.

Table 7: Summary of harvesting and transportation scenarios. Note these factors are based on an assumed average wood basic density of 0.73 t DM m^{-3} green wood. However the actual factors used for each case study (woodlands, native forest and plantations) discussed in Section 4.6, have been adjusted to use the actual basic density for each representative species selected.

Scenario	Harvest basis*	Transport basis*	Distance (km)†	Emissions (kg CO_2 L^{-1})	Harvesting (kg CO_2 t^{-1})	Transport (kg CO_2 t^{-1})	Total (kg CO_2 t^{-1})
1	~	~	~	3.1	0	0	0
2	S	S	50	3.1	22.5	22.8	45.3
3	S	S	100	3.1	22.5	45.6	68.1
4	S	A	200	3.1	22.5	55.9	78.4
5	S	C	400	3.1	22.5	41.4	63.9
6	S	C	800	3.1	22.5	82.8	105.3
7	C	S	50	3.1	10.3	22.8	33.0
8	C	S	100	3.1	10.3	45.6	55.8
9	C	A	200	3.1	10.3	55.9	66.2
10	C	C	400	3.1	10.3	41.4	51.7
11	C	C	800	3.1	10.3	82.8	93.1

* small scale (S), average (A), commercial (C)
† distances shown are one way transportation distances

For all scenarios where firewood was collected commercially as part of a sawlog harvesting regime, the fuel consumption estimates for harvesting were based on the average value from the commercial studies referenced in Table 6. For all scenarios where firewood was collected by private users, the fuel consumption calculations were based on the average of the data obtained from the private collectors as detailed in Table 6.

For the transportation of the firewood, the fuel consumption would depend on the scale of the collection operations. Large operators are more likely to achieve better fuel efficiency per mass of firewood due to their larger trucks. For this analysis, it was assumed that for the distribution of firewood between 50 and 100 km (100 and 200 km round trips) the vehicles were more likely to be smaller. For these cases the average of the data obtained from the small private firewood processors in Table 6 was used. For round trips of 800 and 1600 km, it was assumed that the fuel consumption would best be represented by the larger scale industrial forestry transportation. In these cases the average of the data from large-scale operators in Table 6 was used. For round trips of 400 km, it was assumed that some combination of larger and smaller vehicles would be used and so an average of the two values was used to represent fuel consumption.

4.7 EMISSION OF CO_2 FROM FIREWOOD HEATING

The net emission of CO_2 resulting from each case study in each ecosystem over the 100 year period of simulation was calculated by adding the net changes in carbon storage as a result of establishment of the trees, changes in tree biomass, debris, and harvested products, and due to harvest and transport operations. An equivalent net emission of CO_2 as a result of these processes could be calculated by assuming 1 t C was equal to 3.667 t CO_2 (Appendix 1). Conversion efficiency for the burning of firewood for domestic heating was calculated as the product of net emission of CO_2 (calculated as described above), and the basic energy content of wood (determined as 5.28 kWhr kg^{-1} of dry weight, http://www.ieabioenergy-task32.com/database/biomass.php), and the efficiency of a typical wood heater. Although we assumed here that a typical wood heater had an efficiency of 62% (i.e. 38% of the heat generated is lost up the flue), these may range between 10 to 70% depending on the type of wood heater used (Table 8).

Table 8: Efficiency of wood heaters (www.greenhouse.gov.au/yourhome/technical/fs44_4.htm).

Wood heater	Efficiency (%)
Open fireplace	10
Open fire insert	30
Slow combustion inserts	60
Non-air tight potbelly stoves	40
Slow combustion stoves	70

4.8 SENSITIVITY ANALYSIS

As outlined above, we have made numerous assumptions about important inputs in all the case studies simulated by FullCAM. All of these inputs and assumptions have some uncertainty in their value. Sensitivity analysis of FullCAM provides a formal way in which to investigate how variation in the value of important inputs (such as tree growth rates) influences the predicted carbon storage of an ecosystem (i.e. the net carbon storage within trees, debris and products). Since the second case study was the most likely scenario for firewood collection under each ecosystem, the uncertainty analysis was performed on that case study. The analysis concentrated on examining the impact by altering the management regimes on the carbon storage that was predicted in these case studies. This was carried out by varying the values assumed for:

(i) growth rates;

(ii) thinning or mortality fractions;

(iii) rotation length;

(iv) rates of decay of pools of debris;

(v) material removed at thinning and harvest, and what products this material was used for;

(vi) rates of decay of sawlogs, mill residues, and firewood;

(vii) efficiency of firewood harvesting; and

(viii) distance travelled to deliver firewood.

Clearly, some inputs, such as thinning fractions and rotations lengths, had less uncertainty in their values than others such as decomposition rates of roots and the recovery of firewood following thinning and harvest events.

The sensitivity analysis did not consider correlations between different inputs. For example, in reality the rotation length is likely to influence the thinning regime used, which in turn will influence growth rates. As such interactions were not taken into account, the sensitivity analysis is purely illustrative of how varying inputs may alter CO_2 generated from the collection of firewood.

Table 9: Expected minimum and maximum values of inputs investigated in the sensitivity analysis.

Input		Min. value	Default value	Max. value
Growth rates*		× 0.70	× 1.00	× 1.30
Mortality fraction*		× 0.30	× 1.00	× 1.70
Thinning fraction (% of stems thinned)*		– 5	0	+ 5
Logging frequency (years)*		– 5	0	+ 5
Rates of decomp. of debris (% yr^{-1})	Stem wood	5	12	19
	Bark	15	20	25
	Foliage	25	30	35
	Coarse roots	10	20	30
	Fine roots	20	30	40
Collection of material from ground (%)		65	80	95
Recovery of products (%)	Stem firewood	5	40	45
	Stem slash	45	10	5
	Branch firewood	10	80	90
	Branch slash	90	20	10
	Bark firewood	10	80	90
	Bark slash	90	20	10
Rates of decomp. of products (% yr^{-1})	Sawlogs	0.1	2	5
	Mill residues	25	100	100
	Firewood	25	50	100
Harvest effic. (private, kg CO_2 t^{-1})		48.1	68.1	88.1
Harvest effic. (commercial, kg CO_2 t^{-1})		31.7	51.7	71.7
Distance travelled (private, km)		50	100	800
Distance travelled (commercial, km)		50	400	800
Efficiency of burn (%)		10	62	70

* For each case study the minimum and maximum values used in the sensitivity analysis were determined by adjusting the default value by a given percentage or value because these values differ between case studies.

FIVE

RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter we report and discuss the predicted net change in carbon storage in biomass of trees, debris, and in harvested products (i.e. sawlogs, mill residues and firewood), as well as the net release of carbon as a result of establishment of trees, and harvest and the subsequent transport of products. Based on these predictions we then estimate the net emission or storage of carbon, and thus net greenhouse gas emissions, resulting from the various firewood collection case studies for each ecosystem. Finally, a sensitivity analysis demonstrates how altering some of the assumptions can affect the estimated net greenhouse gas emissions resulting from collection of firewood.

5.2 CARBON RELEASED DUE TO ESTABLISHMENT OF TREES

Only the plantation ecosystem was assumed to have an emission of carbon due to the establishment of trees on ex-farmland. Based on the work by Wells (1985) and assumptions outlined in Section 3.2, we calculated that 0.10 t C ha^{-1} were required for site preparation, and that 0.01 t C ha^{-1} were required for nursery maintenance, and another 0.01 t C ha^{-1} for planting of seedlings. This gave a total of 0.12 t C ha^{-1}, or 0.44 t CO_2 ha^{-1}, for establishment of a new plantation.

5.3 NET CARBON STORAGE IN BIOMASS OF TREES

As described in Section 3.3, net carbon storage in biomass of trees was estimated using the FullCAM model and the assumed rates of growth for typical woodland, native forest and plantation ecosystems in the 600–800 mm rainfall region of eastern Australia.

5.3.1 Woodlands

We predicted that over the 100 year simulation period, standing stem volume and stem MAI (assuming average age of 95 years) averaged 76 m^3 ha^{-1}, and 0.80 m^3 ha^{-1}yr^{-1}, respectively for all the woodland case studies on the Northern Tablelands (Table 10). Average aboveground biomass was predicted to be 73 t DM ha^{-1} (Fig. 4). However, due to the death of some of the older trees, the aboveground biomass decreased over the period of simulation from 77 to 69 t DM ha^{-1}.

Table 10: Predicted stem volume, MAI, and aboveground biomass of the woodland, native forest and plantation case studies. Values in parenthesis represent predicted measurements of growth for the coppiced plantation.

	Woodlands*	Native forest#	Plantations#
Stem volume (m^3 ha^{-1})	76	208	456 (97.9)
MAI (m^3 ha^{-1} yr^{-1})	0.80	2.77	13 (6.52)
Aboveground biomass (t DM ha^{-1})	73.0	156	407 (98.0)
Biomass (t DM ha^{-1})			
Stem	59.1	140	359
Branches	3.98	6.24	1.34
Bark	6.12	4.04	40.7
Foliage	3.36	5.56	5.92
Coarse roots	19.3	31	102
Fine roots	1.43	3.56	6.40

* Average over the 100 year simulation period
# Maximum values predicted (i.e. prior to a harvest event)

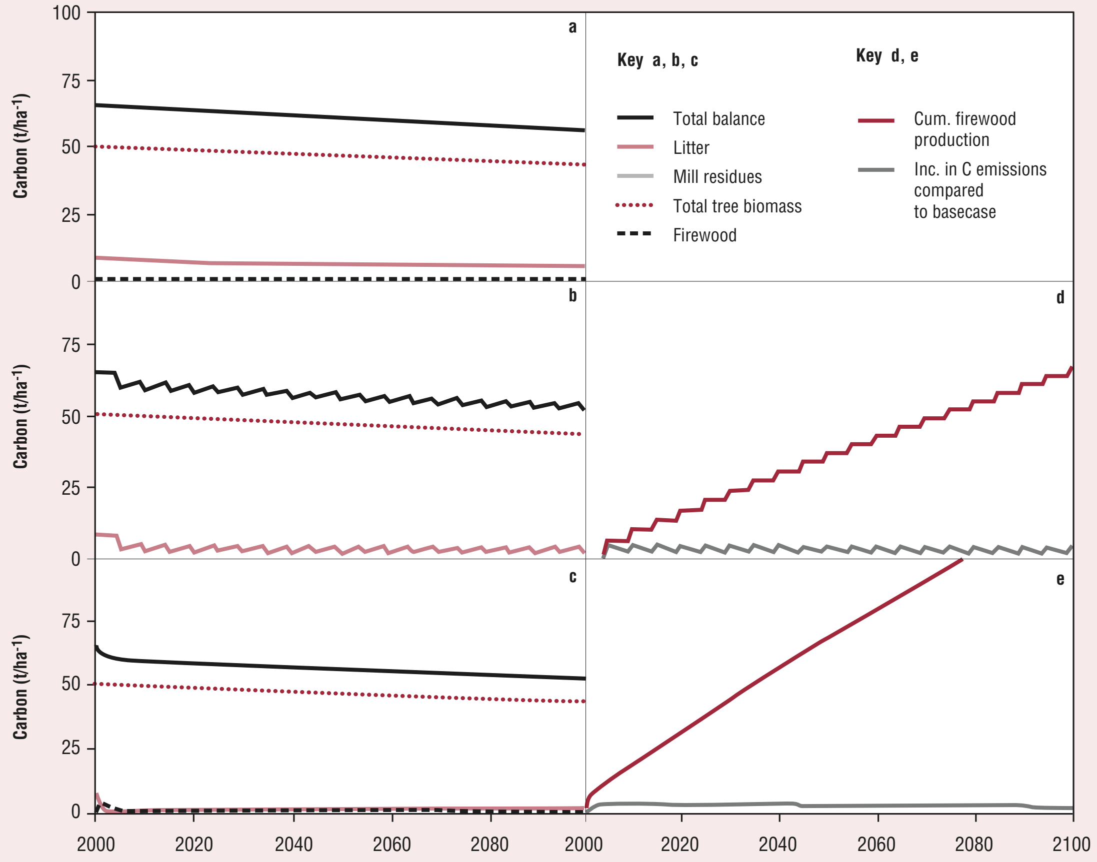

Figure 4: Change in pools of carbon in the woodland case studies where: (a) no firewood was collected (base case or case study one), (b) firewood was collected from the ground every five years (case study two), and (c) firewood was collected annually from both the ground and from dead trees (case study three). Net accumulation of firewood, and the increase in emissions of carbon as a result of utilisation of firewood (i.e. increase in CO_2 emissions compared to case study one) are given for case study two (d) and case study three (e).

