GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 148–175, doi: 10.1111/j.1757-1707.2011.01115.x

An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia

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Abstract

We provide a quantitative assessment of the prospects for current and future biomass feedstocks for bioenergy in Australia, and associated estimates of the greenhouse gas (GHG) mitigation resulting from their use for production of biofuels or bioelectricity. National statistics were used to estimate current annual production from agricultural and forest production systems. Crop residues were estimated from grain production and harvest index. Wood production statistics and spatial modelling of forest growth were used to estimate quantities of pulpwood, in-forest residues, and wood processing residues. Possible new production systems for oil from algae and the oilseed tree *Pongamia pinnata*, and of lignocellulosic biomass production from short-rotation coppiced eucalypt crops were also examined. The following constraints were applied to biomass production and use: avoiding clearing of native vegetation; minimizing impacts on domestic food security; retaining a portion of agricultural and forest residues to protect soil; and minimizing the impact on local processing industries by diverting only the export fraction of grains or pulpwood to bioenergy. We estimated that it would be physically possible to produce 9.6 GL yr^{-1} of first generation ethanol from current production systems, replacing 6.5 GL yr^{-1} of gasoline or 34% of current gasoline usage. Current production systems for waste oil, tallow and canola seed could produce 0.9 GL yr^{-1} of biodiesel, or 4% of current diesel usage. Cellulosic biomass from current agricultural and forestry production systems (including biomass from hardwood plantations maturing by 2030) could produce 9.5 GL yr^{-1} of ethanol, replacing 6.4 GL yr^{-1} of gasoline, or ca. 34% of current consumption. The same lignocellulosic sources could instead provide 35 TWh yr^{-1}, or ca. 15% of current electricity production. New production systems using algae and *P. pinnata* could produce ca. 3.96 and 0.9 GL biodiesel yr^{-1}, respectively. In combination, they could replace 4.2 GL yr^{-1} of fossil diesel, or 23% of current usage. Short-rotation coppiced eucalypt crops could provide 4.3 GL yr^{-1} of ethanol (2.9 GL yr^{-1} replacement, or 15% of current gasoline use) or 20.2 TWh yr^{-1} of electricity (9% of current generation). In total, first and second generation fuels from current and new production systems could mitigate 26 Mt CO_2-e, which is 38% of road transport emissions and 5% of the national emissions. Second generation fuels from current and new production systems could mitigate 13 Mt CO_2-e, which is 19% of road transport emissions and 2.4% of the national emissions lignocellulose from current and new production systems could mitigate 48 Mt CO_2-e, which is 28% of electricity emissions and 9% of the national emissions. There are challenging sustainability issues to consider in the production of large amounts of feedstock for bioenergy in Australia. Bioenergy production can have either positive or negative impacts. Although only the export fraction of grains and sugar was used to estimate first generation biofuels so that domestic food security was not affected, it would have an impact on food supply elsewhere. Environmental impacts on soil, water and biodiversity can be significant because of the large land base involved, and the likely use of intensive harvest regimes. These require careful management. Social impacts could be significant if there were to be large-scale change in land use or management. In addition, although the economic considerations of feedstock production were not covered in this article, they will be the ultimate drivers of industry development. They are uncertain and are highly dependent on government policies (e.g. the price on carbon, GHG mitigation and renewable energy targets, mandates for renewable fuels), the price of fossil oil, and the scale of the industry.

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Keywords: Australian national assessment, bioelectricity, biofuel, biomass, GHG mitigation

Received 14 February 2011 and accepted 25 March 2011

Introduction

Bioenergy (biofuels and/or bioelectricity) sourced from renewable feedstocks is part of a spectrum of energy technologies, which can provide low-emission alternatives to Australia's current dependence on coal and oil. In this article, the extent to which biomass could contribute to energy production and to greenhouse gas (GHG) mitigation is assessed in a consistent and transparent analysis across a broad range of biomass feedstocks in Australia.

Australia currently imports 30% of its oil products; however, this is projected to increase to 76% by 2030 (Geoscience Australia and ABARE, 2010). Only about 0.5% of Australia's transport fuel is currently supplied from biomass (Geoscience Australia and ABARE, 2010). Electricity is produced from coal (76%), gas (16%) and oil (1%), and there is a 7% contribution from renewable resources, comprising hydro (4.5%), wind (1.5%) and cofiring of biomass with coal (0.9%) (Geoscience Australia and ABARE, 2010). Residues from timber and sugar processing are also used to generate process heat and/or electricity within some processing facilities. Currently, use of these feedstocks produce 294 ML yr^{-1} of biofuels and 2.2 TWh yr^{-1} of electricity (Geoscience Australia and ABARE, 2010; Stucley, 2010).

Although the current contribution of biomass to total energy production in Australia is small, there are widely varying claims about the opportunity for scale-up (Bartle *et al.*, 2007; Mathews, 2007b; O'Connell *et al.*, 2007; Odeh & Tan, 2007). Some see Australia, with a large land-mass and low population, as a major potential global contributor to bioenergy production (e.g. Mathews, 2007a). Various studies provide starkly different estimates of the potential contributions of different biomass feedstocks. For example, the estimates of the potential contribution of biomass to energy in 2050 for Oceania include: 38–102 EJ yr^{-1} including 2–5 EJ yr^{-1} from agricultural and forestry residues (Smeets *et al.*, 2007); 29–53 EJ yr^{-1} (Hoogwijk *et al.*, 2005); 18 EJ yr^{-1} (de Vries *et al.*, 2007); and 10 EJ yr^{-1} based on wood production (van Vuuren *et al.*, 2009).

The major sources of variation and uncertainty for global and country-specific assessments are many. Different types of potential (theoretical, technical, environmental, economic, implementation) are estimated in different studies, and the type of potential is usually not explicitly defined (Smeets *et al.*, 2009). Other major sources of variation include the age of the study (early studies scoping the broad theoretical or upper technical limits are quickly eclipsed by further studies imposing various constraints); nomenclature and classification of biomass and land-use types; the type of modelling approach; and the assumptions and scenarios (Dornburg *et al.*, 2008; Rettenmaier *et al.*, 2008). These factors make consistent aggregation and comparison difficult, and provide a very inconsistent and uncertain basis for development of government policy and/or industry investment.

Assessing the potential for the future is complex and uncertain – expansion of bioenergy from the current small industry base in Australia will depend on a range of economic and policy settings, and will require the widespread deployment of new energy technologies. In this article, we focus on the potential for scale-up through the lens of biomass supply, which could result from (i) a change in production area, yield or management (e.g. intensification), or diversion of biomass from the current production systems of forestry and agriculture; or (ii) new production systems such as algae, oilseed trees or other purpose-grown energy crops (O'Connell & Haritos, 2010). There are many permutations that could be analysed with different assumptions about performance of new crops, yield improvements of existing crops, changes in land use, which in turn rely on assumptions about population, food sources (in particular protein chains) and global trade (e.g. Hoogwijk *et al.*, 2005; Smeets *et al.*, 2007; Dornburg *et al.*, 2008). There are also great uncertainties and a lack of data on the potential impacts of scaling up biomass production, including impacts on food supply (e.g. Von Braun, 2007; Stoeckel, 2008), GHG emissions (e.g. Crutzen *et al.*, 2008; Searchinger *et al.*, 2008) and other broad-ranging sustainability concerns (e.g. O'Connell *et al.*, 2009) including indirect impacts (Gallagher, 2008).

In this study, we aimed to provide an assessment of some plausible future contributions of bioenergy to fuel security and GHG emissions for Australia. The assessment is not a detailed analysis of complex scenarios of the full range of uncertainties described above; instead, we use a consistent, simple analysis based on physical constraints across feedstock types. The data sources, calculations and rationale for constraints and assumptions (which are uncertain and contestable) are made explicit to assist the reader to interpret, use or recalculate the results.

We estimate biomass production and harvest, diversion to bioenergy, energy produced and GHG mitigation based on our assumptions about physical constraints on the supply of biomass, with no direct consideration of the demand for different types of bioenergy in terms of quantity or price. Each category of biomass has a different emission profile as well as a specific set of sustainability concerns; in this study, we present disaggregated results to allow users to add the categories according to their own assumptions, which may differ from ours.

These results are not predictions: there are many other factors that would need to be considered for predictive modelling. For example, the quantities estimated may be too expensive, there may be other competing uses for the biomass or land, technology will change, and if demand were to become sufficient, greater quantities could be supplied with major land-use change in the longer term. The results do, however, suggest a plausible magnitude of the contribution of bioenergy to Australia's energy supply and GHG emission mitigation, based on several categories of current and new feedstock production systems. They form the basis for more sophisticated future research into biomass supply and carbon mitigation cost curves, and more sophisticated scenario analyses to explore industry and policy development.

Methods

Biomass-energy pathways

There are many technologies available to convert biomass into electricity, gas, or different liquid fuels. These technologies use various types of feedstocks, are produced in different ways and transported different distances – not every feedstock conversion technology is possible or desirable. Analysis of the amount of energy produced and GHG emissions mitigated requires examining pathways from feedstock production, harvest and transport, through to conversion technology, combustion and comparison against a relevant fossil-based energy source. In this article, we define a subset of these bioenergy pathways for analysis (Table 1). The pathways were selected as illustrative of currently commercial first and second generation technologies.

Key parameters in analysis

We defined a limited set of parameters to describe each pathway (Fig. 1). The key parameters and assumptions in their calculations are:

1 *Area*: the area used each year for the production of the feedstock.
2 *Annual production*: the total amount of the specific feedstock grown annually. The parameter of yield or productivity (t ha^{-1}) was often an intermediate step in calculating this parameter where reported statistics on the parameter were not available. The feedstock refers to the portion of the original plant used for bioenergy, for example, the residue from sawn timber production. Multiple feedstocks can originate from one biological production system (e.g. grain and stubble).
3 *Harvest*: the amount of biomass harvested or collected annually. This was based on statistics of actual harvest for some categories of biomass (e.g. agricultural and forest products), and estimated for others (e.g. agricultural and forest residues), as modified by simple technical or environmental constraints.
4 *Diversion*: the proportion of harvested feedstock used for bioenergy production. A simple rationale for diversion of each feedstock is provided.
5 *Conversion rate*: the amount of biofuel (ML) or electricity (kWh) produced from the diverted feedstock via a particular conversion pathway.
6 *Energy carrier*: the amount of biofuel (ML) or bioelectricity (kWh) produced from the feedstock. The amount of bioenergy produced is the product of the amount of feedstock diverted and the conversion rate for the particular pathway.
7 *Energy content*: the energy content of a specified *Energy carrier*.
8 *Displaced GHG emissions*: the GHG emissions from fossil sources that are avoided by substitution with bioenergy sources, based on the most relevant fossil-based comparator.

Table 1 Biomass–bioenergy pathways considered in this paper

Feedstock	Conversion process	Energy product
Starch (wheat, sorghum, barley, oat and triticale grain)	Fermentation	Ethanol
Sucrose (C-molasses and sugarcane sugar)	Fermentation	Ethanol
Oil (canola, animal tallow, waste oil mixture, algae*, *Pongamia* seed*)	Transesterification	Biodiesel
Lignocellulose [Stubble from annual crops, bagasse, sugarcane (whole plant), products and residues from native forest, and hardwood and softwood plantations, wood waste mixture and coppice eucalypt*]	Enzymatic fermentation	Ethanol
Lignocellulose [Stubble from annual crops, bagasse, sugar cane (whole plant), products and residues from native forest, and hardwood and softwood plantations, wood waste mixture and coppice eucalypt*]	Combustion	Electricity

*Feedstock from a new production system, i.e. one that might be grown specifically for bioenergy in the future.

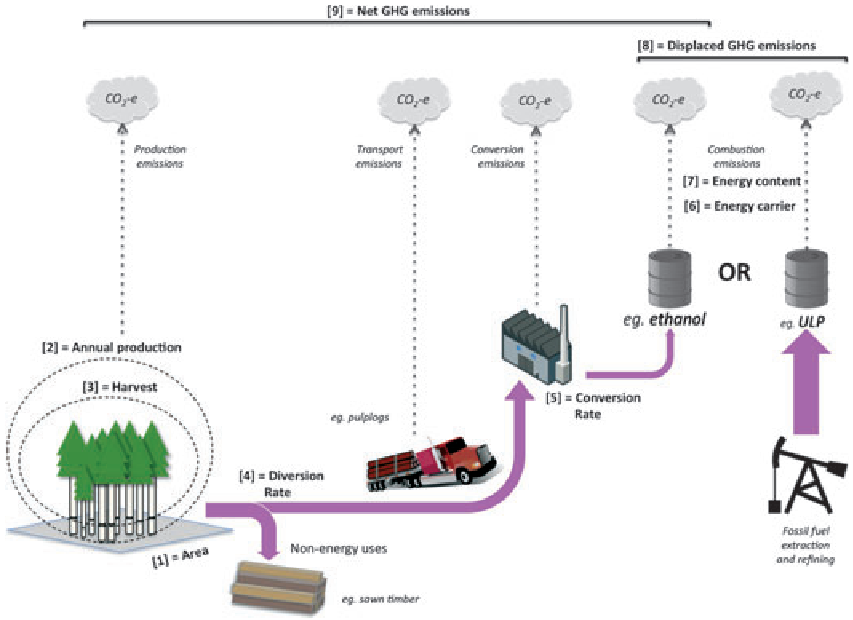


Fig. 1 Schematic diagram showing the key reporting parameters (numbered) and associated constraints and calculations (arrows) used for estimating the potential to displace fossil GHG emissions by using bioenergy.

9 *Net GHG mitigation*: displaced fossil GHG emissions less the GHG emissions associated with production, harvest, transport and processing of biomass, based on life cycle assessment.

The parameters 1–5 are input parameters and parameters 6–9 are output parameters. Both types of parameters are described in more detail in the following section.

We assessed biomass from current production systems of forestry and agriculture, and from waste. Simple assumptions and constraints were applied to provide estimates of the amounts of biofuel, bioelectricity and GHG mitigation that could be obtained by diverting a proportion of this biomass through a specified set of appropriate energy conversion technologies. We did not analyse future possible changes (yield, areal extent or management) to current production systems in this study.

Scoping analyses were conducted for three new biomass production systems often proposed for bioenergy: *Pongamia pinnata* (a leguminous oilseed tree) plantations; algae in ponds fertilized by CO_2; and a short-rotation coppice (SRC) eucalypt grown as part of traditional farming systems. These analyses relied on many more untested assumptions, and the uncertainty was therefore much greater for these systems (especially algae and *P. pinnata*) because they are still in the early stages of research and development.

Estimation of Area, Annual production and Harvest parameters

Values for *Area*, *Annual production* and *Harvest* were collated from the literature where available. In a number of cases, appropriate data were not available, thus methods were developed to provide estimates. Values from different production years and geographical units were synthesized and aggregated to provide national level estimates.

The *Area*, *Annual production* and *Harvest* parameters for the current production systems are given in Table 2, and Fig. 2 shows resource location and potential land areas for growing different feedstocks. The following sections present details for these parameters in relation to current agricultural and forestry production systems.

Current agricultural production systems

Agricultural products. Grain production is reported in Australia (at statistical division level) for the period of 1983–2005, and this study used the averages for 1996–2005 (see Dunlop *et al.*, 2008). Differences in statistical division boundaries over time were dealt with by concording the data prior to aggregation to state and national levels. Estimates of sugar cane harvest, bagasse, C-molasses and sugar production were collated from industry statistics (Anon., 1996–2007; ASMC, 1996–2007) and covered the years 1996–2007 for the five Australian sugar production regions, aggregated to state and national levels. The published statistics were combined with the agricultural land-use data (Knapp *et al.*, 2006) to produce spatial estimates of *Annual production*. The *Area* parameter was assumed not to expand or contract into the future.

The spatial distribution of the *Area* parameters for production of these categories of biomass is shown in Fig. 2a.

Agricultural residues. The residues from grain cropping comprise the stalks of the grain, and this is termed 'stubble' in Australia. The *Annual production* of stubble from wheat, oats, barley, triticale, sorghum, canola and lupins production systems was calculated using published harvest indices (Unkovich *et al.*, 2010) combined with statistics on grain production (Dunlop *et al.*, 2008; O'Connell *et al.*, 2008), and converted to

Table 2 Biomass production from current production systems

Biomass class ⇨ bioenergy form Biomass source	Area ('000 ha)	Annual production (dry kt)	Harvest/ production (%)	Harvest rationale	Annual harvest (dry kt)
Starch ⇨ Ethanol (current)					
Barley grain[*]	3487	6700	100	Average of published data 1996–2005	6700
Grain sorghum grain[*]	677	1753	100		1753
Oat grain[*]	894	1481	100		1481
Triticale grain[*]	351	623	100		623
Wheat grain[*]	11 223	20 935	100		20 935
Sucrose ⇨ Ethanol (current)					
C-molasses[†]	0	1027	86	Total production calculated from average of published data 1996–2005 plus estimated harvest losses and retained trash blanket	887
Sugar cane sugar[*]	418	5520	86		4766
Oil ⇨ Biodiesel (current)					
Canola seed[*]	1060	1382	100	Average of published data 1996–2005	1382
Animal tallow[†]	0	589	100	Residual biomass; harvest = production	589
Waste oil mixture[†]	0	100	100	Residual biomass; harvest = production	100
Lignocellulose ⇨ Electricity OR Ethanol (current)					
Bagasse[†]	418	6377	86	Same as for C-molasses and sugar	5505
Barley stubble[†]	3487	10 931	46	Fraction after retention for soil protection and chaff losses	5006
Canola stubble[†]	1060	3738	39		1455
Chick peas stubble[†]	225	370	0	Unharvestable	0
Field peas stubble[†]	382	724	0		0
Grain sorghum stubble[†]	677	2058	33	Fraction after retention for soil protection and chaff losses	676
Lupin stubble[†]	1199	3447	40		1389
Oat stubble[†]	894	3455	44		1519
Triticale stubble[†]	351	1137	48		547
Wheat stubble[†]	11 223	37 217	46		17 116
Native managed forest residue[§]	9408	5445	30	Retain on-site for environmental and nutrients: 50% of stemwood and all of branch and foliage fraction	1634
Native managed forest pulplog[§]	9408	3363	100	Fraction calculated per 'Methods' section	3363
Native managed forest sawmill residue[¶]	0	1320	100	Published average	1320
Native managed forest sawn timber[§]	9408	763	100	Published average	763
Plantation hardwood forest residue[‡]	991	871	23	Harvested: 100% of stems. On-site retention: all branch and foliage	199
Plantation hardwood pulplog[‡]	991	2037	100	Fraction calculated per 'Methods' section	2037

Table 2 (continued)

Biomass class ⇨ *bioenergy form* Biomass source	Area ('000 ha)	Annual production (dry kt)	Harvest/ production (%)	Harvest rationale	Annual harvest (dry kt)
Plantation hardwood sawmill residue[¶]	0	106	100	Published average	106
Plantation hardwood sawn timber[‡]	991	64	100	Published average	64
Plantation softwood forest residue[‡]	1020	2676	23	Harvested: 100% of stems. On-site retention: all branch and foliage	614
Plantation softwood pulplog[‡]	1020	2115	100	Fraction calculated per 'Methods' section	2115
Plantation softwood sawmill residue[¶]	0	2808	100	Published average	2808
Plantation softwood sawn timber[‡]	1020	2202	100	Published average	2202
Urban wood waste[**]	0	1064	100	Published/calculated average	1064
Lignocellulose ⇨ *Electricity OR Ethanol (likely to come on-stream to 2030 – additional to above)*[††]					
Plantation hardwood forest residue[‡]	Within current forest area	1304	23	Identical to corresponding plantation hardwood (current) rationales above	297
Plantation hardwood pulplog[‡]		3025	100		3025
Plantation hardwood sawmill residue[¶]		182	100		182
Plantation hardwood sawn timber[‡]		95	100		95

{Biomass class} ⇨ {Bioenergy form}: Class of biomass that acts as feedstock in transformation to the bioenergy form.

Production systems of biomass sources are noted:

*agricultural products

†agricultural residues

‡plantation forests

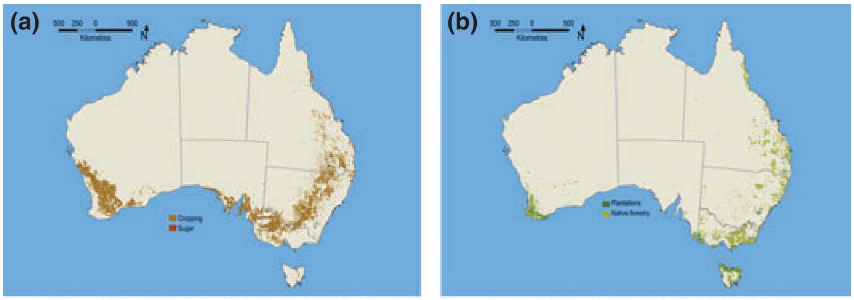
§native forests

¶sawmill residues

**urban residues.

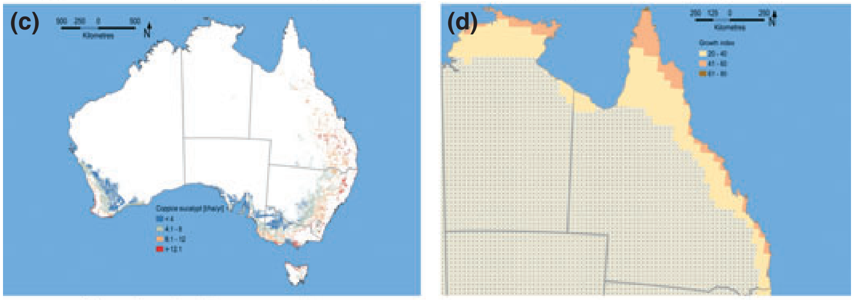
Types of biomass coming on-stream to 2030 are constrained:

††no large increase in wood flow from managed native forests or plantation softwoods, thus report figures for plantation hardwood only.



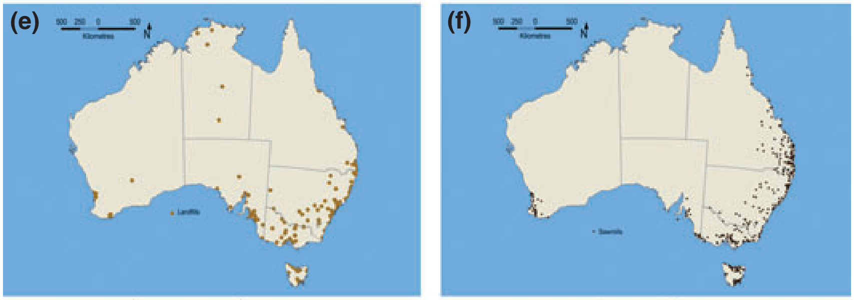
Agricultural production systems

Forest production systems



Short rotation coppice

Pongamia growing zones



Urban wood waste

Sawmills

Fig. 2 Resource location and potential land areas for growing feedstocks [a,b (Knapp *et al.*, 2006), e (Taylor *et al.*, 2010), f (Polglase *et al.*, 2008)].

dry mass (assuming 15% moisture content). Currently, some of this stubble is harvested as straw for animal bedding in Australia, but largely it is retained as part of a minimum tillage farming system, or is grazed or burnt (Herr *et al.*, 2010).

To estimate the proportion of *Annual production*, which forms the *Harvest* estimate, three simple technical and environmental constraints were applied (Dunlop *et al.*, 2008):

- 20% of the nongrain above-ground biomass was chaff and small fractions that are not harvestable due to technical harvesting constraints;
- stubble cannot practically be cut lower than 12.5 cm;
- at least 1 t ha^{-1} of stubble in southern cropping regions and 1.5 t ha^{-1} in northern cropping regions was assumed retained to protect soils from the risks of erosion.

There is an ongoing debate on the impact of stubble removal on soil carbon stocks, water infiltration and evaporation, and soil health in Australia. These are discussed further in Herr *et al.* (2010).

The *Annual production* for tallow and waste oil was based on Beer *et al.* (2005).

Current forest production systems

Plantation forests. It was a more complex task to estimate *Annual production* and *Harvest* parameters from forestry production systems, because they are managed on an estate basis over multiyear rotations. Management and harvesting regimes can be modified within the life of a rotation with thinning and other management options. Statistics are published for the volume of wood products harvested and sold (e.g. sawlogs and pulplogs), but dry mass equivalents of these products and all the other biomass fractions must be estimated, requiring a more complex level of analysis. The *Area* parameter was assumed not to change over time – i.e. no contraction or expansion of the forest estate. The *Annual production*, *Harvest* and *Diversion* parameters were calculated based on current (2009) *Area* (ABARE, 2010). In the case of hardwood plantations, many of the plantings are still young, and the annual production will continue to increase and will double by 2030. Therefore, for this category of plantation, estimates of the additional *Annual production*, *Harvest* and *Diversion* parameters for 2030 were calculated, based on the current *Area*.