These aboveground biomass predictions were consistent with Wall (1997, p 108), who found that biomass of timber and bark (of ≥ 5 cm diam. above the stump) of box/gum woodlands and open forests on the Northern Tablelands range from 28 t DM ha^{-1} at a stand density of about 80 stems per hectare to 121 t DM ha^{-1} at a stand density of about 400 stems per hectare. The predicted aboveground biomass was also within the same order of magnitude as the 84 t DM ha^{-1} maximum aboveground biomass expected for woodlands in the 600–800 mm rainfall zone in the Northern Tablelands (based on AGO productivity surface, R. Waterworth, pers. comm.). It was also compared to estimates of average aboveground biomass for woodlands and scrubs across Australia (42 t DM ha^{-1}, AGO 1998), for *Eucalyptus* spp. at woodlands sites in north-eastern Australia (71 t DM ha^{-1}, Burrows *et al.* 2000), and for black box woodlands in Victoria (50 t DM ha^{-1}, Grierson *et al.* 1992).

Although FullCAM does not simulate the mass of dead trees, when we assumed there was no decomposition of dead wood, we predicted that there would be an accumulation of 36 t DM ha^{-1} of dead wood in the woodlands at equilibrium. Of this, 19 t DM ha^{-1} were found to result from the assumed rate of tree mortality (0.7% per year). This was consistent with the review of coarse woody debris in Australasia (Woldendorp *et al*. 2002), who found in two woodland studies that standing dead wood was 10.5 t DM ha^{-1} and 58.0 t DM ha^{-1}.

5.3.2 Native Forests

For our native forest case studies on the Northern Tablelands, maximum aboveground biomass was predicted to be 156 t DM ha^{-1} (Table 10, Fig. 5) This is in agreement with the 115 to 160 t DM ha^{-1} of expected maximum aboveground biomass of native forests based on the AGO's productivity surface for the 600–800 mm rainfall zone in the Northern Tablelands (R. Waterworth pers. comm.). Our predicted aboveground biomass for the native forests case studies was also in agreement with Wall (1997, p 108). He observed that the biomass of aboveground timber and bark in stringybark forests of the Northern Tablelands ranged from 119 to 297 t DM ha^{-1}, and averaged 189 t DM ha^{-1}. For native forests dominated by stringy bark, Wall (1997, p 156) found that the mass of stems ranged from 103 to 150 t DM ha^{-1}. This was consistent with the maximum stem mass we predicted of 140 t DM ha^{-1} (Table 10).

Maximum stem volume was predicted to be 208 m^3 ha^{-1} for the native forest case studies (Table 10). This result is on the low end of predictions for *E. pilularis* (blackbutt trees) of 63 to 74 years of age on the north coast of NSW, the merchantable volume ranged from 211 to 594 m^3 ha^{-1}, and averaged 365 m^3 ha^{-1} (Horne 1994).

We also predicted that for 75 year old stingybark forests in the Northern Tablelands, stem MAI was 2.77 m^3 ha^{-1} yr^{-1} (Table 10). This was in agreement with 2.25 m^3 ha^{-1}yr^{-1} MAI observed for blackbutt forests growing near Coffs Harbour (RAC, 1992).

If we assumed no decomposition of dead wood, we predicted that there would be an accumulation of 38 t DM ha^{-1} of dead wood, 10 t DM ha^{-1} resulting from the assumed rate of tree mortality (0.2% per year). This was consistent with the review of Woldendorp *et al.* (2002). They found that on average, there was a total of 9.1 t DM ha^{-1} of standing dead wood in dry sclerophyll forests in Australasia (n=6, ranging between 0.2 and 26.6 t DM ha^{-1}, with a standard deviation of 10.0 t DM ha^{-1}).

5.3.3 Plantations

Aboveground biomass was predicted to average 407 t DM ha^{-1} after a 35-year rotation for *E. cladocalyx* plantation near Lismore in Victoria. We predicted that the stem mass was 359 t DM ha^{-1}, stem volume was 456 m^3 ha^{-1}, and MAI was 13.0 m^3 ha^{-1} yr^{-1} (Table 10). Hamilton (2000) found that in the 500–600 mm rainfall zone around Lismore, 10 unmanaged *E. cladocalyx* plantations (ranging in age from 34 to 110 years) had a MAI of around 8.91 m^3 ha^{-1} yr^{-1} (i.e. MAI of merchantable stacked firewood that averaged 14.17 m^3 ha^{-1} yr^{-1}) (Theobald *et al*. 2000). Although this estimate was less than our predicted MAI, Hamilton (pers. comm.) suggested that better sites around Lismore could grow *E. cladocalyx* at MAI of 10 m^3 ha^{-1} yr^{-1} over 35 years (i.e. MAI of merchantable stacked firewood of about 16 m^3 ha^{-1} yr^{-1}), and that with improved management and use of selected seed it is quite likely that even higher growth rates can be achieved. For example, the Australian Low Rainfall Tree Improvement Group is producing improved genetic material for species including *E. cladocalyx.* It is expected that use of improved seed now available combined with best practice silviculture could produce improvements of about 20% over current practices (D. Bush, pers. comm.).

Our predictions of *E. cladocalyx* growth were generally consistent with the productivity measures provided by Theobald *et al*. (2000) (Table 11). Based on their data, we calculated that *E. cladocalyx* plantations in the Lismore region have an average stem volume and MAI of 401 m^3 ha^{-1} and
9.37 m^3 ha^{-1} yr^{-1} at age 35 years. This contrasts to *E. cladocalyx* plantations in lower rainfall regions, such as near the Wongan Hills in Western Australia (392 mm), where the stem mass was only 120 t ha^{-1} after 33 years (Hassall and Associates 1999). Similarly, in western Victoria (You-Yangs, Moriac and Horsham; annual rainfall of 400 to 650 mm), Stackpole and Bandarra (2001) found that the stem volume was only 159 to 181 m^3 ha^{-1} in a 33 to 34 year old *E. cladocalyx* plantation, while in the Wimmera (annual rainfall 400 mm) a 33 year old *E. cladocalyx* plantation had a stem volume of only 108 m^3 ha. Indeed, Stackpole and Bandarra (2001) noted that *E. cladocalyx* was likely to grow best in the 600–700 mm rainfall zones between Geelong, Derrinallum, and Lismore, and was reputed to grow more poorly in lower rainfall regions such as far-western Victoria.

Table 11: Observed MAI and stem volume measurements, and estimated aboveground biomass of *E. cladocalyx* in the Lismore (Victoria) region based on data from Theobald *et al.* (2000).

Site	Rotation (yrs)	Stem volume* (m^3 ha^{-1})	MAI* (m^3 ha^{-1} yr^{-1})
1	34	398	11.71
2	36	362	10.06
3	36	321	8.93
4	37	430	11.62
5	48	523	10.90
8	60	315	5.25
9	48	516	10.74
10	60	345	5.74
Average	*45*	*401*	*9.37*

*Used a conversion factor of 0.629 for firewood:solid wood to obtain estimates of stem wood from measurements of available firewood.

There are a number of young *E. cladocalyx* plantations now being monitored for productivity in the 500–783 mm rainfall region of Australia (Table 12). Results from these trials suggest that the aboveground biomass should increase from an average of about 0.46 to 26 t DM ha^{-1} from age 3 to 8 years, while the stem volume should increase from an average of about 0.39 to 17 m^3 ha^{-1} yr^{-1}. Our predictions are fairly consistent with observed growth rates from these trials. We observed an increase in aboveground biomass from approximately 1 to 19 t DM ha^{-1} from age 3 to 8 years, while the stem volume increased from about 1 to 17 m^3 ha^{-1} yr^{-1}.

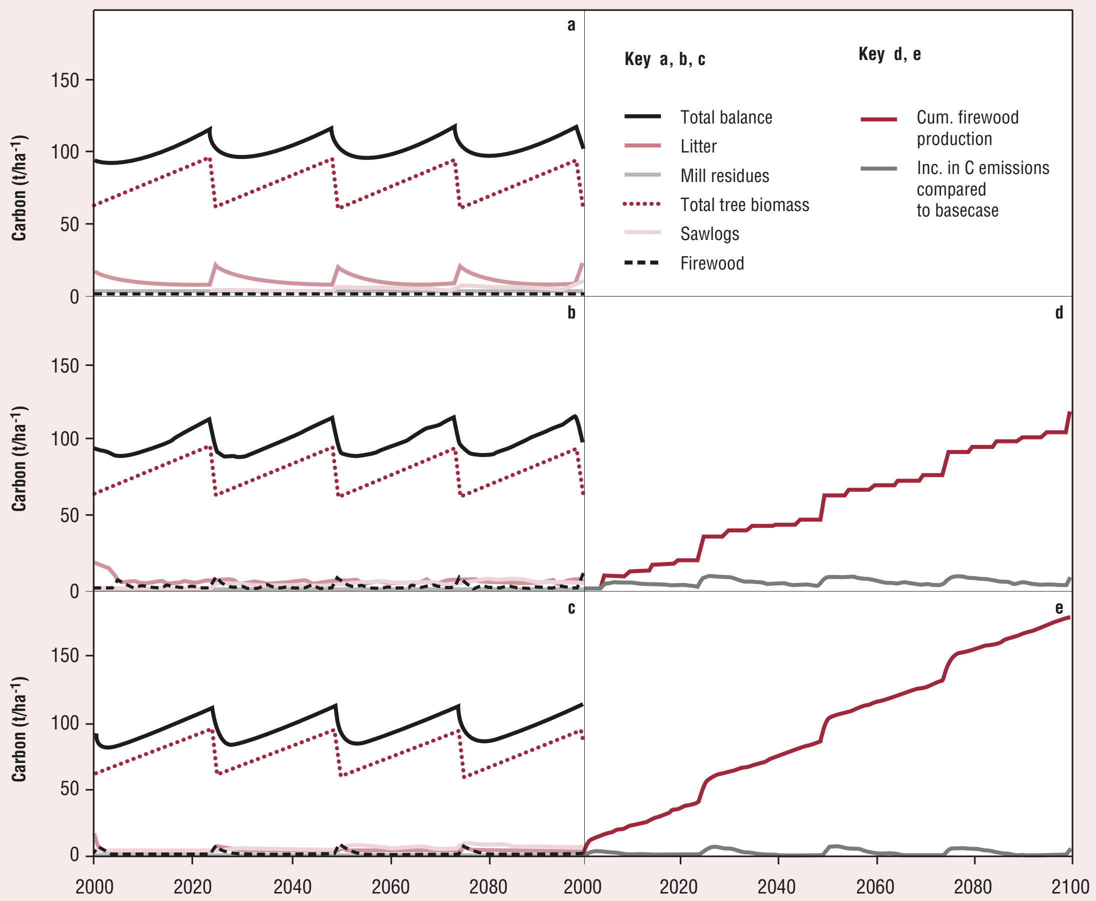

Figure 5: Change in carbon pools in the managed native forests case studies where: (a) no firewood was collected (base case or case study one), (b) firewood was collected from slash residues following selective logging, and also from the collection of dead wood and litter on the ground every five years (case study two), and (c) firewood was collected from slash residues following selective logging, and there was also an annual collection of firewood from both dead trees and dead wood and litter on the ground (case study three). Net accumulation of firewood, and the increase in emissions of carbon as a result of utilisation of firewood (i.e. increase in CO_2 emissions compared to case study one) are given for case study two (d) and case study three (e).