Current *Areas* and *Annual production* parameters for hardwood and softwood plantations (planted forests) were estimated from published figures for average wood production (ABARE, 2010) for the period 2006–2009. Sawlog and pulplog volumes were converted to dry mass equivalents using densities from Ilic *et al.* (2000) for different tree species and ages and the relative total planted area for each species based on data from the National Plantation Inventory (Parsons *et al.*, 2006). Based on this information, average densities of sawlogs and pulplogs from hardwood and softwood plantations were estimated (Table 3).

Current *Annual production* of forest residue was estimated from total sawlog and pulplog production and forest residue fractions from Ximenes *et al.* (2008) and information from forest growers (D. Turner, HVP, personal communication; B. Bradshaw, Gunns Ltd., personal communication; Table 3).

For the forest residue fraction, it was assumed that 100% of the stemwood fraction could be harvested, while the foliage and branches were assumed to be left *in situ* to provide nutrients and organic matter for the next tree crop. The *Harvest* was therefore calculated as 22.8% of the *Annual production* for both plantation hardwood and plantation softwood forest residues.

The future supply of biomass from existing plantations (i.e. projected *Annual production* for 2030 from the current *Area*) was estimated using the forest growth model 3-PG2 (Almeida *et al.*, 2007) and a forest type and extent spatial layer (Montreal Process Implementation Group for Australia, 2008). 3-PG2 was calibrated and validated for three major hardwood species (*Eucalyptus globulus* Labill., *Eucalyptus grandis* W. Hill ex Maiden and *Eucalyptus camaldulensis* Dehnh.) and three major softwood species (*Pinus radiata* D.Don, *Pinus elliottii elliottii* Engelm. x *caribaea* Morelet hybrid and *Pinus pinaster* Aiton) grown across Australia (Polglase *et al.*, 2008). Silvicultural systems were separated into pulpwood only and sawlog plus pulplog and applied in proportion to the predicted production of sawlogs and pulplogs in each national plantation inventory region (Parsons *et al.*, 2007).

Table 3 Assumed densities of sawlogs and pulplogs, and forest and sawmill residue fractions from hardwood and softwood plantations and native forests managed for wood production

Attribute	Softwood plantations	Hardwood plantations	Native forest
Wood density (kg m^{-3})			
Sawlogs	460	580	630
Pulplogs	410	490	630
Forest residue fraction			
Total (% total above ground)	27.3	28.3	50
Stemwood (% total logs)	9	9	60
Sawmill residue fraction (% sawlog)			
Chips	37	24	24
Sawdust and shavings	17	38	38
Sawn timber	47	38	38
Bark*	6	1	1

*Sawlog volumes exclude bark so total of sawmill residues >100%.

Spatial datasets used to model growth included average monthly rainfall, rain days, solar radiation, maximum and minimum temperatures derived from ESOCLIM (Houlder *et al.*, 2000) and frost days (Department of Climate Change, personal communication), soil depth and texture (McKenzie *et al.*, 2000; Polglase *et al.*, 2008), and initial soil water availability (Polglase *et al.*, 2008). Key assumptions regarding initial stocking, thinning and rotation length for the different silvicultural systems in different plantation regions were those used by Polglase *et al.* (2008). In the absence of site quality data, the soil fertility index used in the 3-PG2 model was assumed to be constant at 0.7.

Outputs for above-ground biomass from 3-PG2 were partitioned into stemwood, branches and bark and foliage. Harvest residues were assumed to include total estimated foliage, bark and branch mass. In addition, 10% of stemwood mass was assumed to comprise stemwood harvest residues (<80 mm small end diameter) based on information provided by forest growers (Hancock Victorian Plantations, personal communication; Auspine Ltd., personal communication). The remaining stemwood fraction was split into sawlogs and pulplogs using information from Parsons *et al.* (2007). The same *Harvest* assumptions for proportions of different biomass components were used for 2030 as for current production. The spatial distribution of the plantation forest production zone is shown in Fig. 2b.

Native forests managed for wood production. In Australia, <10% of the native forest estate is managed for wood production. The remaining forest is either managed for conservation or for grazing (grassy woodlands). Only the native forest managed for wood production is examined here as a source of biomass for bioenergy.

Annual production of sawlogs and pulplogs from native forests was estimated using ABARE (2010) data for the average volume of logs harvested between 2006 and 2009. It was assumed that there would be no change in future wood production. These wood volumes were converted to dry mass equivalents using wood density values from Ilic *et al.* (2000) for the primary native forest species harvested (Table 3).

Harvest residues in native forests can comprise 30–75% of total above-ground biomass depending on the products removed (sawlog plus pulplogs, or sawlogs only), forest type (moist vs. dry) and silvicultural system (clearfell vs. selection) with average residue amounts almost double for sawlog only compared with sawlog plus pulplog removal and almost 30% greater for clearfell compared with selective harvest systems (Raison & Squire, 2007; Ximenes *et al.*, 2008). Based on data from Raison & Squire (2007) and Ximenes *et al.* (2008), it was assumed that postharvest residues comprised 50% of total above-ground biomass, with stemwood and large branches making up 60% of total logs (Table 3). It was assumed that only 50% of stemwood residues could be harvested, with the remainder contributing to habitat for flora and fauna. All foliage or branch residues were assumed to be retained on site to assist maintenance of organic matter, nutrients and biodiversity. This averages out as a *Harvest* parameter of 30% across the different fractions of residue. The spatial distribution of the native forest production zone is shown in Fig. 2b.

Sawmill residues. To estimate the current *Annual production* of sawmill residues, the results from a sawmill survey conducted by ABARE (Burns *et al.*, 2009), which provides a state-by-state breakdown of recovery rates for softwood and hardwood mills across Australia, were combined with forestry life cycle inventory data (Tucker *et al.*, 2009). The proportions of chips, bark and other material from hardwood and softwood plantations are given in Table 3. For native forests, 62% of the total sawlog volume was assumed to be converted to sawmill residues, which consisted of 39% chips and 61% sawdust and shavings. It was assumed that the sawlog volume remaining was equal to the production of sawn timber. Sawmill residues from future plantation and native forests were assumed to remain unchanged. The spatial distribution of sawmills is shown in Fig. 2f.

Urban wood waste. The amount of urban wood waste (labelled as *Annual production* parameter in this study for consistency) going to landfill was estimated from survey data using methods described by Taylor *et al.* (2010). Other urban wood waste streams, which are currently diverted (into such products as compost and animal bedding), were not assessed; therefore, the total amount of contestable urban wood waste may, in fact, be slightly higher than the figures presented here. Other forms of organic waste were not assessed. Per capita waste generation was assumed to remain constant into the future. The spatial distribution of the *Area* parameters for production of these categories of biomass is shown in Fig. 2e.

New feedstock production systems

There are many new biomass or oil production systems proposed for energy. In addition to serving as a resource of energy, new production systems may provide both positive and negative collateral impacts once established. This is particularly the case for broad-acre systems such as woody crops. Positive impacts may include restoration of biodiversity and reduction in salinity (Wildy *et al.*, 2004; Bartle *et al.*, 2007); they may bring economic benefits in areas of low agricultural value, diversification of the farm enterprise may help manage the financial risk, and they provide long-term stability to sustain systems with high interannual variation in production. However, a number of adverse impacts may result from the change in land-use – for example, the surface and groundwater hydrology may be affected if planted inappropriately at large scale in some landscapes (Stirzaker *et al.*, 2002), and vegetation clearing may occur in countries, which do not have governance structures to prevent this (Gallagher, 2008; Searchinger *et al.*, 2008).

In this study, we conducted exploratory analyses for algae, *P. pinnata* (L.) Pierre and SRC eucalypt systems. The potential biomass production from the three new production systems, when fully established, is summarized in Table 4 and described in the following sections. New production systems will require land, and the rationale and constraints for our estimates of *Area* are provided.

Algae. Algae holds promise to contribute significantly to biofuel production using both the oil component and bioelectricity from the remaining biomass once the oil is removed. The following exploratory analysis was based on some simple assumptions to estimate the magnitude of the contribution, based on systems using supplementary CO_2.

Currently, there are no industrial-scale facilities for algae production for biofuel in Australia, although there are several proposed production systems and potential locations (e.g. Regan & Gartside, 1983). We assumed a production system based on 400 ha raceway ponds (e.g. Benemann & Oswald, 1996; Campbell *et al.*, 2009a). We assumed that nonlimiting CO_2 could be provided and that algal yields of 55 t ha^{-1} yr^{-1} could be achieved. There are 13 major sites in Australia where point source production of CO_2 is >0.2 Mt yr^{-1} (Regan & Gartside, 1983), including power stations, Coal Seam Methane (CSM) sites and major sources of human and animal waste. These were used to constrain the locations for algal production. The rationale and key parameters are provided in Table 5.

The estimates of algal pond *Area* for the power stations were estimated by Regan & Gartside (1983), and a similar approach was used in this analysis for areal restrictions for CSM, human and animal waste. Many CSM sites occur in areas surrounded by arable land. Likewise, animal waste areas tend to be located near pasture. For human waste, most of the sewage farms are located close to urban centres, so although they have land set aside (e.g. for drying waste), there are restrictions on availability.

We assumed that the upper limit for total potential algal production after land restrictions is taken into account. This equated to 4.0 Mt yr^{-1} of algal oil (Table 5).

SRC eucalypt systems. There is significant opportunity for new plantings of eucalypts, managed as SRC systems on existing agricultural land, to produce large amounts of lignocellulose (e.g. Bartle, 2009). A system of SRC has been researched, established and trialled in Western Australia over the last 25 years. These systems may be dedicated to energy produc-

Table 4 Estimated theoretical *Area* and *Annual production* of future dedicated energy biomass production systems when they have been fully established

Feedstock	Area ('000 ha)	Annual production (dry kt)	Harvest (dry kt)
Algae biomass	80	8000	8000
Coppice eucalypt	2287	14 996	14 996
Pongamia seed	458	2950	2950

Table 5 Variables used in the calculation of oil production from algae

Variable	Assumed	Rationale	References
Yield	15 g m^{-2} day^{-1} or 55 t ha^{-1} yr^{-1}	Best production from a real world large system (>1 ha over period of >12 months)	Huntley & Redalje (2007), Campbell *et al.* (2009a)
CO_2 from power stations			
Annual production of algae	2.6–7.0 Mt yr^{-1}	80 000 ha of land with high sun exposure, close to power stations and coast	Campbell *et al.* (2009a)
CO_2 from Coal Seam Methane (CSM)			
Annual production of algae	0.1–0.3 Mt biomass yr^{-1}	CSM produces brackish to saline water. The usual composition of CSM gases is 87% methane, 11% carbon dioxide and 2% other gases (Air Liquide, 2010). Current Australian production of CSM is 80 PJ yr^{-1} (Geoscience Australia, 2010). Assume 5–10% of the gas volume is CO_2. Equates to105–225 million cubic metres CO_2	Campbell *et al.* (2009a)
CO_2 from human waste			
Annual production of algae	1.1–2.0 Mt yr^{-1}r	Australian waste treatment plants provide ca. 33.8 kg of dissolved carbon per person. Assume population of 22 million, 92.5% urban, i.e. 20.35 million people produce 687 kt yr^{-1} C; equivalent to 2522 kt CO_2	Campbell *et al.* (2009a)
CO_2 from animal waste			
Annual production of algae	0.29–1.22 Mt yr^{-1}	1.2–1.8 million pigs in conditions where manure could be collected, representing 130–200 kt CO_2 yr^{-1}, enough to produce 0.070–0.13 Mt algae biomass yr^{-1}. 27.9 million cattle, but only 1.5 million in feedlots producing between 520–1870 kt CO_2	Campbell *et al.* (2009a)
Annual production total algal biomass	8 Mt yr^{-1}	4.1–10.7 Mt algae without area restrictions 3–8 Mt algal biomass yr^{-1} with area restrictions	
Annual production total algal oil	4.0 Mt yr^{-1}	0.7–4.0 Mt yr^{-1}	

tion, but can also provide other environmental services, such as restoration of biodiversity or reduction of risk of dryland salinity (Bartle *et al.*, 2007) as well as alternative products such as cineole. This exploratory analysis was based on some simple assumptions to estimate a potential expansion opportunity for SRC systems in rows or blocks, integrated within existing farming systems.