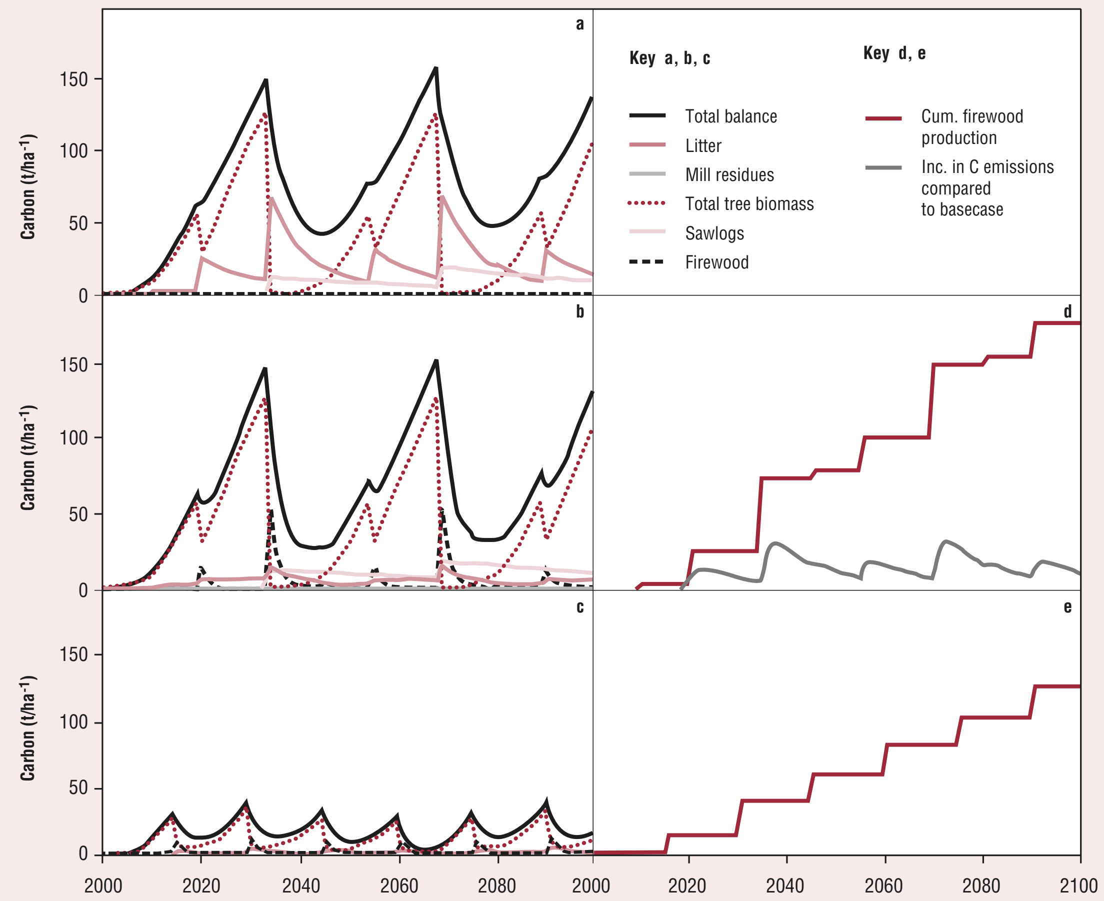

Figure 6: Change in carbon pools in the plantation case studies where: (a) no firewood was collected (base case or case study one), (b) collection of firewood at each thinning and harvesting operation from the thinnings, slash from thinning and harvest, and dead wood and litter on the ground (case study two) (c) collection of firewood from the harvested material, slash, and dead wood and litter on the ground following coppicing every 15 years (case study three). Net accumulation of firewood, and the increase in emissions of carbon as a result of utilisation of firewood (i.e. increase in CO_2 emissions compared to case study one) is given for case study two (d) and net accumulation of firewood is given for case study three (e).

Table 12: Estimated aboveground biomass of *E. cladocalyx* based on height and DBH data from a tree performance database—TREDAT (Vercoe et al. 1997). It was assumed that the main bole of the tree is conical, the biomass of branches and leaves were 25% of the main bole and that stem density was 0.758 t m^{-3}.

Site	Lat.	Long.	Age	Rainfall	Aboveground biomass	Stem volume
			(yrs)	(mm)	(t ha^{-1})	(m^3 ha^{-1})
1	34.50	135.50	3.17	530	0.03	0.03
2	34.50	135.50	3.17	500	0.04	0.02
3	34.55	136.73	3.17	530	0.09	0.10
4	32.72	138.10	3.17	530	0.14	0.16
5	33.03	138.20	3.17	530	0.15	0.17
6	35.57	136.63	3.17	530	0.19	0.22
8	33.03	138.20	3.17	500	0.27	0.11
9	32.72	138.10	3.17	500	0.31	0.13
10	35.57	136.63	3.17	500	0.42	0.18
11	37.97	143.33	3.17	500	0.58	0.24
12	37.97	143.33	3.17	530	0.89	1.04
13	NA	NA	3.42	783	2.38	2.27
14	31.72	148.67	6.25	750	5.95	3.92
15	31.72	148.67	6.25	670	12.95	8.54
16	31.72	148.67	6.25	700	14.39	9.49
17	NA	NA	7.67	600	25.92	17.10

The coppiced plantation case study had a shortened rotation length, and therefore had an average above ground biomass production of only 98.0 t DM ha^{-1} with a MAI and stem volume of 6.52 m^3 ha^{-1} yr^{-1} and 97.9 m^3 ha^{-1}, respectively (Table 10, Fig. 6. Consistently, Holloway (2000) estimated that, for a coppiced plantation on a 15 year rotation, 100 t DM ha^{-1} would be produced. This was equivalent to a MAI of 8.33 m^3 ha^{-1} yr^{-1} (assuming a basic wood density of 0.8 t m^{-3}).

5.4 NET CARBON STORAGE IN MATERIAL ON THE GROUND

Net carbon storage in the material on the ground such as litter and coarse woody debris, was estimated using the FullCAM model and assumed rates of turnover of eucalypt tree components, and their subsequent decomposition (Section 3.4).

5.4.1 Woodlands

Given that the rate of tree stocking in the woodlands example was only about 58 stems per hectare, the mass of litter on the ground is unlikely to be very high. Following removal of firewood, we predicted an average of only 7.16 (case study 2) and 3.06 (case study 3) t DM ha^{-1} over the 100 year simulation period (Table 13, Fig. 4). However, in the absence of firewood collection, we predicted that the mass of litter averaged only about 13.4 t DM ha^{-1} over the 100 year simulation period. This was consistent with the observation that woodlands in south-eastern Australia have a litter mass of 10 to 14.4 t DM ha^{-1} (Gill *et al.* 1981).

Table 13: Predicted total mass of material on the ground (including fine litter and coarse woody debris), and mass of the coarse woody debris, in the woodland, native forest and plantation case studies.

	Total mass (t DM ha^{-1}) Pre-harvest	Total mass (t DM ha^{-1}) Post-harvest	Coarse wood (t DM ha^{-1}) Pre-harvest	Coarse wood (t DM ha^{-1}) Post-harvest
*Woodlands**				
Case 1	13.4	NA	6.11	NA
Case 2	7.16	NA	2.30	NA
Case 3	3.06	NA	0.49	NA
Native forest				
Case 1	14.3	40.7	5.36	30.4
Case 2	10.0	10.3	2.36	5.97
Case 3	3.84	9.37	0.42	5.63
Plantations				
Case 1	44.5	278	25.8	21.2
Case 2	23.2	55.5	4.91	38.6
Case 3	11.9	20.6	4.40	16.3

*Average over the 100 year simulation period

Based on a review of coarse woody debris in Australian forest ecosystems, Woldendorp *et al.* (2002) found that average mass of litter in woodlands was 14.7 t DM ha^{-1} (n=13, ranging between 3.9 and 35.5 t DM ha^{-1} with a standard deviation of 8.2 t DM ha^{-1}), while the amount of coarse wood on the ground averaged 21.6 t DM ha^{-1} (n=4, ranging between 11.6 and 40.0 t DM ha^{-1} with a standard deviation of 13.1 t DM ha^{-1}). In the absence of firewood collection from woodlands, we predicted that coarse wood on the ground averaged only 6.11 of the total 13.4 t DM ha^{-1} of litter. This was probably due to our assumption of a small but steady rate of tree mortality of 0.7% per year whereas tree death is likely to occur irregularly and result in periodically high accumulations of dead wood. Furthermore, the assumed rates of decomposition of dead wood are probably slower than predicted using FullCAM. In the version of FullCAM used, we assumed no water limitation to decomposition, when in fact low moisture content in such low rainfall regions would limit decomposition.

5.4.2 Native Forests

Following removal of firewood, we predicted that mass of material on the forest floor was no greater than about 10 t DM ha^{-1} (Table 13, Fig. 5). However, in the absence of firewood collection, we predicted that prior to a harvest event, mass of material on the forest floor averaged 14.3 t DM ha^{-1}, of which 5.36 t DM ha^{-1} was coarse wood. Consistently, Watson (1977) observed that for native forests in the Armidale area of NSW, the mass of litter on the forest floor was 12.65 t DM ha^{-1}. Similarly, Hutson (1985) predicted that litter mass under native forests (*E. obliqua-E. baxteri*) in a low rainfall (690 mm) region was only 11.53 t DM ha^{-1}. Others (Maheswaran and Attiwill 1987; Adams and Attiwill 1986; Crockford and Richardson 1998) have found that in 75 to 100 year old native forests in low rainfall regions (570–850 mm) of south-eastern Australia, the total mass of litter on the forest floor ranged between 10 and 22 t DM ha^{-1}.

Based on a review of coarse woody debris in Australian forest ecosystems, Woldendorp *et al.* (2002) also found that the average mass of litter in dry sclerophyll forests was 14.3 t DM ha^{-1} (n=32, ranging between 1.5 and 46.2 t DM ha^{-1} with a standard deviation of 9.5 t DM ha^{-1}), while the amount of coarse wood on the ground averaged 50.9 t DM ha^{-1} (n=14, ranging between 5.1 and 221.1 t DM ha^{-1} with a standard deviation of 64.4 t DM ha^{-1}). Although our predictions of coarse wood on the ground (5.36 to 30.4 t DM ha^{-1}) were less than the average observed by Woldendorp *et al.* (2002), they were within the range expected.

5.4.3 Plantations

It was predicted that prior to harvest, the litter layer mass had built up to an average of 44.5 t DM ha^{-1} in the absence of firewood collection (Table 13) of which 25.8 t DM ha^{-1} comprised coarse wood. These predictions of litter mass and coarse woody material on the ground were in the range observed by Woldendorp *et al*. (2002) for eucalypt plantations. They found that although litter mass averaged 13.6 t DM ha^{-1} (n=24, standard deviation of 9.0 t DM ha^{-1}), it ranged between 2.7 and 39.4 t DM ha^{-1}, and while the amount of course wood on the ground averaged 10.3 t DM ha^{-1} (n=14, standard deviation of 12.1 t DM ha^{-1}), it ranged between 1.2 and 49.0 t DM ha^{-1}. Similarly, Jones *et al*. (1999) found that *E. globulus* plantations grown in low rainfall regions (600–650 mm) had a total litter layer mass of 30 to 39 t DM ha^{-1}, of which 19 to 28 t DM ha^{-1} was coarse woody material.

Collecting a majority of the slash and litter for firewood production at thinning and harvesting events decreased the litter layer mass to only 23.2 t DM ha^{-1} (Table 13). If the plantation was coppiced for the purpose of firewood collection, we predicted that litter layer mass averaged only 11.9 t DM ha^{-1}.

5.5 NET CARBON STORAGE IN HARVESTED PRODUCTS

Net carbon storage in harvested products was estimated using the FullCAM model with assumed rates of thinning, harvesting and recovery of thinned/harvested material (Section 4.1) for each case study, and also were general assumptions made regarding decomposition of sawlogs, mill residues and firewood (Section 3.5).

5.5.1 Woodlands

It was assumed that the only product being harvested from woodlands was firewood. We predicted that if firewood was collected from fallen timber once every five years, then a total of 137 t DM ha^{-1} of firewood would be available (Table 14), or 6.65 t DM ha^{-1} every five years, which equates to 1.37 t DM ha^{-1} yr^{-1}. If we assumed that firewood was collected on an annual basis from both the ground and dead trees, then it was calculated that a total of 245 t DM ha^{-1} of firewood would be available, or 2.45 t DM ha^{-1} yr^{-1}. Wall (1997, p 108) estimated that 20 to 105 t DM ha^{-1} was available from box/gum woodlands and open forests in the Armidale region.

Table 14: Predicted mass of products produced during the 100 year simulation period of the woodland, native forest and plantation case studies.

	Sawlogs (t DM ha^{-1})	Mill residues (t DM ha^{-1})	Firewood (t DM ha^{-1})
Woodlands			
Case 1	0.00	0.00	0.00
Case 2	0.00	0.00	137
Case 3	0.00	0.00	245
Native forest			
Case 1	28.0	78.3	0.00
Case 2	28.0	78.3	246
Case 3	28.0	78.3	360
Plantations			
Case 1	97.3	276	0.00
Case 2	97.3	276	728
Case 3	0.00	0.00	513

5.5.2 Native Forests

In the native forest case studies, it was predicted that about 7.1 t DM ha^{-1} sawlogs were produced (and 20 t DM ha^{-1} of mill residues) after each (25 year) selective harvest event. Over the 100 year simulation period, this equated to a total sawlog production of about 28 t DM ha^{-1}, and a total mill residue production of 78 t DM ha^{-1} (Table 14).

We predicted that if firewood is collected from dead wood, bark and leaf material on the ground once every five years (case study two), and that most of the slash from harvesting is used for firewood, then a total of 246 t DM ha^{-1} of firewood would be available, or 12.3 t DM ha^{-1} every five years, or 2.46 t DM ha^{-1} yr^{-1}. If we assumed that firewood was collected on an annual basis from both the ground and dead trees, and that most of the slash from harvesting is used for firewood (case study three), then it was calculated that a total of 360 t DM ha^{-1} of firewood would be available, or 3.60 t DM ha^{-1} yr^{-1}. This was in agreement with the findings of Wall (1997, p 108), who calculated that an average of 107 to 250 t DM ha^{-1} of firewood would be available from *E. laevopinea* forests on the Northern Tablelands region of NSW.

5.5.3 Plantations

In the first two plantation case studies, it was predicted that about 48.7 t DM ha^{-1} sawlogs were produced (and 109 t DM ha^{-1} of mill residues) after each harvest. This equated to a total sawlog production of about 97 t DM ha^{-1}, and a total mill residue production of 276 t DM ha^{-1} over the 100 year simulation period (Table 14). No sawlogs or mill residues were produced from the coppiced plantation case study.

It was predicted that, in a *E. cladocalyx* plantation, a total of 728 t DM ha^{-1} would be available after 100 years of collecting a majority of the slash and litter for firewood production at thinning and harvesting events. This is equivalent to 7.28 t DM ha^{-1} yr^{-1}, or 8.82 m^3 ha^{-1} (assuming a conversion factor of 0.825 t m^{-3} for *E. cladocalyx* firewood, Theobald *et al*. 2000). If the plantation was coppiced for the purpose of firewood collection, it was estimated that a total of 512 t DM ha^{-1} of firewood would be available for collection over a 100 year period, or 5.12 t DM ha^{-1} yr^{-1}, or 6.22 m^3 ha^{-1} yr^{-1}. Hamilton (2000) noted that a 34 to 37 year old coppiced *E. cladocalyx* plantation had between 387 and 484 t DM ha^{-1} of firewood available. This would be equivalent to about 8.31 to 10.4 t DM ha^{-1} yr^{-1}, which is slightly higher to the 5.13 t DM ha^{-1} yr^{-1} we observed in case study three.

5.6 CARBON RELEASED DUE TO HARVEST AND TRANSPORT

This section describes how we estimated emissions of CO_2 resulting from production and combustion of fossil fuel used in harvesting and transport operations, and from the actual harvest and transport operations themselves.

5.6.1 Woodlands

The most likely scenario for firewood collection from woodlands is small-scale operation by private collectors, because about half of the firewood collected in Australia each year is collected by small-scale suppliers and wood merchants who primarily collect their firewood from riverine forest and woodlands (Driscoll *et al*. 2000). It was also assumed that the firewood collected from woodlands would be used locally and so would be transported less than 100 km. Therefore, scenario three was assumed to be the most likely harvest and transport scenario for case studies two and three (Table 7). It was calculated that 7.59 and 13.6 t CO_2 were emitted per hectare in case studies two and three respectively, as a result of harvesting and transport of firewood (Table 15).

Table 15: Most likely case study scenarios for harvest and transport of firewood and the total CO_2 emissions resulting from these operations.

	Likely scenario	Emissions from harvest & t'port	Adjusted emissions from harvest & t'port	Firewood Collected	Total emission of CO_2
		(kg CO_2 t^{-1})	(kg CO_2 t^{-1}) *	(t DM ha^{-1})	(t CO_2 ha^{-1})
Woodlands					
Case 1	1	0.00	0.00	0.00	0.00
Case 2	3	68.1	55.2	137	7.59
Case 3	3	68.1	55.2	245	13.6
Native Forest					
Case 1	1	0.00	0.00	0.00	0.00
Case 2	3	68.1	93.8	246	23.1
Case 3	10	51.7	71.2	360	25.6
Plantations					
Case 1	1	0.00	0.00	0.00	0.00
Case 2	10	51.7	50.3	728	36.6
Case 3	10	51.7	50.3	513	25.8

*Adjusted assuming basic density of *E. melliodora* (0.90 t DM m^{-3} green wood) (Ilic *et. al*, 2000) for woodlands, *E. laevopinea* (0.53 t DM m^{-3} green wood) (Bootle, 1983) for native forest and *E. cladocalyx* (0.75 t DM m^{-3} green wood) (Ilic *et. al*, 2000) for plantations instead of the average basic density (0.73 t DM m^{-3} green wood) discussed in the caption to Table 7 (Section 3.6.3).

5.6.2 Native Forests

The most likely scenario for firewood collection from case study two of the native forests is small-scale operation by private collectors where the travel distance is less than 100 km (200 km round trips) (Table 7). In the third case study, scenario 10 is most likely since the maximum amount of firewood would probably be collected in a commercial operation, and since such a large quality of firewood was collected, transport distance is likely to be around 400 km (800 km round trips). It was therefore calculated that, as a result of harvesting and transport of firewood, 23.1 and 25.6 t CO_2 were emitted per hectare in case studies two and three, respectively (Table 15).

5.6.3 Plantations

The utilisation of plantations for firewood production is likely to be a commercial operation, and since such a large quality of firewood is collected, we assumed that it would be transported 400 km to major markets. Therefore scenario 10 was used for both case study two and three (Table 7). We estimated that a total of 36.6 and 25.8 t CO_2 were emitted per hectare in case studies two and three, respectively as a result of harvesting and transport of firewood (Table 15).

5.7 TOTAL GREENHOUSE GAS EMISSIONS

Here we add together the various sources and sinks for carbon in the various case studies for the woodland, native forest and plantation ecosystems. As we are interested in the effect of collecting firewood on CO_2 emissions from these various ecosystems, calculated changes in carbon storage are expressed here as net emission of CO_2. Therefore, within a given case study, a net storage (or removal) of carbon observed over the simulation period would result in a negative (or positive) net emission of CO_2.

5.7.1 Woodlands

The assumptions that the rate of mortality of trees was 0.7% per year, with no tree replacement, meant that there was a net decline in storage of carbon within biomass of trees that was equivalent to 23.1 t CO_2 ha^{-1} (Table 16).

Table 16: Total emission of CO_2 from establishment of trees, ecosystem (growth, decomposition of debris and products), and harvesting and transport of firewood.

	CO_2 emissions (t CO_2 ha^{-1})						
	Establish	Tree biomass*	Debris*	Products*	Sub-Total	Harvest and transport	Total
Woodland							
Case 1	0.00	23.1	10.6	0.00	33.7	0.00	33.7
Case 2	0.00	23.1	25.1	-0.11	48.1	7.59	50.5
Case 3	0.00	23.1	27.2	-3.59	46.7	13.6	60.3
Native forests for sawlog production							
Case 1	0.00	3.92	-2.03	-27.1	-25.2	0.00	-25.2
Case 1+	0.00	3.92	-2.03	0.00	1.89	0.00	1.89
Case 2	0.00	3.92	52.5	-55.7	0.72	23.1	23.9
Case 2+	0.00	3.92	52.5	-28.6	27.8	23.1	50.9
Case 3	0.00	3.92	54.2	-53.5	4.62	25.6	30.2
Case 3+	0.00	3.92	54.2	-26.5	31.6	25.6	57.2
Plantations for sawlog production							
Case 1	0.44	-300	-174	-33.7	-507	0.00	-507
Case 1+	0.44	-300	-174	0.00	-474	0.00	-474
Case 2	0.44	-300	-84.4	-54.9	-439	36.6	-402
Case 2+	0.44	-300	-84.4	-21.2	-405	36.6	-368
Plantations for firewood production							
Case 3	0.44	-83.2	-33.6	-8.82	-126	25.8	-100

*Estimated as the average annual change in carbon (expressed as net CO_2 equivalent emitted) multiplied by 100 years, or as the average accumulation of carbon during a 35-year rotation (plantation case studies 1 and 2), or during a 60-year cycle of four coppiced rotations (plantation case study 3).
+Carbon stored in sawlog products was unaccounted.