The continent was split into four 'geoclimatic zones' suitable for four different 'model' eucalypt species (see Polglase *et al.*, 2008). Each 'model' species was used to give indicative growth rates for trees appropriate for that geoclimatic zone. The geoclimatic zones were:

1 southern wet [>550 mm mean annual rainfall (MAR), south of 29° S];
2 southern dry (275–550 mm MAR, south of 29° S);
3 east coast tropics and subtropics (>800 mm MAR, north of 35° S, east of 144° E); and
4 northern savanna and semiarid (>275 mm MAR, north of 29° S, excluding zone 3).

Table 6 Species, planting layout, initial stocking and rotation length used to model biomass production from new SRC eucalypt plantings across four Australian geoclimatic zones (after Polglase *et al.*, 2008)

	Geoclimatic zone			
Parameter	1	2	3	4
Species	*Eucalyptus globulus*	'mallee'	*Eucalyptus grandis*	*Eucalyptus camaldulensis*
Layout	Blocks	Strips	Blocks	Blocks
Stocking	2500	2500	2500	2500
Rotation	5 years	5 years	5 years	5 years

SRC, short-rotation coppice.

Model species, planting layout, initial stocking, systems and rotation lengths used for each zone are summarized in Table 6. Parameterization of the 3-PG2 model for 'mallee' systems (based on three species – *Eucalyptus polybractea* R.T.Baker, *Eucalyptus loxophleba* ssp. *lissophloia* L.A.S.Johnson & K.D.Hill and *Eucalyptus kocchii* Maiden & Blakely) was as described in Polglase *et al.* (2008). The data used to parameterize 3-PG2 for 'mallee' systems were from strip plantings 2–6 trees wide, with the bays of at least 40 m in width in between planted with grain crops, as described by Bartle *et al.* (2009). The data used to parametrize 3PG-2 for the other modelled species were from block plantings. It was assumed that all plantings would be coppice systems with no fallow period between harvest and replanting, and that all above-ground biomass (i.e. stems, branches, foliage and bark) would be harvested.

The modelled outputs for each zone were combined to form a spatial layer of *Annual production* categorized into different productivity classes (<4, 4–8, 8–12 and >12 t DM production ha^{-1} yr^{-1}). This was intersected with a spatial layer on land use (Knapp *et al.*, 2006). The *Area* parameter was defined assuming that 5% of all cleared land (defined as two categories 'Grazing modified pastures' and 'Cropping') would be planted to this SRC eucalypt system (Table 7). The SRC systems were assumed to be evenly distributed through these land-use categories – the trees constitute a small component of each farm. The biomass production was a weighted average across the potentially plantable area, rather than the production from any specific area.

The SRC biomass production system was considered a land use sympathetic with, rather than competitive with, food production. There could be a minor production loss for total agricultural production, but this was not modelled. It was assumed that there would be no significant reduction in the *Diversion* parameter of other biomass feedstocks (e.g. stubble) because of the small proportion of the total production diverted to bioenergy. Thus, 2.3 million ha out of a total 45 million ha of available cleared land with >275 mm MAR was assumed to be planted (Fig. 2a). *Annual production* under these constraints was estimated at 15 Mt dry biomass (Table 4). Establishment rates are unlikely to exceed 100 000 ha yr^{-1}, thus it would take two to three decades to establish such resource.

Pongamia pinnata. In Australia, small areas of *P. pinnata* are found in the northern tropical areas of Australia, particularly along the coastal fringe, and has been proposed as a potential future source of oil for biofuel (Scott *et al.*, 2008). An exploratory analysis of the opportunities for *P. pinnata* was conducted.

Herbarium records of the worldwide geographical distribution of *P. pinnata* from the Global Biodiversity Information Facility (GBIF, 2010) and Australia's Virtual Herbarium Web Database (Council of Heads of Australasian Herbaria, 2009) were collated. A CLIMEX™ Compare Locations model (Sutherst *et al.*, 2010) was developed to estimate the ecological niche of *P. pinnata*. Australian and overseas location records were used to infer the parameters for range-limiting stress functions. This approach has been used to model successfully the potential range and climate response of many shrubs and trees (e.g. Kriticos *et al.*, 2003; Potter *et al.*, 2009). The climatic potential for *P. pinnata* growth was estimated using a combination of published observations (Gary Seaton, personal communication; FAO, 2007) and ecologically reasonable parameters. The resulting CLIMEX™ model was applied to Australia using the 0.5 degree dataset for climate averages (1961–1990) developed by the Climate Research Unit at the University of East Anglia (New *et al.*, 2002).

Where the ecoclimatic index is >1, the species is thought to be capable of naturalizing, so long as all nonclimatic factors are also suitable. The annual growth index (GIA) for Australia was classified into four zones of climatic growth potential (0–20, 21–40, 41–60 and 61–80% of maximum productivity). The areas (1 km^2 grid resolution) of high growth potential in Australia (40–80%) were then overlayed with the 2001/2002 resolution Australian land use at 1 km^2 (Knapp *et al.*, 2006) using ArcGIS (ESRI, 2009).

Requirements for optimal growth and seed set suggest that commercial growth of *P. pinnata* would be confined to tropical and subtropical areas of Australia (Australian Biological Resources Study, 1993). Limited experimental trials have been established in Australia, ranging from a few trees to plantings of 300 ha, but these are <3–5 years old – production data from Australia will not be available for another decade (Koch & Walker, 2009; ABC Landline, 2010; Bita *et al.*, 2010). We therefore could not assign a reliable predictive relationship between this growth potential and oil production. We assumed that for the 41–60%

Table 7 Area of land planted, and annual wood production from SRC eucalypts assuming crops established on 5% of each category of land use and productivity class

	Productivity class (t DM yr^{-1})				
Land-use category	<4	4–8	8–12	>12	All
Grazing modified pastures					
Area (ha)	173 020	405 150	397 370	160 235	1 135 775
$tDMyr^{-1}$	506 741	2 368 547	3 858 423	2 339 203	9 072 914
Cropping					
Area (ha)	524 420	466 870	137 450	22 120	1 150 860
$tDMyr^{-1}$	1 535 921	2 729 369	1 334 626	322 921	5 922 837
Total					
Area (ha)	697 440	872 020	534 820	182 355	2 286 635
$tDMyr^{-1}$	2 042 662	5 097 916	5 193 049	2 662 124	14 995 751

SRC, short-rotation coppice.

productivity zone, an average oil yield of 2 t ha^{-1} yr^{-1} could be obtained. There are limited data available, but a range of 0.8–2.5 t ha^{-1} yr^{-1} has been proposed (Table 8).

There is very little land in the 60–80% productivity zone, and we did not explore the use of any of that land for Pongamia plantations. Likewise, we did not consider land in the 0–40% productivity zone, but use of irrigation may enable some of it to be used. Water requirements are poorly known for seed production, but local experience suggests that irrigation may be required during the establishment phase of the plantings (first 7 years) in dry tropical and subtropical areas and sometimes subsequently to ensure seed set (Gary Seaton, personal communication). Water availability in northern Australia is limited and the most likely option for expanding irrigation is in the use of groundwater, with an estimate of ca. 600 GL yr^{-1} of potentially useable groundwater. This groundwater could provide irrigation for 40 000–60 000 ha (Northern Australia Taskforce, 2009).

There is 15.6 million ha of land in the 41–60% productivity zone that is subject to a range of land uses (Table 9). We made a conservative (but still very practically challenging in terms of new plantation establishment) assumption that 3% (458 000 ha) of this land to be used for growing *P. pinnata* without irrigation. There are some irrigated lands within this zone used for crop and grazing which could be used for *P. pinnata* instead of food production, but this would be driven by the economics of, and societal attitude towards, replacing high-value irrigated agriculture with an oilseed tree. Some land labelled 'Managed resource protection' (which contains traditional Indigenous uses), and 'Grazing natural land' could be potentially used for *P. pinnata*, subject to local clearing or zoning leglization and economic drivers. The availability of land in some areas where *P. pinnata* will grow will also be restricted by other legislation and policy, such as the Wild Rivers Act (Queensland), which has seen at least two separate *P. pinnata* ventures made economically unviable due to the inability to establish further plantations within close proximity to wild rivers (Koch & Walker, 2009; Bita *et al.*, 2010).

Given the many unknowns and complexities, in this study, we simply assumed that 458 000 ha of land might be converted to Pongamia plantations – the category of land allocated was not specified in our model, and the substitution effects were not modelled. According to the assumptions provided in Table 9, we estimated an *Annual production* of Pongamia oil of 916 000 t yr^{-1}.

Estimation of Diversion parameters

For each category of harvested biomass, a *Diversion* parameter was estimated to define the proportion of *Harvest* biomass that would be used as a feedstock for bioenergy. The technical and environmental constraints related to removing the biomass from the area grown are described as part of the *Harvest* parameter. This is a contestable parameter, which ultimately will vary with economic and policy settings. Table 10 lists our simple assumptions on diversion of biomass, with a transparent rationale for each. More complete explanations are provided in the following section.

Table 8 Variables used in the estimation of oil yield from *Pongamia pinnata* plantations established for bioenergy in Australia

Variable	Assumed	References
Tree seed production	8–24 kg seed $tree^{-1}$ yr^{-1} (ca. 10 000 seeds per tree; seed weight ca. 1.8 g; seed oil content ca. 30%)	Meher *et al.* (2006), Pradhana *et al.* (2008), Scott *et al.* (2008)
Stocking	350 trees ha^{-1}	Scott *et al.* (2008), Centre for Integrative Legume Research (2009)
Oil yield	2 t ha^{-1} yr^{-1} (range 0.8–2.5 t ha^{-1})	Calculated from references above

Table 9 Area of land (ha) for combinations of land-use categories and potential productivity (growth index) zones for *Pongamia pinnata* in northern Australia (see Fig. 2d)

	Growth index range		
Land-use category	0–40	41–60	60–80
Agricultural land (incl. cropping, horticulture, modified pastures)	48 582 979	458 240	–
Forestry	14 456 478	556 391	–
Grazing natural vegetation	417 007 123	3 691 079	15 898
Managed resource protection	93 582 794	4 867 023	90 691
Mining	119 795	4259	–
Nature conservation	50 777 325	2 154 027	3275
Other	128 343 119	3 879 330	60 103
Grand total	752 869 612	15 610 350	169 968
Area assumed (ha)	0	458 000	Not assessed
Annual production of oil assumed (t yr^{-1})	0	916 000	Not assessed

Table 10 Assumed *Diversion* for each biomass category, and the rationale

Biomass class ⇨ *Bioenergy form* Biomass source	Annual harvest (dry kt)	Diversion/ harvest (%)	Annual diversion (dry kt)	Diversion rationale
Starch ⇨ *Ethanol (current)*				
Barley grain[*]	6700	65	4355	Equivalent to average export fraction 1996–2005, to minimize impact on domestic food security
Grain sorghum grain[*]	1753	22	386	
Oat grain[*]	1481	11	163	
Triticale grain[*]	623	0	0	
Wheat grain[*]	20 935	75	15 701	
Sucrose ⇨ *Ethanol (current)*				
C-molasses[†]	887	50	444	Amount equivalent to export fraction
Sugar cane sugar[*]	4766	78	3741	Amount equivalent to export fraction, 1996–2005
Oil ⇨ *Biodiesel (current)*				
Canola seed[*]	1382	56	774	Amount equivalent to average export fraction 1996–2005
Animal tallow[†]	589	100	589	Does have existing competing markets, but diversion away from these has no major conflict with food security
Waste oil mixture[†]	100	100	100	
Algae biomass[*]	8000	100	8000	Dedicated energy crop
Pongamia seed[*]	2950	100	2950	Dedicated energy crop
Lignocellulose ⇨ *Electricity OR Ethanol (current)*				
Bagasse[†]	5505	50	2752	Current use for cogeneration at mills, increased by infrastructure improvements, releases material for other bioenergy uses
Barley stubble[†]	5006	50	2503	Assumed 50% of areas can be economically harvested
Canola stubble[†]	1455	50	728	
Grain sorghum stubble[†]	676	50	338	
Lupin stubble[†]	1389	50	694	
Oat stubble[†]	1519	50	760	
Triticale stubble[†]	547	50	273	
Wheat stubble[†]	17 116	50	8558	
Short-rotation coppice eucalypt[‡]	14 996	100	14 996	Dedicated energy crop
Native managed forest residue[§]	1634	100	1634	Assume can divert with no further constraints after harvest
Native managed forest pulplog[§]	3363	88	2960	Amount equivalent to average export fraction, 1996–2005
Native managed forest sawmill residue[¶]	1320	50	660	Retain 50% for board, pulp, paper, burning in kiln
Native managed forest sawn timber[§]	763	0	0	High-value product not likely to be used as feedstock
Plantation hardwood forest residue[‡]	199	100	199	Assume divert with no further constraints after harvest
Plantation hardwood pulplog[‡]	2037	92	1874	Amount equivalent to average export fraction 1996–2005
Plantation hardwood sawmill residue[¶]	106	50	53	Retain 50% for board, pulp, paper, burning in kiln
Plantation hardwood sawn timber[‡]	64	0	0	High-value product not likely to be used as feedstock