As the stand density decreased due to tree mortality, so too did the mass of carbon stored in the pools of debris, this being equivalent to 10.6 t CO_2 ha^{-1} in the absence of firewood collection. Storage of carbon in the debris decreased even further when firewood was collected. When firewood was assumed to be collected every five years (case study two), the debris pool released an equivalent of 25.1 t CO_2 ha^{-1}, and when collected annually (case study three), 27.2 t CO_2 ha^{-1} was released from the debris. Collection and burning of firewood is likely to increase emissions of CO_2 in the short-term because while decomposition of dead wood on the ground may take several decades, firewood is burnt within only two years of collection.

Although no products were produced in the first case study of woodlands, in the other case studies firewood was collected. At the end of the simulation period, a small amount of this collected firewood had not yet been burnt, and so there was a net storage of carbon that was equivalent to a sequestration of 0.11 and 3.59 t CO_2 ha^{-1} (Table 16).

As 137 and 245 t DM ha^{-1} of firewood was collected by small-scale operators that travelled only 100 km to deliver this wood in case studies two and three, respectively (Section 4.6), the total emissions resulting from harvest and transport of firewood was calculated to be between only 7.59 and 13.6 t CO_2 ha^{-1}.

Adding together the carbon stored or released in biomass, debris, products, and harvest and transport, we calculated that in the absence of firewood collection (case study one), net emission of CO_2 from a typical woodland on the Northern Tableland region was only 33.7 t CO_2 ha^{-1}, and was primarily due to tree mortality. However, harvesting 137 t DM ha^{-1} of firewood (case study two) results in a net emission of 50.5 t CO_2 ha^{-1}, while harvesting 245 t DM ha^{-1} of firewood (case study three) results in a net emission of 60.3 t CO_2 ha^{-1}.

Assuming a basic energy content of wood of 5.28 kWhr kg^{-1} of dry weight, and a wood heater efficiency of 62% (Section 4.7), we calculated that 450 MWhr of energy would be produced from the 137 t DM ha^{-1} of firewood collected from case study two. This gave a net emission of greenhouse gas of 0.11 kg CO_2 per kWhr generated. For the 245 t DM ha^{-1} of firewood collected from case study three, we calculated that 804 MWhr of energy was produced, and therefore gave a net emission of greenhouse gas of 0.07 kg CO_2 per kWhr generated. These results suggest that regardless of how firewood was collected from woodlands, there is a net emission of CO_2 due to the burning of this wood for domestic heating. However, it was more efficient in greenhouse terms to collect firewood from the woodland from both the ground and dead trees on an annual basis (case study three) rather than just collecting the dead wood on the ground once every five years (case study two).

5.7.2 Native Forests

Throughout the simulation period, the native forest ecosystem was assumed to be near equilibrium with respect to growth increments, and so there was no emission of CO_2 due to establishment, and emission of CO_2 due to changes in storage of carbon in the tree biomass was slight, being only 3.92 t CO_2 ha^{-1} (Table 16). This could be attributed to the 0.2% per year mortality, and subsequent decline in carbon storage in the tree biomass.

As observed with woodlands, the stand density slightly decreased due to tree mortality and so the mass of carbon stored in the pools of debris also slightly declined, this being equivalent to 2.03 t CO_2 ha^{-1} in the absence of firewood collection. As expected, storage of carbon in the debris decreased even further when firewood was collected, and ranged between 52.5 and 54.2 t CO_2 ha^{-1}.

In all case studies of native forest ecosystems, about 14 t C ha^{-1} was in sawlogs (Section 4.5) and so was largely tied-up as stored carbon. This accounted for an equivalent sequestration of 27.1 t CO_2 ha^{-1} (Table 16). In the case studies where firewood was collected, some of the firewood remained unburnt at the end of the simulation period, and so even more carbon was sequestered. In case study two, an equivalent of 55.7 t CO_2 ha^{-1} was sequestered in wood products, with about half of this (28.6 t CO_2 ha^{-1}) being sequestered in firewood. Similarly in case study three, an equivalent of 53.5 t CO_2 ha^{-1} was sequestered in wood products, with about half (26.5 t CO_2 ha^{-1}) being sequestered in firewood.

In case study two, 246 t DM ha^{-1} of firewood was assumed to be collected by small-scale operators that travelled only 100 km for delivery, and the total emissions resulting from harvest and transport of firewood was calculated to be 23.1 t CO_2 ha^{-1}. Emission resulting from harvest and transport of firewood was calculated to be greater for the third case study, at 25.6 t CO_2 ha^{-1}, and this was due to the assumption that firewood was collected by commercial operators, more firewood was collected (an extra 113 t DM ha^{-1}), and the distance to the market was assumed to be greater compared to the second case study.

Adding amounts of carbon stored or released in biomass, debris, products, and harvest and transport, we calculated that in the absence of firewood collection (case study 1), in a typical native forest in the Northern Tableland region, there was a net sequestration of carbon equivalent to 25.2 t CO_2 ha^{-1}. However, harvesting 246 t DM ha^{-1} of firewood (case study 2) results in a net emission of 23.9 t CO_2 ha^{-1}, while harvesting 360 t DM ha^{-1} of firewood (case study 3) results in a net emission of 30.2 t CO_2 ha^{-1}.

We calculated that 806 MWhr of energy was produced from the 246 t DM ha^{-1} of firewood collected from case study two that the basic energy content of wood was assumed to be 5.28 kWhr kg^{-1}, and the efficiency of combustion was 62% (Section 4.7). This gave a net emission of only 0.03 kg CO_2 per kWhr generated. If we do not count the carbon stored in sawlog products, then we would expect a net emission of 0.06 kg CO_2 per kWhr generated. For the 360 t DM ha^{-1} of firewood collected from case study three, we calculated that 1,177 MWhr of energy was produced, and therefore gave a net emission of greenhouse gas of only 0.03 kg CO_2 per kWhr generated, or 0.05 kg CO_2 per kWhr not accounting for carbon stored in sawlog products. These results suggest that regardless of how firewood was collected from native forests, the net emission of CO_2 due to the burning of this wood for domestic heating was relatively small per unit of energy generated. Thus there is a significant benefit in terms of fossil fuel emissions.

5.7.3 Plantations

There is an emission of 0.44 t CO_2 ha^{-1} during the establishment of new plantations on ex-farmland (Section 4.2). Because the net storage of carbon in farmland was assumed to be zero, so as the trees grew, there was large increase in carbon storage in the plantation. This was equivalent to a net sequestration of 300 t CO_2 ha^{-1} after a 35 year rotation (case studies 1 and 2), or 83.2 t CO_2 ha^{-1} after a cycle of four coppiced rotations (after which the stand was re-planted, case study three) (Table 16).

The storage of carbon in debris was assumed to be zero in farmland, but as the plantation grew and eventually produced litter, carbon was stored in coarse woody debris. This resulted in an average net sequestration of carbon of 174 t CO_2 ha^{-1} in the absence of firewood collection (case study one). However when firewood was removed, an average of only 84.4 t CO_2 ha^{-1} was sequestered in debris during a 35 year rotation. In a coppiced plantation grown for the purpose of firewood collection, an average of only 33.6 t CO_2 ha^{-1} was sequestered in debris.

On average over a 35 year rotation, an equivalent of 33.7 t CO_2 ha^{-1} was sequestrated in sawlogs (Table 16). Where firewood was also collected in case study two, it resulted in even more carbon being sequestered (in products), totalling 54.9 t CO_2 ha^{-1}, with carbon stored in firewood contributing a sequestration of 21.2 t CO_2 ha^{-1}. In contrast, where trees were coppiced (case study three), no sawlogs were produced to effectively tie up the carbon, and so an equivalent of only 8.82 t CO_2 ha^{-1} was sequestered in the firewood.

Emission resulting from harvest and transport of firewood was relatively high in the plantation case studies, being 36.6 t CO_2 ha^{-1} in case study two where 728 t DM ha^{-1} of firewood was collected, and 25.8 t CO_2 ha^{-1} in case study three where 513 t DM ha^{-1} of firewood was collected. Not only was the amount of firewood collected relatively large compared to that collected under woodlands and native forests, but it was also assumed that the commercial operators that collected the firewood from plantations transported it a relatively large distance (i.e. 400 km one-way).

Adding together the carbon stored or released in establishment, biomass, debris, products, and harvest and transport, we calculate that in the absence of firewood collection (case study one), in a typical plantation near Lismore, there was a net sequestration of carbon on site equivalent to 507 t CO_2 ha^{-1}. This value decreased as a result of the collection of firewood. Harvesting 728 t DM ha^{-1} of firewood (case study two) resulted in an average sequestration of carbon of

402 t CO_2 ha^{-1}. Since the plantation was newly established on ex-farmland, most of this carbon (74%) was sequestered as a result of the average increase in biomass at the site. Where coppiced plantations were established for firewood collection (case study three), a total 513 t DM ha^{-1} of firewood was estimated to have been available, and resulted in an average sequestration of 100 t CO_2 ha^{-1}, again with most of this (83%) sequestered in tree biomass.

Assuming a basic energy content of wood of 5.28 kWhr kg^{-1} of dry weight, and a wood heater efficiency of 62% (Section 4.7), we calculated that 2,384 MWhr of energy was produced from the 728 t DM ha^{-1} of firewood collected from case study two. This gave a net sequestration of 0.17 kg CO_2 per kWhr, or 0.15 kg CO_2 per kWhr if we do not count the carbon stored in sawlog products. For the 513 t DM ha^{-1} of firewood collected from case study three, we calculated that 1,679 MWhr of energy was produced, and therefore gave a net sequestration equivalent to 0.06 kg CO_2 per kWhr generated. These results suggest that regardless of how firewood was collected from plantations, the accumulation of carbon in the tree biomass and in dead wood meant there was a net sequestration of CO_2 following establishment of the plantation and removal of firewood. However, it was more efficient to collect firewood from the thinnings and residues left after harvest than from harvesting coppiced trees grown for the purpose of firewood production.

5.8 SENSITIVITY ANALYSIS

In Section 4.8 we outlined some of the inputs to FullCAM and we assumed values that were uncertain or could easily be within a given range. We estimated a minimum and maximum value that these inputs were likely to have (Table 9). Below we describe how the range in value of these inputs within the second case study of each ecosystem affected: (i) predicted net emissions of CO_2, (ii) amount of firewood collected, and (iii) the net cost (in terms of net emission of CO_2) of the energy produced from burning the firewood for domestic heating.

Table 17: Sensitivity analysis results for woodlands case study two.