Table 10 (continued)

Biomass class ⇨ Bioenergy form Biomass source	Annual harvest (dry kt)	Diversion/ harvest (%)	Annual diversion (dry kt)	Diversion rationale
Plantation softwood forest residue[‡]	614	100	614	Assume divert with no further constraints after harvest
Plantation softwood pulplog[‡]	2115	25	529	Amount equivalent to average export fraction 1996–2005
Plantation softwood sawmill residue[¶]	2808	50	1404	Retain 50% for board, pulp, paper, burning in kiln
Plantation softwood sawn timber[‡]	2202	0	0	High-value product not likely ever to be used as feedstock
Urban wood waste[**]	1064	70	745	30% wood contaminated and may not be suitable
Lignocellulose ⇨ Electricity OR Ethanol (forestry-sourced biomass coming on-stream to 2030 – additional to above)[††]				
Plantation hardwood forest residue[‡]	297	100.00	297	Identical to corresponding plantation hardwood (current) rationales above
Plantation hardwood pulplog[‡]	3025	92.00	2796	
Plantation hardwood sawmill residue[¶]	182	50.00	91	
Plantation hardwood sawn timber[‡]	95	0.00	0	

{Biomass class} ⇨ {Bioenergy form}: Class of biomass that acts as feedstock in transformation to bioenergy form.

Production systems of biomass sources are noted:

[*] agricultural products;

[†] agricultural residues;

[‡] plantation forests;

[§] native forests;

[¶] sawmill residues;

[**] urban residues.

Types of biomass coming on-stream to 2030 are constrained:

[††] no large increase in wood flow from Managed native forests or Plantation softwoods, thus report figures for Plantation hardwood only.

Agricultural products. The *Diversion* parameter for agricultural products was based on export fractions for food crops. Data for 1996–2005 were extracted from ABARE (2001–2006) statistics and averaged across the decade as a ratio of export to production (Table 10). This is an upper estimate based on maintaining domestic food security, a somewhat arbitrary but transparent assumption. The export fraction is, of course, food for people overseas, but Australia also exports and imports grain products. The export of Australia's primary food products provides foreign income, which may be used to purchase, among other things, food imports. The issue of indirect impacts on food security is a complex one and beyond the scope of the current study, and is further dealt with in the 'Discussion' section.

Agricultural crop residues. The rate of harvest of agricultural residues (primarily stubble biomass) is reduced by technical considerations (minimum cutting height above ground) and environmental constraints. A maximum of 50% of *Harvest* was assumed to be divertible, because much of the stubble was produced at low spatial density and therefore probably not feasible to collect and divert bioenergy.

Plantation forests. Assumed maximum rates of *Diversion* from plantations were based on environmental considerations and demand from existing domestic industries (Table 10). There is 100% diversion of forest residues – environmental constraints were applied in the *Harvest* parameter, and there are no competing markets. It was assumed that no sawlogs and only the export fraction of pulplogs could be diverted to bioenergy. The remaining material is mostly used for domestic production of sawn timber, boards, and pulp and paper. The fraction of pulplogs exported as wood chips was based on the average for 2006–2009 from ABARE (2010).

Native forests. *Diversion* of sawlogs, pulplogs and forest residues for bioenergy was estimated as for plantations (Table 10).

Sawmill residues. There were limited data on existing uses of sawmill residues, but it was assumed that 50% of chips were used for domestic board, pulp and paper production and for this analysis were not be diverted to bioenergy. Similarly, it was assumed that 50% of sawdust and shavings were already used as boiler fuel for providing heat for kiln drying timber. Although most of the remaining sawdust and shavings are currently used for board production and most bark is likely to be used in garden products, a *Diversion* parameter of 50% was assumed (Table 10).

Urban wood waste. The reported urban wood waste entering landfill may contain up to 30% contaminated wood, which may not be suitable for bioenergy depending on the technology used (Taylor *et al.*, 2005). Therefore, the *Diversion* parameter excluded this proportion (Table 10).

Algae, coppice eucalypt and Pongamia. As these crops were assumed to be dedicated energy crops, *Diversion* was assigned a value of 100% of *Harvest* (Table 10).

Estimation of Conversion rate parameters for selected bioenergy technologies

There are a range of energy conversion technologies either extant, or under development. The *Conversion rate* depends on the nature of the biomass material, the conversion technology and the scale at which it is deployed. The very small set of biomass–bioenergy pathways used in this study is presented in Table 1.

Standard factors to enable the conversion of each biomass type to bioenergy were assumed where possible. In some cases, the conversion factors had to be calculated from energy density and conversion efficiency data because relevant references did not provide conversion rates *per se* (Table 11). The production of ethanol generates a number of coproducts. Fermentation produces dry distiller's grain, which is not considered in this study (but see Braid, 2007 for a review). Enzymatic fermentation only operates on the cellulosic component; however, the conversion factors and emissions used consider the ratio of lignin in the feedstock and account for the use of the energy in the lignin during the conversion process. The conversion emissions appearing in this Table are discussed in the following section.

Estimation of parameters for net GHG mitigation

Production, transport and conversion emissions. The estimation of GHG emissions is a very complex topic which, to be done rigorously, requires a full life cycle assessment for each biomass–bioenergy pathway, using consistent system boundaries, allocation rules and parameters relevant to the local production systems (e.g. ISO 14040). A comprehensive and consistent analysis has not been undertaken for the range of biomass production systems and technology pathways covered in this paper. Instead, we provide a simplified GHG account for each pathway, drawing on the most appropriate available literature and unpublished CSIRO data. Issues relating to this simplified approach and the variation are further detailed in the discussion.

Energy content, Displaced GHG emissions and Net GHG mitigation. The *Energy content* and *Net GHG mitigation* parameters for each biomass–bioenergy pathway were calculated. Life cycle emissions for each pathway were subtracted from those of the comparator fossil energy which it would displace (as per Smith *et al.*, 2008) (Fig. 1). Life cycle emissions used for gasoline, diesel and electricity were 2.6 kg CO_2-e L^{-1}, 2.9 kg CO_2-e L^{-1}, and 955 kg CO_2-e MWh^{-1}, respectively (Department of Climate Change, 2009). The emissions associated with each feedstock to bioenergy pathway were calculated by adding the emissions associated with production, transport, conversion and combustion. These were sourced directly from literature for production and transport (Table 12) and conversion (Table 11) where possible (e.g. Farine *et al.*, 2008; Yu *et al.*, 2008; Tucker *et al.*, 2009) or estimated from literature (e.g. Biswas & John, 2009; Foust *et al.*, 2009) combined with unpublished CSIRO data. Emissions of N_2O and CH_4 associated with the combustion of each fuel were calculated using the National Greenhouse Accounts Factors (Department of Climate Change, 2009) as follows: 0.08 kg CO_2-e L^{-1} (ethanol), 0.12 kg CO_2-e L^{-1} (biodiesel), 20.3 kg CO_2-e MWh^{-1} (electric-

Table 11 Conversion process, rate of conversion, and associated GHG emissions used to calculate biofuel and bioenergy production for each feedstock category (*new feedstocks are italicized*)

Feedstock (conversion process)	Conversion rate	Conversion emissions[11]
Starch to ethanol (fermentation)	(L t^{-1})	(kg CO_2-e L^{-1})
Barley grain	330[1]	0.5
Grain sorghum grain	390[2]	0.5
Oat grain	410[1]	0.5
Triticale grain	400[1]	0.5
Wheat grain	362[3]	0.5
Sucrose to ethanol (fermentation)	(L t^{-1})	(kg CO_2-e L^{-1})
C-molasses	270[4]	0.6
Sugar cane sugar	560[5]	0.6
Oil to biodiesel (transesterification)	(L t^{-1})	(kg CO_2-e L^{-1})
Algae biomass	495[6]	0.5
Pongamia seed	296[7]	0.5
Canola seed	400[3]	0.5
Animal tallow	894[8]	0.5
Waste oil mixture	874[8]	0.5
Lignocellulose to ethanol (enzymatic ferm.)	(L t^{-1})	(kg CO_2-e L^{-1})
Bagasse	300[9]	0.3
Stubble (all types)	335[9]	0.0
SRC eucalypt	288[9]	0.0
Native forest pulpwood and residues	288[9]	0.2
Plantation hardwood and softwood	288[9]	0.1
Urban wood waste	288[9]	0.1
Lignocellulose to electricity (combustion)	(MWh t^{-1})	(kg CO_2-e MWh^{-1})
Bagasse	0.8[10]	18.0
Stubble (all types)	1.02[10]	21.6
SRC eucalypt	1.35[10]	21.6
Native forest products and residues	1.35[10]	28.8
Plantation hardwood products and residues	1.35[10]	28.8
Plantation softwood products and residues	1.35[10]	28.8
Urban wood waste	1.35[10]	20.8

Values are rounded and therefore emissions are not true zero. GHG, greenhouse gas.

[1] Kim & Dale (2004), [2] Sheorain *et al.* (2000), [3] Smeets *et al.* (2005), [4] Panesar *et al.* (2006), [5] Australian Cane Growers Council (2005), [6] Campbell *et al.* (2009b), [7] calculated from Kumar *et al.* (2006), Sureshkumar *et al.* (2008), [8] Beer *et al.* (2005), [9] IEA (2004), [10] calculated from Department of Climate Change (2009), [11] CSIRO unpublished LCA data based on review of the literature, e.g. Foust *et al.* (2009).

ity from lignocellulose). Emissions caused by indirect impacts (such as the production emissions associated with replacing the biomass that has been removed from the market) were not included.

The biofuel replacement (ethanol, biodiesel) for each fossil comparator (gasoline, diesel) was calculated based on the energy content of each fuel type (Table 13). Bioelectricity was assumed to replace that produced from black coal.

Results

Amounts of biomass and bio-oils potentially available as feedstocks for bioenergy

Table 2 summarizes the annual harvest, or potentially harvestable amounts, of a range of biomass types from current production systems. There are significant amounts of grains (>30 Mt yr^{-1}), sugar (~5 Mt yr^{-1}), bagasse (>5 Mt yr^{-1}), crop stubble (>25 Mt yr^{-1}) and forest pulpwood + forest residues (~10 Mt yr^{-1}, and increasing to ~13 Mt yr^{-1} by 2030).

When fully established, the new production systems examined (Tables 4, 5, 9) might provide ~14 Mt yr^{-1} of wood from SRC eucalypts, and ~5 Mt yr^{-1} of oils from algae and Pongamia plantations. There is considerable uncertainty regarding when and if these feedstocks might be available for bioenergy.

Energy assessment

The amount of energy which could be produced from biomass sources estimated to be available for bioenergy

Table 12 Estimated GHG emissions due to production and transport, for a range of bioenergy feedstocks

Feedstock	Production emissions (kg CO_2-e t^{-1})	Transport emissions (kg CO_2-e t^{-1})
Starch		
Barley grain	166[1]	8[2]
Grain sorghum grain	166[1]	8[2]
Oat grain	166[1]	8[2]
Triticale grain	166[1]	8[2]
Wheat grain	166[1]	8[2]
Sucrose		
C-molasses	0	Low
Sugar cane sugar	200[1]	6[2]
Oil		
Canola seed	333[1]	8[2]
Animal tallow	0	0
Waste oil mixture	0	0
Algae biomass	−1.61[4]	−1.75[4]
Pongamia seed	310[6]	8[6]
Lignocellulose		
Bagasse	0[1]	0
Barley stubble	9[2]	16[2]
Canola stubble	9[2]	16[2]
Chick peas stubble	9[2]	16[2]
Field peas stubble	9[2]	16[2]
Grain sorghum stubble	9[2]	16[2]
Lupins stubble	9[2]	16[2]
Oat stubble	9[2]	16[2]
Triticale stubble	9[2]	16[2]
Wheat stubble	9[2]	16[2]
Native forest residue	36[3]	11[3]
Native forest pulplog	118[3]	11[3]
Native forest sawmill residue	21[3]	11[3]
Native forest sawn timber	721[3]	11[3]
Plantation hardwood forest residue	39[3]	22[3]
Plantation hardwood pulplog	104[3]	17[3]
Plantation hardwood sawmill residue	26[3]	22[3]
Plantation hardwood sawn timber	706[3]	22[3]
Plantation softwood forest residue	32[3]	22[3]
Plantation softwood pulplog	65[3]	17[3]
Plantation softwood sawmill residue	26[3]	22[3]
Plantation softwood sawn timber	676[3]	22[3]
Urban wood waste	0	Low
SRC eucalypt	31[5]	14[5]

Transport distances generally 50 km unless otherwise indicated [1] Farine *et al.* (2008), [2] calculated from Farine *et al.* (2008, 2010), Herr *et al.* (2010), [3] calculated from Tucker *et al.* (2009); [4] Campbell *et al.* (2009a): net GHG emissions from algal productions systems are very site-specific, and also depend on any carbon credits generated as a result of production of electricity from algal biomass following extraction of oil. The negative values shown here reflect a scenario where carbon credits have been produced; [5] estimated from Yu *et al.* (2008) which assume a higher growth rate than our study, as well as a longer transport distance; [6] estimated from production emissions minus fertilizer in Biswas & John (2009). GHG, greenhouse gas.

was calculated as a product of *Diversion* (proportion of *Harvest* used as a feedstock for bioenergy) (Table 10) and the *Conversion rate* of each feedstock to each form of bioenergy (Table 11). The results of this calculation for biofuels (ethanol and biodiesel) and bioelectricity are shown in Table 14 and Fig. 3.

Within the technical and physical constraints applied in this study, it would be physically possible to replace a significant proportion of the current use of liquid fossil fuels with biofuels based on Australian-produced biomass feedstocks. Australia's current liquid fuel usage is 19.2 GL yr^{-1} of gasoline and

Table 13 Energy equivalence ratio applied when using biofuels to replace fossil fuels

Biofuel	Ethanol	Biodiesel
Energy content (MJL^{-1})	23.4[1]	33.2[1]
Replaced fossil fuel	Gasoline	Diesel
Energy content (MJL^{-1})	34.2[1]	38.6[1]
Energy ratio (biofuel/fossil fuel)	0.68	0.86

[1] Department of Climate Change (2009).

18.2 GL yr^{-1} of diesel (ABARE, 2009). The contribution that first generation biofuels from current production systems could make towards replacing this was 9.6 GL yr^{-1} of ethanol from the export fraction (Table 14). This would replace 6.5 GL yr^{-1} of gasoline, or 34% of current gasoline usage. Oil products (waste oil, tallow and canola seed) could contribute 0.9 GL of biodiesel, replacing 0.8 GL or 4% of current diesel usage. Cellulosic biomass from current agricultural and forestry production systems (including biomass from hardwood plantations maturing by 2030) could produce up to 9.5 GL of ethanol. This would provide replacement for 6.4 GL yr^{-1} of gasoline, or ca. 33% of current consumption.

Similarly, the use of lignocellulose from forestry and agricultural biomass could make a contribution to current electricity usage via direct combustion. Australia's current electricity generation is 230 TWh yr^{-1} (ABARE, 2009). Lignocellulose from current forestry and agricultural production systems (including biomass from hardwood plantations maturing by 2030) could provide 35 TWh, or ca. 15% of current electricity production.

Whilst a significant portion of the current supply of either ethanol or electricity could be met based on current production figures, there are smaller opportunities for the production of biodiesel through first generation technologies. Up to 0.9 GL of biodiesel could be produced from current canola, waste oil and tallow based on our diversion assumptions. Based on our assumptions for new production systems (which are highly uncertain), *P. pinnata* could produce ca. 0.9 GL of biodiesel based on 458 000 ha of new plantings. Algae, based on ponds utilizing CO_2-rich sources, could produce ca. 3.96 GL $yr^{-1}$of biodiesel. Combined, these new production systems could replace 4.2 GL of fossil-based diesel, or 23% of current usage.

Estimates of lignocellulose from new production systems for lignocellulose was based on incorporation of SRC eucalypt plantings into agricultural landscapes. Based on 5% of cleared agricultural land dedicated to SRC eucalypts, 4.3 GL of ethanol could be produced (2.9 GL replacement, or 15% of current gasoline use) or 20.2 TWh of electricity (9% of current generation).

Net GHG mitigation

Australia's annual GHG emissions for 2008 were estimated at 549.5 Mt CO_2-e, of which 167.3 Mt CO_2-e was attributed to coal-based electricity and 69.2 Mt CO_2-e to road transport (Department of Climate Change and Energy Efficiency, 2010). It is possible to partly mitigate these emissions by utilizing biomass to produce biofuels to replace fossil fuels, or by combustion of biomass to produce electricity and avoid the burning of coal. The estimated mitigation potential for biomass diverted to bioenergy is shown in Table 14.

Diversion of the export fraction of currently produced starch, sugar and oil to ethanol and biodiesel could mitigate ca. 5.85 Mt CO_2-e, equivalent to 8.4% of current road transport emissions, or 1% of Australia's total annual emissions (Table 14 and Fig. 3). Lignocellulosic ethanol from current agricultural and forestry systems (including biomass from hardwood plantations maturing by 2030) could mitigate ca. 9 Mt CO_2-e by replacing fossil fuels. This would account for 13% of annual road transport emissions, or 1.6% of total emissions in Australia. Due to the high emissions associated with electricity generation, this same biomass combusted and used to replace coal-based electricity could amount to 30 Mt CO_2-e of emissions mitigated per annum. This would represent a saving of 18% of current coal-based electricity emissions, or 5.4% of total emissions nationally.

The three new production systems analysed could contribute significantly to mitigation of fossil-fuel based emissions. Algae used for biodiesel were estimated at 6.4 Mt CO_2-e. This represents a saving of ca. 9% of annual road transport emissions, or 1% of national emissions. *Pongamia pinnata* plantations could mitigate 0.9 Mt CO_2-e, which is 1% of road transport emissions, but would contribute very little to total national emissions. Modest assumptions on *Area* were used in this analysis, and mitigation potential could be higher if more land were planted. Likewise, ethanol from SRC eucalypt could provide a GHG mitigation of 4.5 Mt CO_2-e (6.5% of road transport emissions). However, diverting these to electricity may mitigate 17.8 Mt CO_2- e, which is 10.6% of annual electricity emissions, or 3% of the national emissions each year.

In total, first and second generation fuels from current and new production systems could mitigate 26 Mt CO_2-e, which is 38% of road transport emissions, and 5% of the national emissions. Second generation fuels from current and new production systems could mitigate 13 Mt CO_2-e, which is 19% of road transport emissions, and 2.4% of the national emissions Lignocellulose from current and new production systems could mitigate 47 Mt CO_2-e, which is

Table 14 Production of biofuel and bioelectricity, and estimates of GHG mitigation

		Based on harvest			Based on diversion		
Biomass class ⇨ Bioenergy form	Emissions mitigated per unit bioenergy	Amount	Energy	Emissions mitigated	Amount	Energy	Emissions mitigated
Starch ⇨ Ethanol (current)	kg CO_2-e L^{-1}	ML	PJ	Mt CO_2-e	ML	PJ	Mt CO_2-e
Barley grain	0.66	2211	52	0.99	1437	34	0.64
Grain sorghum grain	0.74	684	16	0.34	150	4	0.08
Oat grain	0.76	607	14	0.32	67	2	0.03
Triticale grain	0.75	249	6	0.13	0	0	0
Wheat grain	0.71	7578	177	3.64	5684	133	2.73
Subtotals (current)	–	11 329	265	5.42	7338	173	3.48
Sucrose ⇨ Ethanol (current)	kg CO_2-e L^{-1}	ML	PJ	Mt CO_2-e	ML	PJ	Mt CO_2-e
C-molasses	1.09	239	6	0.18	120	3	0.09
Sugar cane sugar	0.72	2669	62	1.31	2095	49	1.02
Subtotals (current)	–	2908	68	1.49	2215	52	1.11
Oil ⇨ Biodiesel (current)	kg CO_2-e L^{-1}	ML	PJ	Mt CO_2-e	ML	PJ	Mt CO_2-e
Algae biomass	1.88	3960	131	6.41	3960	131	6.41
Pongamia seed	0.8	873	29	0.6	873	29	0.6
Canola seed	1.02	553	18	0.49	310	10	0.27
Animal tallow	1.87	527	17	0.85	527	17	0.85
Waste oil mixture	1.87	87	3	0.14	87	3	0.14
Subtotals (current)	–	6000	198	8.49	5757	190	8.27
Lignocellulose ⇨ Ethanol (current)	kg CO_2-e L^{-1}	ML	PJ	Mt CO_2-e	ML	PJ	Mt CO_2-e
Bagasse	1.39	1652	39	1.56	826	19	0.78
Barley stubble	1.61	1677	39	1.84	839	20	0.92
Canola stubble	1.61	487	11	0.53	244	6	0.27
Grain sorghum stubble	1.61	226	5	0.25	113	3	0.12
Lupins stubble	1.61	465	11	0.51	233	5	0.26
Oat stubble	1.61	509	12	0.56	254	6	0.28
Triticale stubble	1.61	183	4	0.2	92	2	0.10
Wheat stubble	1.61	5734	134	6.29	2867	67	3.15
SRC eucalypt	1.53	4319	101	4.5	4319	101	4.50
Native managed forest residue	1.31	470	11	0.42	470	11	0.42
Native managed forest pulplog	1.02	969	23	0.67	852	20	0.59
Native managed forest sawmill residue	1.58	380	9	0.41	190	4	0.2
Plantation hardwood forest residue	1.39	57	1	0.05	57	1	0.05
Plantation hardwood pulplog	1.18	587	14	0.47	540	13	0.43
Plantation hardwood sawmill residue	1.52	30	1	0.03	15	0	0.02
Plantation softwood forest residue	1.39	177	4	0.17	177	4	0.17
Plantation softwood pulplog	1.29	609	14	0.54	152	4	0.13
Plantation softwood sawmill residue	1.52	809	19	0.84	404	9	0.42
Urban wood waste	1.59	306	7	0.33	215	5	0.23
Subtotals (current)	–	19 646	459	20.05	12 859	300	13.04
Plantation hardwood forest residue (extra to 2030)	1.39	86	2	0.08	86	2	0.08
Plantation hardwood pulplog (extra to 2030)	1.18	871	20	0.	801	19	0.64
Plantation hardwood sawmill residue (extra to 2030)	1.52	52	1	0.05	26	1	0.03
Subtotals (extra to 2030)	–	1009	23	0.83	913	22	0.75

Table 14 (continued)

		Based on harvest			Based on diversion		
Biomass class ⇨ Bioenergy form	Emissions mitigated per unit bioenergy	Amount	Energy	Emissions mitigated	Amount	Energy	Emissions mitigated
Lignocellulose ⇨ Electricity	kg CO_2-e GWh^{-1}	GWh	PJ	Mt CO_2-e	GWh	PJ	Mt CO_2-e
Bagasse	917	4404	16	4.04	2202	8	2.02
Barley stubble	889	5106	18	4.54	2553	9	2.27
Canola stubble	889	1484	5	1.32	742	3	0.66
Grain sorghum stubble	889	689	2	0.61	345	1	0.31
Lupins stubble	889	1417	5	1.26	708	3	0.63
Oat stubble	889	1550	6	1.38	775	3	0.69
Triticale stubble	889	558	2	0.5	279	1	0.25
Wheat stubble	889	17 458	63	15.51	8729	31	7.76
SRC eucalypt	880	20 244	73	17.81	20 244	73	17.81
Native managed forest residue	871	2205	8	1.92	2205	8	1.92
Native managed forest pulplog	810	4540	16	3.68	3995	14	3.24
Native managed forest sawmill residue	889	1781	6	1.58	891	3	0.79
Plantation hardwood forest residue	856	268	1	0.23	268	1	0.23
Plantation hardwood pulplog	787	2750	10	2.16	2530	9	1.99
Plantation hardwood sawmill residue	881	143	1	0.13	71	0	0.06
Plantation softwood forest residue	865	829	3	0.72	829	3	0.72
Plantation softwood pulplog	845	2855	10	2.41	714	3	0.6
Plantation softwood sawmill residue	879	3791	14	3.33	1895	7	1.67
Urban wood waste	914	1436	5	1.31	1005	4	0.92
Subtotals (current)	–	73 508	264	64.44	50 980	184	44.54
Plantation hardwood forest residue (extra to 2030)	856	401	1	0.34	401	1	0.34
Plantation hardwood pulplog (extra to 2030)	787	4083	15	3.21	3756	14	2.95
Plantation hardwood sawmill residue (extra to 2030)	881	245	1	0.22	123	0	0.11
Subtotals (extra to 2030)	–	4729	17	3.77	4280	15	3.4

{Biomass} ⇨ {Bioenergy form}: Class of biomass that acts as feedstock in transformation to bioenergy form. GHG, greenhouse gas.