	Total CO_2equivalent (t CO_2 ha^{-1})		Total firewood collected (t DM ha^{-1})		Net CO_2 cost for energy (kg CO_2 $kWhr^{-1}$)	
Input	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Default	50.5	–	137	–	0.11	–
Growth rates	67.3	18.4	131	143	0.17	0.06
Mortality fraction (7%)	-46.7	108	142	132	-0.08	0.25
Thinning fraction	NA	NA	NA	NA	NA	NA
Rotation length	NA	NA	NA	NA	NA	NA
Rates of decomp. of debris	30.3	57.7	159	115	0.06	0.15
Collection of material from ground	48.4	52.3	118	155	0.12	0.10
Recovery of products	NA	NA	NA	NA	NA	NA
Rates of decomp. of products	45.6	55.8	137	137	0.10	0.12
Harvest efficiency (private collector)	48.2	52.7	137	137	0.11	0.12
Harvest efficiency (commercial operation)	NA	NA	NA	NA	NA	NA
Distance travelled (private collector)	47.9	54.6	137	137	0.11	0.12
Distance travelled (commercial operation)	NA	NA	NA	NA	NA	NA
Efficiency of wood heater	50.5	50.5	137	137	0.70	0.10

5.8.1 Woodlands

The sensitivity analysis indicated that for woodlands, the main factors influencing the amount of CO_2 emitted per unit of energy generated were the efficiency of the wood heater (which could vary between 10% for open fires to 70% for slow combustion stoves), the mortality of trees (which could vary between 0.20 and 1.20% per year), and the assumed growth increments of woodlands (assumed to be within the range of plus or minus 30% of the default value) (Table 17 and Fig. 7). Assumed rates of decomposition of debris were also important, although other factors such as efficiency of harvesting firewood and the distance the wood was transported, were less important.

5.8.2 Native Forests

Table 18 and Figure 8 show that for native forests, the main factors influencing the amount of CO_2 emitted per unit of energy generated were the assumed growth increments of native forests (assumed to be within the range of plus or minus 30% of the default value), the efficiency of the wood heater (which could vary between 10% for open fires to 70% for slow combustion stoves), rates of decomposition of products (which for sawlogs, could vary between 0.1 and 5% per year), frequency of selective harvest operations (which could vary between 20 and 30 years) and the fraction of stems removed in each selective logging event (which could vary between 33 and 43%). Other factors were less important, particularly the fraction of dead wood or other litter on the ground that was collected.

Table 18: Sensitivity analysis results for native forest case study two.

	Total CO_2equivalent (t CO_2 ha^{-1})		Total firewood collected (t DM ha^{-1})		Net CO_2 cost for energy (kg CO_2 $kWhr^{-1}$)	
Input	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Default	23.9	–	246	–	0.03	–
Default (with sawlogs excluded)	50.9	–	246	–	0.06	–
Growth rates	111	-63.1	203	289	0.17	-0.07
Mortality fraction (0.06, 0.34)	4.63	42.9	249	248	0.01	0.05
Thinning fraction	-18.7	61.4	247	247	-0.02	0.08
Rotation length	78.0	-2.73	244	242	0.10	0.00
Rates of decomp. of debris	-11.5	38.8	279	222	-0.01	0.05
Collection of material from ground	21.0	27.1	227	270	0.03	0.03
Recovery of products	4.71	23.9	192	255	0.01	0.03
Rates of decomp. of products	-41.2	63.1	246	246	-0.05	0.08
Harvest efficiency (private collector)	17.1	30.6	246	246	0.02	0.04
Harvest efficiency (commercial operation)	NA	NA	NA	NA	NA	NA
Distance travelled (private collector)	16.1	36.5	246	246	0.02	0.05
Distance travelled (commercial operation)	NA	NA	NA	NA	NA	NA
Efficiency	23.9	23.9	246	246	0.18	0.03

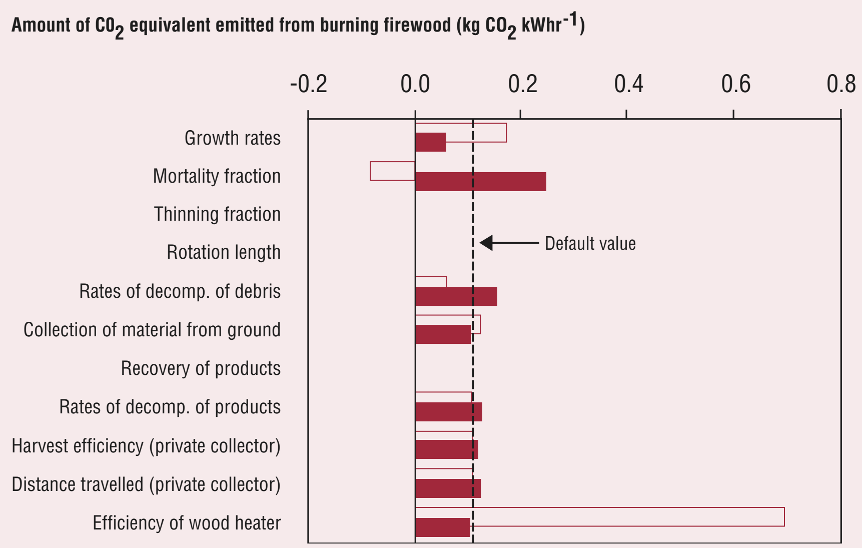

Figure 7: Calculated amount of CO_2 equivalent generated from the burning of firewood collected from the woodland case study two when key input values are varied between the minimum (clear bars) and maximum (red bars) value expected. Black dotted line indicates the amount of CO_2 equivalent generated when default values were used for key inputs.

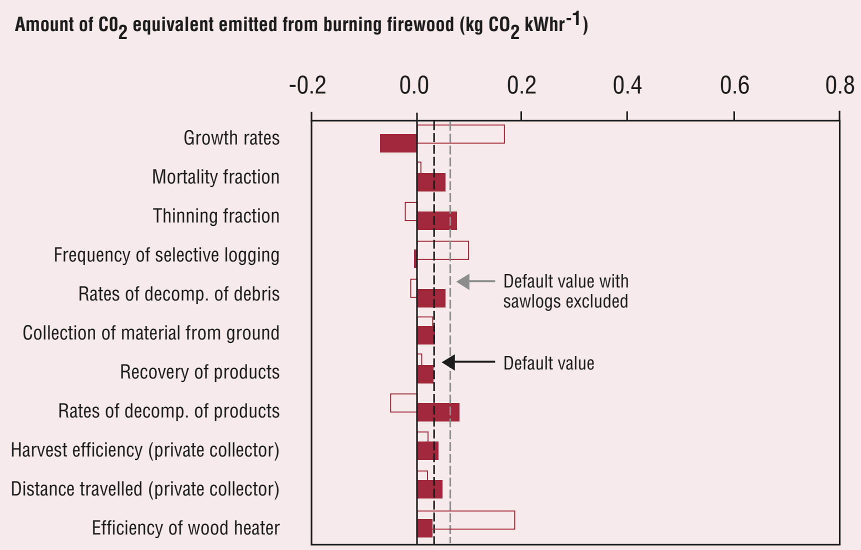

Figure 8: Calculated amount of CO_2 equivalent generated from the burning of firewood collected from the native forest case study two when key input values are varied between the minimum (clear bars) and maximum (red bars) value expected. Black dotted line indicates the amount of CO_2 equivalent generated when default values were used for key inputs. Grey dotted line indicates the amount of CO_2 equivalent generated when default values were used for key inputs and it was assumed that there was no accumulation of carbon in sawlog products.

5.8.3 Plantations

The sensitivity analysis indicated that for a plantation grown on a 35 year rotation, the main factors influencing the amount of CO_2 emitted per unit of energy generated were the efficiency of the wood heater (which could vary between 10% for open fires to 70% for slow combustion stoves), recovery of products following a thinning or harvest event, the length of the rotation (which could vary between 30 and 40 years), and decomposition rates of products (Table 19 and Fig. 9). We assumed that in a low firewood collection scenario, recovery of products would entail the collection of between only 5 and 10% of the stem, branch and bark slash (Table 9), while in a high firewood collection scenario, recovery of products would entail the collection of 45% of the stems, and 90% of the branches and bark slash. Interestingly, growth rates and thining fractions were relatively unimportant in influencing the amount of CO_2 emitted per unit of energy generated from the burning of plantation firewood.

Table 19: Sensitivity analysis results for plantation case study two.

	Total CO_2 equivalent ($t\ CO_2\ ha^{-1}$)		Total firewood collected ($t\ DM\ ha^{-1}$)		Net CO_2 cost for energy ($kg\ CO_2\ kWhr^{-1}$)	
Input	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Default	-402	–	728	–	-0.17	–
Default (with sawlogs excluded)	-369	–	728	–	-0.15	–
Growth rates	-281	-523	510	947	-0.17	-0.17
Mortality fraction	NA	NA	NA	NA	NA	NA
Thinning fraction	-414	-390	716	740	-0.18	-0.16
Rotation length	-275	-427	785	668	-0.11	-0.20
Rates of decomp. of debris	-449	-380	768	698	-0.18	-0.17
Collection of material from ground	-404	-401	713	742	-0.17	-0.16
Recovery of products	-435	-397	489	762	-0.27	-0.16
Rates of decomp. of products	-453	-370	728	728	-0.19	-0.16
Harvest efficiency (private collector)	NA	NA	NA	NA	NA	NA
Harvest efficiency (commercial operation)	-416	-389	728	728	-0.17	-0.16
Distance travelled (private collector)	NA	NA	NA	NA	NA	NA
Distance travelled (commercial operation)	-416	-373	728	728	-0.17	-0.16
Efficiency	-402	-402	728	728	-1.05	-0.15

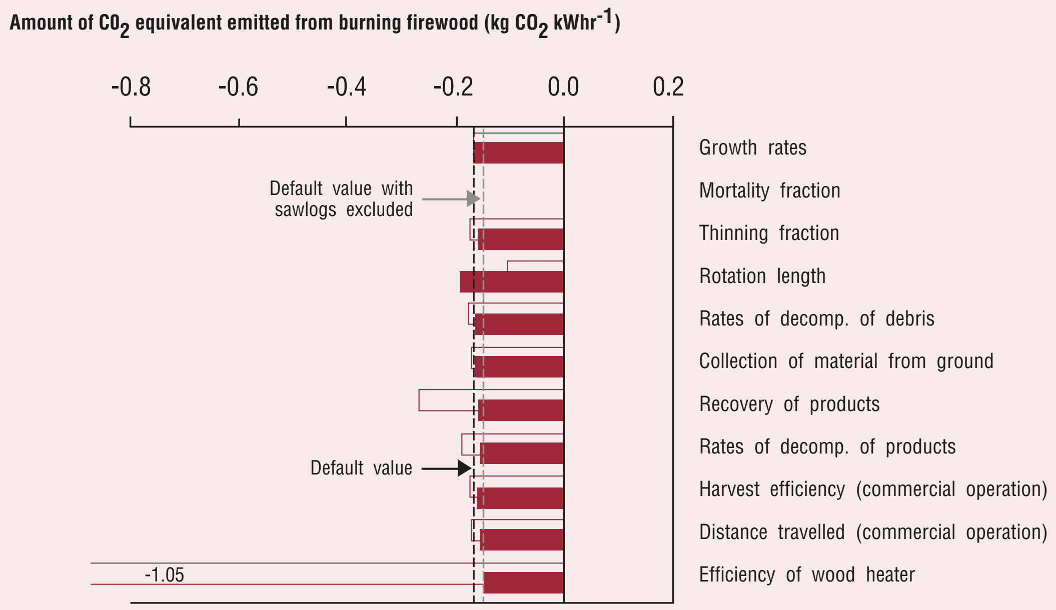

Figure 9: Calculated amount of CO_2 equivalent generated from the burning of firewood collected from the plantation case study two when key input values are varied between the minimum (clear bars) and maximum (red bars) value expected. Black dotted line indicates the amount of CO_2 equivalent generated when default values were used for key inputs. Grey dotted line indicates the amount of CO_2 equivalent generated when default values were used for key inputs and it was assumed that there was no accumulation of carbon in saw log products.