28% of electricity emissions and 9% of the national emissions.

The emission mitigation per unit energy production is also provided in Table 14. First generation ethanol from grains and sugar ranged from 0.66 to 1.09 kg CO_2-e L^{-1}, while second generation ethanol from lignocellulose ranged 1.02–1.61 kg CO_2-e L^{-1}, depending on the particular production system and the fraction of biomass assessed. Algal biomass had the highest unit mitigation with 1.88 kg CO_2-e L^{-1}. Lignocellulosic electricity ranged from 787 kg CO_2-e GWh^{-1} (pulplog) to 917 kg CO_2-e GWh^{-1} (bagasse).

Discussion

There are many uncertainties regarding future economic and policy settings that would drive demand for bioenergy, as well as the relative demand for different types of biofuels or bioelectricity. These uncertainties include the price of conventional oil, the price of non-conventional hydrocarbon fuels, the cost of GHG emissions (and other aspects of the design of GHG mitigation policies), choices in engine technology (especially, liquid fuel vs. electricity), increases in efficiency of biofuel technology over time, costs of growing and collecting biomass, the cost and availability of land, competition for biomass from other uses (including food, animal feed and fibre), and consumer attitudes to biofuels and particular biomass production systems. We have made no attempt to estimate these uncertainties in this study, but instead have provided the basis for such analyses in the future by providing a physical basis for the magnitude of future supply of a range of feedstocks.

The estimates provided in this article are lower than many others (e.g. Hoogwijk *et al.*, 2005; Smeets *et al.*,

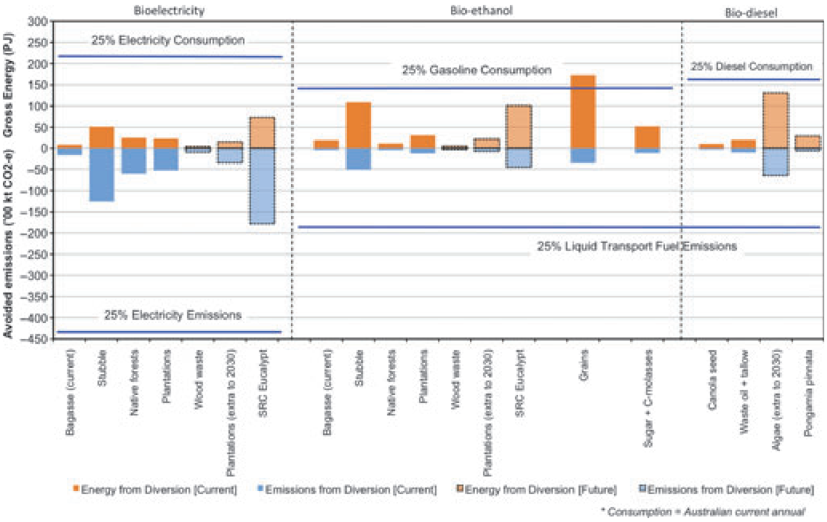


Fig. 3 Potential gross energy production (positive part of bars) as bioelectricity, bio-ethanol or bio-diesel from diverted fraction of current and future biomass feedstocks, and the fossil fuel GHG emissions mitigated (negative part of bars). Dashed boxes represent new future feedstock production. Horizontal lines represent 25% of 2008 Australian national consumption for energy products (electricity, gasoline or diesel, ABARE 2009b), and 25% of the 2008 GHG emissions from each sector (Department of Climate Change and Energy Efficiency, 2010). The Cellulose to Ethanol or Lignocellulose to Electricity represent the same biomass, and should not be double counted.

2007; de Vries *et al*., 2007). There are a few reasons for this: in comparison with most international studies, we have assumed minimal land-use change for the new biomass production systems, no future yield increases in current production systems, and conservative rates of removal of biomass residues from current agricultural and forestry production systems. This means that we have produced a somewhat conservative estimate of the biomass potential for Australia in comparison with other authors.

These issues deserve further detailed consideration. In addition to these factors, we will further consider uncertainty and variability. We have estimated the mean for each of the parameters and carried this through the calculations without any explicit treatment of uncertainties. In the following sections, we provide some commentary on uncertainty, and on the relative importance of various factors.

Area, Annual production and Yield trends

Area and land-use change. . The availability of suitable land will be a major constraint to the expanded production of feedstocks for bioenergy in Australia. Many of the global assessments of bioenergy potential are based on assumptions about availability of large amounts of 'surplus', 'idle', 'set-aside' or 'marginal' land (e.g. Hoogwijk *et al*., 2005; Smeets *et al*., 2007; Milbrandt & Overend, 2009). In the present study, we did not consider any land to be marginal, surplus or idle, and did not analyse a change in *Area* for current agricultural or forest production systems. As described in the 'Methods' section, we used relatively modest and simplified assumptions for the areas of new production systems to show the relative magnitude of future prospects. Most cleared land is already used for some form of agriculture (cropping or grazing), thus substitution with bioenergy crops may involve a degree of trade-off with food production. Clearing of native vegetation is highly restricted under current legislation in most Australian states (O'Connell *et al*., 2009). A more complete analysis of future biomass production remains to be conducted, and would need to be underpinned by a more robust and substantiated set of assumptions about the drivers for land-use change, the market and nonmarket values of land in Australia, as well as the broader economic and policy settings.

Current production systems

This analysis was based on *Area* and *Annual production* estimates averaged over several years of historical production. There were, in some cases, large variations in the annual production of some forms of biomass, usually related to annual rainfall or other climatic conditions. *Annual Production* has been used to minimize the number of parameters in this assessment, but it can be disaggregated to *Area* × *Yield*. Many of the international assessments for bioenergy are based on assumptions of the historical yield increases continuing into the future (e.g. Smeets *et al*., 2007). Much of the Australian landscape is dominated by soils of low fertility, and by low and variable rainfall (Hamblin & Kyneur, 1993) that constrain yields and the suitability of land for producing crops or woody biomass. The prospect for increasing grain crop yields in Australia is limited. Between 1950 and 1990, the average wheat grain yield increase was only 8 kg ha^{-1} yr^{-1} (Hamblin & Kyneur, 1993) – well below that in many other countries. For example, most west European countries had grain yield increases in excess of 100 kg ha^{-1} yr^{-1} in the same period, and a large percentage of the growth in production from these countries has been through yield increases as opposed to land-use change (Lywood *et al*., 2009) – the opposite is true in Australia (Dunlop *et al*., 2003). A number of studies forecast large yield improvements for Australia, such as Elobeid *et al*. (2009), who estimate a 29% increase in wheat yield, equivalent to 45 kg ha^{-1} yr^{-1}, between 2008/2009 and 2018/2019. Unkovich *et al*. (2010) found that yield increases are only achieved by reducing the nongrain biomass proportion.

Expansion of the *Area* for production of current agriculture is likely only in high-risk and low-yielding locations, and risk itself may also be a limiter in achieving higher yields (Keating & Carberry, 2008). Any increase in Australia's national average yield is therefore unlikely to be substantial enough to contribute to increased production, and certainly nowhere nearly as great as that forecast by Elobeid *et al*. (2009). We have therefore assumed no *Area*, or *Yield* or *Annual production* increases for current production systems in this study.

Increased planting of agricultural oilseed crops may also be limited. Planting of Canola in higher rainfall areas, and mustard in the lower rainfall zone, could reach at least 2 Mha yr^{-1}; however, this would represent a large increase. These crops are highly sensitive to rainfall with high risk of failing in poor years, and with only modest returns in very good years. Thus, the future of crop oilseed production in Australia remains uncertain.

Future production of biomass from existing forestry plantations is largely dependent on four factors: (i) the current area planted; (ii) the age class distribution; (iii) expected rotation lengths; and (iv) whether plantations are replanted after harvest. While most softwood plantations are already approaching maximum yield, the rapid expansion in hardwood plantation area over the past 12 years means that only a fraction of these plantations have reached their maximum yield. It is expected that wood production from hardwood plantations will increase from 4.8 million m^3 yr^{-1} currently to 15.7 million m^3 yr^{-1} by 2020 (Parsons *et al*., 2007). As a result of these trends, total forest biomass production is expected to increase from current levels of ca. 18–27 Mt yr^{-1} over the coming decade. In contrast to wood production from plantations, log removal from native forests has been decreasing, from 10 million m^3 yr^{-1} in 2002–2003 to 8 million m^3 yr^{-1} in 2008–2009 (ABARE, 2010), but may have now stabilized. The recent collapse of the Managed Investment Schemes (MIS), which were driving rapid expansion of hardwood plantation development has, however, made investors wary and the replanting of currently established plantations after the current rotation more uncertain.

New production systems

There is significant opportunity to integrate woody crops (such as belts or blocks of coppice eucalypts) with traditional farming systems, with little or no loss, and sometimes a benefit, for agricultural yields. This study showed the possibility of producing a large amount of biomass up to 15 M dry t yr^{-1}) by about 2030. This is a conservative estimate compared with that in Bartle *et al*. (2007) who estimated 37 M dry t yr^{-1} from 1.5% of land in the 300–400 mm zone, and 8% of the 401–600 mm zone of the Australian wheat belt. Major scaling up of woody biomass production systems, especially where these involve significant change in land use, does have the potential for adverse environmental and social impacts, and thus requires careful planning at the landscape/catchment scale. Many aspects of this production system have already been studied (e.g. Wildy *et al*., 2004 for hydrology; Wu *et al*., 2008 energy balance).

Our analysis shows good prospects to produce oil (up to 4 Mt yr^{-1}) from algae. However, most of the international work relies (as does the analysis presented in this article) on bench-scale science, limited outdoor data and extrapolation based on untested assumptions about production and economics (Darzins *et al*., 2010). Significant breakthroughs will be required in algal mass culture and cultivation, harvesting and dewatering, downstream processing technologies for extraction and fractionation, fuel conversion and co-products (US Department of Energy, 2010). The basic biology of algal physiology and regulation of biochemical pathways and strain selection also require breakthrough research (Campbell *et al*., 2009a; Darzins *et al*., 2010; US Department of Energy, 2010). Rapid scale-up of bio-oil production from algae is unlikely within the next decade.

Pongamia pinnata shows some promising characteristics as a future source of biofuels (Scott *et al*., 2008). However, there are a range of uncertainties relating to the commercial establishment of large-scale plantations of *P. pinnata* in Australia. The CLIMEX^{TM} annual growth index (GIA) used in this exploratory study does not provide an absolute indication of growth potential, but rather an index of relative growth potential. The relationship between plant growth potential and oil production potential is likely to be nonlinear and require experimental trials to provide parameters for models. A useful interim step may be to conduct a gradsect across study plots, which are well established and where oil production yield (and quality) and plant size characteristics (e.g. basal diameter and canopy diameter) can be characterized for a range of plant ages along with site characteristics such as cultivar type and horticultural practices (e.g. irrigation). This approach is not a substitute for the establishment of a network of well-designed long-term field trials in Australia. Comprehensive studies are needed to determine oil yields across different environments, tree age, well-defined genetic stock and extraction techniques (Gary Seaton, personal communication; Pandravada *et al.*, 2006). Given the limited knowledge of the agronomy of the crop, the lack of data relating future yields to site conditions, and limitations to the amount of suitable land, the scale-up of planting and oil production face significant uncertainties. There is a clear opportunity for systematic step-wise development of this industry over the next decade or two, in parallel with a targeted research programme to address the major knowledge gaps.

Several other feedstocks which may contribute to bioenergy in the future were not considered in this study. Grasses (other than existing crops) were excluded due to large uncertainties with estimating primary production, harvesting potential and environmental impacts; however, current research is investigating the areas and associated production potential for grass biomass in Australia. *Jatropha curcas* is another oilseed tree that is being used in India, Africa and South America for biofuel production, but it is listed as a noxious weed in two Australian states. Plants which may be compatible with current agricultural systems (such as agave or sweet sorghum), and arid zone plants such as halophytes (e.g. *Salicornia*) also require further investigation. In addition, there are several other sources of municipal, urban or industrial waste, horticultural and food processing residues, which have not been assessed in this study and remain to be quantified adequately.

Water and irrigation

Low yields have large impacts on the economics of feedstock production and collection. Irrigation is one frequently presented means of increasing yields of current dryland cropping (e.g. Milbrandt & Overend, 2009) and of allowing cropping in 'marginal' land. However, this is an impractical solution for increasing biomass production in much of Australia due to existing water shortages in most agricultural regions and energy requirements for pumping irrigation and drainage water. In addition, irrigation is likely to be preferentially used in the production of high-value food crops, where the income per hectare may be several times the returns from biofuel feedstocks.

Spatial distribution of biomass

A number of issues surround the low yields and distributed nature of cropping in Australia when considering using agricultural products or residues for bioenergy. National average annual yields of oilseeds, grains and crop stubble are below 2 t ha^{-1}, which would make the economic harvest and transport of the stubble component challenging. Herr *et al.* (2010) investigated potential concentrated zones for grain stubble production within a 50 km diameter catchment, and found several regions with reliable availability in most years – but detailed economic and supply chain studies for stubble remain to be conducted.

Although plantations and multiple-use native forests represent only a small proportion of total land area at a state level, in individual regions, they can occupy 10–20% of the total land area. This can provide stable and concentrated production 'hot spots' (Parsons *et al.*, 2006; Montreal Process Implementation Group for Australia, 2008). A feature of forest production systems is the potentially high density (sometimes >100 t ha^{-1}) of in-forest residues – many fold greater than in grain production systems.

Temporal variability of biomass supply

Variability in Australian climatic conditions is important – some studies (e.g. Milbrandt & Overend, 2009) use data from only 1 year, yet most of Australia's agriculture and forestry regions are characterized by high interannual variation in rainfall and yields. For example, over the period 1997–2006, south-eastern Australia had a mean annual rainfall of 511 mm with a standard deviation of 89.6 mm (Murphy & Timbal, 2008). Furthermore, the trend is for decreasing rainfall, with longer dry periods and fewer large wet events to replenish water stocks. Interannual variation in rainfall has critical implications for grain crops. For example, between 1997 and 2005, annual wheat production in Australia ranged from 10.0 to 25.7 Mt (Australian Grain, 2008), with the minimum and maximum occurring in consecutive years (2002 and 2003, respectively). This has even greater impact on the availability of stubble, where several years in the period 1996–2005 generated very low stubble availability (<10 Mt nationally, Herr *et al.*, 2010). These years of production shortage would have implications for ability to meet demand, and for feedstock prices.

Forest products and residues, and other perennial woody crops can provide some buffer against dry years. Current plantations are located in higher rainfall zones – a continuation of decreasing mean annual rainfall currently being experienced in south-eastern Australia (Murphy & Timbal, 2008) may have an impact on wood production. SRC forestry specifically tailored to bioenergy will also be prone to the effects of declining rainfall over the longer term.

Diversion of biomass to feedstocks for bioenergy

Currently, Australia is a net exporter of many primary food products, and it may be possible to divert a proportion of this into energy. Whilst this exported biomass is currently beyond Australia's domestic market requirements, diversion away from food markets may have indirect effects on sustainable food security and land-use change at the global scale, although the impacts are very difficult to quantify and are hotly debated (e.g. Von Braun, 2007; Searchinger *et al.*, 2008; O'Connell *et al.*, 2009). As food is a fundamental and irreplaceable human need, many in the 'food vs. fuels' debate regard food production as a higher order priority for use of land and water resources. The UN-Energy (2007) frames food security in four dimensions including (i) availability (related to food production); (ii) access; (iii) stability; and (iv) utilization, or the nutritional value of the food. As the debate matures, attitudes to diversion may evolve – for example, sugar and grains have different nutritional value. The diversions used in this report constitute a relatively minor fraction of global commodity markets (e.g. comparison of the annual average production 1996–2005 for Australian exports with world production is, for coarse grains, 10.98/892.3 Mt = 1.23%; wheat 20.95/582 Mt = 3.6%; oilseeds 2.47/309.3 Mt = 0.8%). However, the aggregate effects on the world markets from multiple countries applying such logic would be much more significant.

Uncertainty relating to the acceptable level of removal of in-forest residues is high. We have assumed levels of residue retention based on the generally nutrient-limited conditions under which Australian forests grow, as well as the need to maintain biodiversity and soil carbon. It is also costly to remove foliage and branch harvest residues for bioenergy. However, in parts of Europe, these are routinely collected and used during whole-tree harvest operations (Röser *et al.*, 2006).

There is intense concern in Australia regarding the potential use of material from native forests for bioenergy. Provided that harvesting operations are well-planned and conducted, ecological values can be protected (Raison & Squire, 2007). However, it is imperative that societal values be incorporated into any decisions about the use of biomass from any source, and particularly from native forests, if bioenergy is to gain support (O'Connell *et al.*, 2005, 2009; Raison & Squire, 2007). In our analysis, native forest residues and pulplogs made a significant contribution to the estimates of potential bioenergy production and GHG mitigation. The disaggregated data (Tables 10 and 14) provide the reader with the information to make estimates using different assumptions about the diversion of biomass from native forest (or any other production system).

Uncertainty in GHG emissions

There are a number of sources of uncertainty when estimating GHG mitigation potential of biomass. Significant amongst these is the quantity of N_2O emissions associated with the production process (Crutzen *et al.*, 2008). Whilst the life cycle assessment data used in these studies all accounted for N_2O emissions, they generally used standard emission factors for Australian production systems. However, there are large uncertainties associated with these emission factors, for example, Bartle *et al.* (2009) found N_2O emissions from fertilizer used in dryland cropping to be 0.02% of the applied fertilizer nitrogen, whereas Thorburn *et al.* (2010) found emissions in sugarcane to be 3–5% of the applied nitrogen – both values are very different from the 1.25% assumed as the standard emission factor (Department of Climate Change, 2009). If permission to clear native vegetation was provided, the GHG emissions associated with that would need to be factored in. Any change in land use that required clearing of vegetation often has a large impact on GHG emissions (e.g. Gallagher, 2008; Searchinger *et al.*, 2008).

All of the GHG assessments used in this study are static and do not take into account possible changes to reduce the emission intensity of the fossil and electrical inputs and processes. Further studies to provide specific, dynamic LCA and underpinning inventory data are required across biomass production systems, regions and specific energy technologies are required to improve the analysis presented here. In providing a simple accounting of GHG in this article, emission reductions from electricity and transport sectors would not be counted in those sectors – the emissions would appear in refining and agriculture sectors. The savings of emissions in one particular sector, and the associated offset in another have not been modelled in this paper and this would be useful further research.

Sustainability assessment and certification

There are different sustainability issues surrounding the use of feedstocks from different production systems – for example, there are significant issues of community concern around the use of native forest residues, or the use of food or feed grain for ethanol. The data in the Tables are presented in disaggregated form so that readers can add the fractions as they view appropriate.

Assessment of economic factors including cost of production, cash flows and NPV of the biomass production system *per se*, as well as the cost of producing biofuel through the target technologies, is required. The economics is critical to sustainability – however, this is only one element. Many governments and market segments consider that a broader set of quantitative, robust and independently verified (or certified) sustainability credentials are vital for the bioenergy industry to expand globally (e.g. UNEP, 2007; van Dam *et al.*, 2008; O'Connell *et al.*, 2009). There are many different sustainability assessment systems under development in the international arena. Some of these are targeted at providing a bioenergy market with some confidence about sustainability (e.g. the Roundtable for Sustainable Palm Oil), while others are targeted as requirements by governments (e.g. the New South Wales Government in Australia has specified that industry must report against the Roundtable for Sustainable Biofuels to qualify under a biofuels mandate). A process has also begun for a standard to be developed under the ISO. Australia does not yet have a broad certification system for bioenergy, although there are several systems in place for forestry.

There are particular sustainability issues relevant to proposed new production systems (algae, production of new woody crops or establishment of *P. pinnata* plantations) because these often involve deployment of new technologies or land base, and generally involve more uncertainty. The nature of the sustainability issues is often location-specific, scale-dependent, and differs with feedstock type. Resolution of these requires a capacity for spatial analysis, and good processes for involvement of 'local stakeholders' and the broader community in decision making.

Conclusions and future work

This article has quantified the current production of biomass in Australia, and some exploratory new production systems in terms of the opportunities for producing bioenergy and mitigating GHG emissions from fossil energy sources. The results showed that there is potential for Australia to produce a significant amount of energy from biomass.

The results showed that there was a greater GHG mitigation obtained through use of biomass for electricity production compared with liquid fuel. This is consistent with analyses conducted by others (e.g. Campbell *et al.*, 2009b). The analysis of the use of biomass for energy must, however, go beyond simple energy output and GHG mitigation. Different types of energy (electricity, liquid fuel based on oils or lignocellulose) will be important to different sectors of the energy market. For example, some forms of energy are in a particular form that is not easily replaceable by other forms of energy – liquid fuels for aircraft are much more difficult to replace than liquid fuels for passenger vehicles, which could use electricity or gas (Dale, 2007, 2008).

The availability of suitable land and water will be a major constraint to the expanded production of feedstocks for bioenergy in Australia. Most cleared land is already used for some form of agriculture (cropping or grazing), thus any substitution with bioenergy crops will involve a degree of trade-off with food production. Clearing of native vegetation is highly restricted by regulation. Account needs to be taken of the considerable year-to-year variation in biomass production by annual agricultural crops caused by marked climatic variability in Australia. Woody biomass production is less sensitive to climatic variability, thus integration of agricultural and woody biomass production systems may help improve the reliability of biomass supply within the year, and from year to year. There are more limited opportunities for using currently produced plant-derived oils, as well as for expanding plant-based oil production in Australia. In addition to the implications to land-use change, there are major research challenges to address for algae and for *Pongamia* (or other new oilseed plants which are in early stages of commercialization). A step-wise approach to industry development is required, as also further large-scale investment in research.

There is a range of important sustainability issues related to any major scale-up of feedstock production or diversion for bioenergy in Australia. There could be either positive or negative impacts. Environmental impacts such as those on soil, water, and biodiversity can be significant because of the large land base involved, and the likely use of intensive harvest regimes. These would need to be carefully managed. Social impacts could be significant if there were large-scale change in land use or management. The economics of feedstock production is uncertain, and subject to rapid change due to government policy, the price of fossil oil, and the scale of the industry.

A well-planned and integrated bioenergy industry could have major benefits for Australia in terms of improved fuel security, significant savings in the future cost of imported oil, significant GHG mitigation, and benefits from land remediation and rural and regional development. Whilst there is sufficient available biomass to support industry expansion in the short- to medium-term (5–10 years), a longer term (20–50 years) strategy is needed to facilitate major scale-up. Policies and mechanisms to achieve effective linkage between feedstock producers, feedstock processors, and the purchasers of biofuels, bio-electricity and other biomass coproducts will be required if the bioenergy industry is to develop.

Our analysis provides a credible and robust basis for future research. The data can be used to broadly assess the contribution by different sources and fractions of feedstocks as determined by the user. More importantly, it provides the basis for researching biomass supply and carbon mitigation cost curves for different biomass types feeding to different conversion technology pathways (for fuel, or in the future for biorefineries). The data provided here can also be used as the basis for more sophisticated scenario analysis at local, national and international scales to further assess the future contribution of bioenergy to energy supply and carbon mitigation in the light of various policy levers, or carbon and energy prices. More robust analyses of the full economics and sustainability implications of each biomass production system–bioenergy pathway will also be required to underpin industry development.

Acknowledgements

We thank Victoria Haritos and Andrew Warden for input on energy technology specifications; Peter Thorburn and Andrew Higgins for sugar data; Evelyn Krull, Paul Graham and two anonymous reviewers for review of the manuscript. Thomas Brinsmead, Peter Gresshoff and Gary Seaton provided useful comments on the manuscript. This research has been funded by CSIRO's Energy Transformed Flagship.

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