SIX

CONCLUSIONS

Storage of carbon in biomass of trees, debris, and in harvested products (i.e. sawlogs, mill residues and firewood), and the release of carbon as a result of establishment of trees, harvest and the subsequent transport of products all contributed to the predicted net change in storage of carbon in the woodland, native forest and plantation ecosystems that were simulated. Plantations sequestered much more carbon in the tree biomass and debris pools than the other two ecosystems, and this was not fully offset by the release of carbon due to the greater energy costs associated with the establishment, harvest and transport operations in plantation systems. Woodland systems were degrading because old dying trees were not being replaced, while native forests were in a state of near equilibrium with respect to increments of tree growth. Therefore, in plantations there was a net sequestration of carbon that was equivalent to about 100 to 500 t CO_2 ha^{-1}, while less than about 25 t CO_2 ha^{-1} was sequestered in native forests, and there was a release of between about 30 and 60 t CO_2 ha^{-1} in woodland ecosystems.

Collection of firewood decreased storage of carbon in the debris pool, and this was not fully offset by an increased storage of carbon in the product pool because firewood is generally burnt within two years of collection. Therefore in woodlands, when firewood was collected every five years from the ground, net emission of greenhouse gas increased by 20.0 t CO_2 ha^{-1}, and when firewood was collected each year from both the ground and dead trees, an extra 26.6 t CO_2 ha^{-1} was emitted (Table 16). Similarly, when firewood was collected from slash following harvest of native forests every 25 years, as well as being collected from material on the ground every five years, net emission of greenhouse gas increased by 49.0 t CO_2 ha^{-1}. Collection of firewood from slash following harvest every 25 years in addition to the annual collection of firewood from material on the ground and from dead trees, resulted in an extra 55.4 t CO_2 ha^{-1} being emitted. In the plantation ecosystem, the collection of firewood decreased storage of carbon by an equivalent of 107 t CO_2 ha^{-1} when wood was collected from thinnings, slash and material on the ground. The collection of firewood from coppiced logs, slash and material on the ground resulted in an increased storage of carbon equivalent to 100 t CO_2 ha^{-1}.

It was beyond the scope of the present study to attempt a complete analysis of the substitution opportunities firewood might offer across a range of circumstances for a variety of energy sources. However, a simplified analysis was carried out to allow some provisional comparisons to be made.

When firewood from the woodland ecosystem was used for domestic heating, we calculated that the net amount of greenhouse gas emitted decreased from 0.11 to 0.07 kg CO_2 per $kWhr^{-1}$ of heat produced as the amount of firewood removed from the system (and therefore the amount of heat energy produced) increased from 137 to 245 t DM ha^{-1} (and from 450 to 804 MWhr ha^{-1}). In the native forest ecosystem, we calculated that as the net change in storage of carbon over the simulation period was so small, the net amount of CO_2 emitted as a result of burning collected firewood was negligible (<0.03 kg CO_2 per $kWhr^{-1}$ of heat produced) regardless of whether 246 or 360 t DM ha^{-1} of firewood was collected. We calculated that the net amount of greenhouse gas sequestered was 0.17 kg CO_2 per $kWhr^{-1}$ of heat produced from burning the 728 t DM ha^{-1} of firewood collected from plantations on a 35 year rotation. However if a plantation was coppiced for the purpose of firewood production, over a cycle of four coppiced rotations (before re-planting), the average accumulation of carbon in the tree biomass and debris was much smaller than the average accumulation of carbon during a 35 year rotation. Therefore, only 0.06 kg CO_2 per $kWhr^{-1}$ of heat was produced from burning the 513 t DM ha^{-1} of firewood collected from coppiced plantations.

Based on the assumptions we have made in this study (Section 4), we found that, in terms of limiting net greenhouse gas emissions, firewood is generally more favourable for domestic heating than other non-renewable sources of energy. There is a direct substitution of fossil fuel emissions, with little additional emissions associated with the production and collection of firewood (Figure 10). This was particularly so when firewood was collected from the thinnings, slash and other residues of a commercially grown plantation (Figure 6).

Currently, only 10.5% of Australia's electricity comes from renewable power. Of this renewable power source, 78% comes from the burning of biomass (half of this biomass being wood, and the rest bagasse), while hydro- and wind-energy account for only 21% and 1% of the renewable energy utilised (http://www.greenhouse.gov.au/renewable/overview.html). However, when compared to other renewable sources of energy, firewood was not always the most favourable source in terms of limiting greenhouse gas emissions. For example when not including greenhouse gas emission resulting from the operation and construction schemes, hydro-electricity results in no release of greenhouse gases during the production of electricity, yet utilising firewood from native forests and woodlands does.

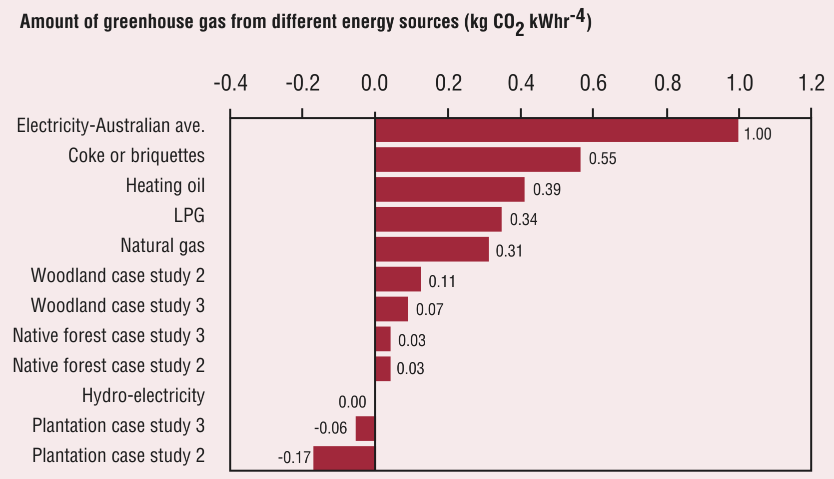

Figure 10: Comparison of CO_2 released per unit of energy produced (kg CO_2 $kWhr^{-1}$) for different sources of domestic heating. Data on non-firewood energy sources comes from AGO (2002). Note that it is assumed that: (i) firewood is burnt at 62% efficiency, (ii) electricity is used by a radiator or fan heater at 100% efficiency (use of a reverse-cycle air conditioner could reduce emissions per unit of heat delivered by about two-thirds), (iii) greenhouse gases generated by electricity supply are averaged across Australia except for Tasmania, where hydro-electricity is used, and (iv) greenhouse gases generated during the operation and construction of power plants are not included.

Clearly, there are a lot of broad assumptions made when simulating case studies for systems we know relatively little about. This means that we need to be cautious when making inferences from the results presented above. Although our results do indicate that using firewood from woodlands was better than most other forms of domestic heating in terms of limiting emission of greenhouse gases, one must be careful when evaluating firewood use from woodlands. This is due to our sensitivity analysis indicating that emission of greenhouse gases would actually be equal to or higher than alternative forms of heating if growth rates were only 70% of our assumptions, and if tree mortality was slightly higher at 1.2% per year, or if the firewood was burnt in an open fireplace rather than in an open fire insert or another type of wood heater. All of these assumptions are within realistic expectations. Furthermore, as discussed in Section 3, many remnant woodlands are degrading, and in the interest of maintaining biodiversity, extra pressure must not be placed on these ecosystems through firewood harvest that threatens maintenance of habitat including dead wood or standing dead trees.

Native forests may potentially be an efficient source of firewood for domestic heating as long as the increment of growth was greater than 2.38 m^3 ha^{-1} (i.e. at least 70% of our default assumption). Our results suggest that a minimum amount of carbon will be emitted if firewood is only collected about every five years from dead wood and other litter on the ground.

It is most favourable to collect firewood for domestic heating from newly established plantations, particularly when firewood is collected (from thinnings, slash, and other material on the ground) as part of a commercial operation in a plantation established for production of sawlogs. Sensitivity analysis indicated that even when this firewood is burnt in an open fireplace (with an efficiency of only 10%), there is still a net sequestration of carbon due to carbon storage, particularly in the new standing forest. Growing a coppiced plantation solely for the purpose of firewood production was also very favourable in terms of emission of greenhouse gas.

In our study, plantations were assumed to be established on ex-farmland that initially stored no carbon, and so we predicted a large increase in the storage of carbon in these ecosystems. Such a scenario is clearly ideal in that it allows for both the production of heat energy from firewood, and also an increased storage of carbon. However, if plantations were grown either as a sustainably managed second rotation, or on an ex-native forest site, then it is likely that carbon storage would either not increase or increase slightly. Such systems would then be comparable to the native forest case studies simulated in this report. Therefore, even if plantations are not established on ex-farmland, firewood collection from these systems would still be more favourable in terms of greenhouse gas emissions than using other alternative sources of energy.

SEVEN

REFERENCES

Adams, M.A., and Attiwill, P.M. (1986). Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. II. Indices of nitrogen mineralization. Plant and Soil, 92, 341–362.

AFFA (2003). Data obtained from the web site of Agriculture, Fisheries and Forestry Australia www.affa.gov.au

AGO (1998). National Greenhouse Gas Inventory. Land Use Change and Forest Sector 1990–1996. Australian Greenhouse Office, Canberra.

AGO (2001). Emission factors for transport fuels. Australian Greenhouse Office, Canberra. From http://www.greenhouse.gov.au/ggap/internet/transval.html

AGO (2002). Global Warming Cool it: A home guide to reducing energy costs and greenhouse gases. Australian Greenhouse Office, Canberra.

ANZECC (2001). National approach to firewood collection and use in Australia. Australian and New Zealand Environment and Conservation Council, Canberra. 40 pp.

Athanassiadis D. (2000). Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. 255: 135–143.

Baldwin, G.J. (1994). Age and size class reconstruction of a eucalypt forest using forest inventory and dendrochronological techniques. Nat. Res. Thesis, Department of Ecosystem Management, University of New England, Armidale. 98 pp.

Beer, T., Grant, T., Williams, D., and Watson, H. (2002). Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. Atmospheric Environment, 36: 753–763. See also paper by same authors produced for the AGO in 2001 available at: http://www.greenhouse.gov.au/transport/comparison/index.html

Berg S. (1995). The environmental load of fossil fuels in Swedish forestry—an inventory for an LCA. In: Fruhwald, A. and Sol-berg, B., editors. EFI Proceedings No. 8, Hamburg, Germany, 53–60.

Bootle, K.R. (1983). Wood in Australia. Types, properties and uses. McGraw-Hill, Sydney, Australia

Burrows, W.H., Hoffmann, M.B., Compton, J.F., Back P.V., Tait, L.J. (2000). Allometric relationships and community biomass estimates for some dominant eucalypts in Central Queensland woodlands. Australian Journal of Botany, 48, 707–714.

CAB International (2001). Forestry Compendium – Global Module. CABI International, Wallingford. CD-ROM.

Chudleigh, P., and Zoretto, A. (1999). Commercial prospects for low rainfall agroforesty. Rural Industries Research and Development Corportation, 1999.

Crockford, R.H., and Richardson, D.P. (1998). Litterfall, litter and associated chemistry in a dry sclerophyll eucalypt forest and pine plantation in south-eastern Australia. I. Litterfall and Litter. Hydrological Processes; 12: 365–384.

Driscoll, D.A., Milkovits, G. and Freudenberger, D. (2000). Impact and use of firewood in Australia. CSIRO Sustainable Ecosystems, Canberra. 62 p.

EEC (2001). Box-ironbark forests & woodlands investigation : final report. Environment Conservation Council. East Melbourne, Vic.

Fitzpatrick T. (2001). Note on diesel usage rates for post harvest recovery of residues for fuel and implications for net CO_2 emissions. Forestry Tasmania, Technical Report.

Fung, P.Y.H., Kirschbaum, M.U.F., Raison, R.J., and Stuckley, C. (2002) Biomass and Bioenergy 22: 223–236

Gifford, R.M. (2000). Carbon contents of above-ground tissues of forest and woodland trees. National Carbon Accounting System Technical Report No. 22. Australian Greenhouse Office, Canberra. 18 pp.

Gill, A.M., Groves, R.H., and Noble, I.R. (1981). Fire and the Australian Biota. Australian Academy of Science, Canberra.

Grierson, P.F., Adams, M.A., and Attiwill, P.M. (1991). Carbon storage in soil and in forest products. SECV Report. p 18, table 3.

Grierson, P.F., Adams, M.A., and Attiwill, P.M. (1992). Estimates of the carbon storage in the above-ground biomass of Victoria's forests. Australian Journal of Botany. 40: 631–640.

Groves, K. W. and Chivuya, A.M. (1989). Firewood evaluation of four Australian-grown tree species. In Boland, D.J. (ed.). Trees for The Tropics. Australian Centre for International Agricultural Research, Canberra. 159–169 pp.

Hamilton, L. (2000). Commercial sugar gum plantations for firewood and sawlog production. In Anon. (ed.) A Burning Issue: shifting the firewood and escalating firewood industries from woodlands to plantations. Bendigo, 8–9 June 2000. Victorian National Parks Assocation.

Hassall & Associates (1998). Carbon sequestration in low rainfall areas: the measurement of plantations of trees in Victoria. Environment Australia, Canberra.

Hassall & Associates (1999). The measurement of plantations of trees in Western Australia to improve the estimates of carbon sequestration in low rainfall areas. Environment Australia, Canberra.

Hinkel, K. M. (1989). Wood burning for residential space heating in the United States: an energy efficiency analysis. Applied Geography. 9: 259–272.

Holloway, R. (2000). Carbon credits, firewood and firewood production. In Anon. (ed.) A Burning Issue – shifting the firewood and escalating firewood industries from woodlands to plantations. Bendigo, 8–9 June 2000. Victorian National Parks Association.

Hopkins, A. (2002). Farmers barking up the right tree. The Age, 18-6-2002, p. 5.

Horne, R. (1994). Thinning schedules for blackbutt regrowth forests. State Forest of NSW Technical Paper 54.

Hutson, B.R. (1985). Rates of litterfall and organic matter turnover at three South Australian indigenous forest. Aust. J. Ecol. 10: 351–359.

Ilic, J., Boland, D., McDonald, M., Downes, G., and Blakemore, P. (2000). Wood Density Phase 1 – State of Knowledge. Australian Greenhouse Office, Canberra, Australia, NCAS Technical Report No. 18. 218 pp.

Jaakko Poyry (1999). Usage and Life Cycle Analysis of Wood Products. National Carbon Accounting System Technical Report No. 8. Australian Greenhouse Office, Canberra. 78 pp.

Jones, H.E., Madeira, M., Herraez, L., Deighton, J., Fabiao, A., Gonzalez-Rio, F., Marcos, M.F., Gomez, C., Tome, M., Feith, H., Magalhaes, M.C., Howson, G., Proe, M., Smith, C.T., and Lowe, A.T. (1999), The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. Special issue. Indicators of sustainable forest management. Papers presented at the IEA Bioenergy Task XII workshop, Eddleston, Scotland, 20–25 September 1997. 122 pp.

Korpilahti, A . (1998). Finnish forest energy systems and CO_2 consequences. Biomass and Bioenergy. 15 (4/5): 293–297.

Maheswaran, J., and Attiwill, P.M. (1987). Loss of organic matter, elements, and organic fractions in decomposing *Eucalyptus microcarpa* leaf litter. Can. J. Bot. 65, 2601–2606.

Mussared, D. (1992). Wood-collecting 'threat to environment'. Canberra Times, 25-06-92,. P 4.

Myers. B.J., Theiveyanathan, S., O'Brien, N.D. and Bond, W.J. (1996). Growth and water use of effluent-irrigated *Eucalyptus grandis* and *Pinus radiata* plantations. Tree Physiology. 16: 211–219.

Parlene, L. & Clark, J. (2000). Firewood from existing plantation's – a first cut. Paper prepared for the 'A Burning Issue' Conference, Bendigo 2000.

Paul, K., Polglase, P., Coops, N., O'Connell, T., Grove, T., Mendham, D., Carlyle, C., May, B., Smethurst, P. and Baillie, C. (2002). Modelling change in soil carbon following afforestation or reforestation. NCAS Technical Report No. 29. Australian Greenhouse Office, Canberra. 106 pp.

Paul, K., (2003). Modelling change in litter and soil carbon following afforestation or reforestation: Calibration of the FullCAM model. NCAS Technical Report No. [to be allocated]. Australian Greenhouse Office, Canberra.

Polglase, P, Snowdon, P. Tivi Theiveyanathan, Paul, K.I., and Raison, J (2002). The Carbon Accounting Toolbox: Calibration to *E. globulus* and *P. radiata*, and uncertainty analysis. Australian Greenhouse Office, Canberra.

RAC (1992). Forest and Timber Inquiry. Resource Assessment Commission. Australian Government Publishing Service, Canberra. Vol 2b. Table N1.

Richards, G.P. (2001). The FullCAM Carbon Accounting Model: Development, Calibration and Implementation for the National Carbon Accounting System. (Australian Greenhouse Office, Canberra, Australia, NCAS Technical Report No. 28). 49 pp.

Sambo S.M. (1997). Fuel consumption estimates for typical coastal British Columbia Forest operations. Forest Engineering Research Institute of Canada Technical Note.

Schwaiger H, and Schlamadinger B. The potential of fuelwood to reduce greenhouse gas emissions in Europe. Biomass and Bioenergy. 15 (4/5): 369–377.

SFNSW (2000). Native Forest Silviculture Manual. State Forests of New South Wales, Sydney. 48 pp.

Snowdon, P., Eamus, D., Gibbons, Pl, Khanna, P., Keith, M., Raison, J and Kirschbaum, M. (2000). Synthesis of allometrics, review of root biomass and design of future woody biomass sampling stragies. NCAS Technical Report no.17, Australian Greehouse Office, Canberra. 116 pp. pg 38, Table 2.16.

Stackpole, D. and Bandarra, G. (2001). Review of species and silviculture for hardwood sawlog production from plantations in the West Victoria RFA region. Centre for Forest Tree Technology, Report No. 2001–29. 6 pp.

Steinbeck, K. 1982. Short-rotation forestry as a biomass source: an overview. In: Shrub, A., Chartier, P. and Schleser, G. (eds.). Energy form Biomass. 2nd EC conf. Berlin, 20–23 Sept., 1982, p. 163–171.

Theobald, M.R.L, Hamilton, L., Lang, A. and Gower, A. (2000). Determination and quantification of yields and growth for unmanaged sugar gum plantations in the Lismore (Victoria) district. Report for Corangamite Farm Forestry Network and the University of Melbourne. 13 pp.

Traill, B.J. (1993). Forestry, birds, mammals and management in box and ironbark forest. Victorian Naturalist 110. 11–14.

URS (2001). An assessment of the CO_2 implications of Basslink. Supporting Study no. 15, Basslink Pty. Ltd.

Vercoe, T, Clarke, B., Crawford, D. and Marcar, N. (1997) The CSIRO development of TREDAT, a tree performance database: MPTDAT. In: (Eds. T. Vercoe, and B. Clarke) Tree performance databases and selection systems. Proceedings of a meeting held in Canberra, 8–9 March, 1995. Canberra: CSIRO Forestry and Forest Products pp. 23–25.

Wall, J. (1997). Sustainability of the Armidale firewood industry on the Northern Tablelands of New South Wales: resource yield, supply, demand and management options. PhD thesis, University of New England, Armidale. 417 pp.

Watson, G.W. (1977). Metabolism of forest floor. M. Sc. thesis, Univ. of New England.

Wells, K.F. (1985). An energy analysis for a *Pinus radiata* plantation. PhD thesis, Australian National University. 147 pp.

Woldendorp, G., Keenan, K.T. and Ryan, M.F. (2002). Coarse woody debris in Australian Forest Ecosystems. A report for the National Greenhouse Strategy. Bureau of Rural Sciences.

EIGHT APPENDIX

UNITS

Different units are used in particular sections of the following report. For example, weight of wood is important for calculating transport energy costs, but carbon dioxide (or carbon) uptake is important for calculating greenhouse gas emission consequences. Exact conversion rates differ because of various carbon and moisture contents, but the following conversion rates can generally be used:

1 tC = 3.667 t CO_2 ≈ 2 t DM (dry weight of wood) ≈ 4 t (wet weight of wood)

Energy is generally expressed in terms of kilowatt hours or Joules and is converted as follows:

1 kWhr = 3.6 MJ

MEAN ANNUAL INCREMENT

Tree growth is often described in terms of mean annual increment (MAI). This is defined as the average annual increase in volume of individual trees or stands up to the specified point in time. It is usually expressed in $m^3\ ha^{-1}\ yr^{-1}$. Commercial forestry often concentrates on the production of sawlogs, so volume measurements are usually defined in terms of merchantable volume, which is the amount of sound wood in a single tree or stand that is suitable for marketing under given economic conditions. This volume comes from the main stems up to a defined top end diameter (say 10 cm). However, for firewood purposes the end log and major branches (up to 6–8 cm diameter) can be used. Also stacked firewood will contain significant voids of air, so care has to be taken that MAI based on measurements of stacked firewood (see, for example, Hamilton 2000) are not compared directly with normal commercial MAI figures. Theobald *et al*. (2000) show how 10.00 m^3 of seasoned *E. cladocalyx* firewood is equivalent to 6.29 m^3 of seasoned solid wood (i.e. ratio of wood:firewood of 0.629).